Project acronym: SURE-Farm

Project no.: 727520

Start date of project: June 2017

Duration: 4 years

D5.5 Impacts of future scenarios on the resilience of farming systems across the EU assessed with quantitative and qualitative methods

Work Performed by P8 INRAE (lead), P1 WU, P3 EVILVO, P4 UoG, P6 SLU, P7 UiB, P9 UPM, P10 UNITUS, P12 IAMO, P13 IEA-AR, P14 UNWE, P15 IRWiR PAN

Francesco ACCATINO, Wim PAAS, Hugo HERRERA, Franziska APPEL, Corentin PINSARD, Yong SHI, Lilli SCHÜTZ, Birgit KOPAINSKY, Katarzyna BAŃKOWSKA, Jo BIJTTEBIER, Jasmine BLACK, Camelia GAVRILESCU, Vitaliy KRUPIN, Gordana MANEVSKA-TASEVSKA, Franziska OLLENDORF, Mariya PENEVA, Jens ROMMEL, Carolina SAN MARTÍN, Simone SEVERINI, Bárbara SORIANO, Stela VALCHOVSKA, Mauro VIGANI, Erwin WAUTERS, Katarzyna ZAWALIŃSKA, Cinzia ZINNANTI, Miranda MEUWISSEN, Pytrik REIDSMA.

(francesco.accatino@inrae.fr)

Due date	31/May/2020
Version/Date	Final 28/May/2020
Work Package	WP5
Task	T5.3
Task lead	INRAE
Dissemination level	Public

TABLE OF CONTENTS

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Please cite this deliverable as:

Accatino, F., Paas, W., Herrera, H., Appel, F., Pinsard, C., Shi, Y., Schütz, L., Kopainsky, B., Bańkowska, K., Bijttebier, J., Black, J., Gavrilescu, C., Krupin, V., Manevska-Tasevska, G., Ollendorf, F., Peneva, M., Rommel, J., San Martín, C., Severini, S., Soriano, B., Valchovska, S., Vigani, M., Wauters, E., Zawalińska, K., Zinnanti, C., Meuwissen, M., Reidsma, P. 2020. D5.5 Impacts of future scenarios on the resilience of farming systems across the EU assessed with quantitative and qualitative methods. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

EXECUTIVE SUMMARY

For improving the sustainability and resilience of EU farming systems, it is important to assess their likely responses to future challenges under future scenarios. In the SURE-Farm project, a five-steps framework was developed to assess the resilience of farming systems. The steps are the following: 1) characterizing the farming system (resilience of what?), 2) identifying the challenges (resilience to what?), 3) identifying the desired functions (resilience for which purpose?), 4) assessing resilience capacities, and 5) assessing resilience attributes. For assessing the resilience of future farming systems, we took the same approach as for current farming systems, with the addition that future challenges were placed in the context of a set of possible future scenarios, (i.e., Eur-Agri-SSP scenarios).

We evaluated future resilience in 11 case studies across the EU, using a soft coupling of different qualitative and quantitative approaches. The qualitative approach was FoPIA-SURE-Farm 2, a participatory approach in which stakeholders identified critical thresholds for current systems, evaluated expected system performance when these thresholds would be exceeded, envisaged alternative future states of the systems (and their impact on indicators and resilience attributes), as well as strategies to get there. Quantitative approaches included models simulating the behavior of the systems under some specific challenges and scenarios. The models differed in assumptions and aspects of the farming systems described: Ecosystem Service modelling focused on the biophysical level (considering land cover and nitrogen fluxes), AgriPoliS considered, with an agent-based approach, socio-economic processes and interactions within the farming system, and System Dynamics, taking a holistic approach, explored some of the feedback loops mechanisms influencing the systems resilience from both a qualitative and quantitative approach.

Each method highlighted different aspects of the farming systems. For each case study, results coming from different methods were discussed and compared. The FoPIA-SURE-Farm 2 assessment highlighted that most farming systems are close to critical thresholds, primarily for system challenges, but also for system indicators and resilience attributes. System indicators related to food production and economic viability were often considered to be close to critical thresholds. The alternative systems proposed by stakeholders are mostly adaptations of the current system and not transformations. In most case studies, both the current and alternative systems are moderately compatible with 'Eur-Agri-SSP1 – Agriculture on sustainable paths', but little with other Eur-Agri-SSPs'. From the point of view of ecosystem services and nitrogen fluxes, the more resilient case studies are those able to provide multiple services at the same

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

time (e.g., hazelnut cultivations in Italy and vegetable and fruit cultivation in Poland, able to provide good levels of both food production and carbon storage) and those well connected with other neighbouring farming systems (e.g., the Dutch case study receiving manure by the livestock sectors). The System Dynamic simulation (applied quantitatively for the Dutch and French case study) highlighted the need to develop resources that can increase farmers' flexibility (e.g., access to cheap credit, local research and development, and local market). It also showed that innovation, networks, and cooperation contribute to building resilience against economic disturbances while highlighting the challenges for building resilience to environmental threats. From the application of AgriPoliS to the German case study it was concluded that changes in direct payment schemes not only affect the farm size structure, but also the functions of the farming system itself and therefore its resilience.

The report showed complementarity between different methods and, above all, between quantitative and qualitative approaches. Qualitative approaches are needed for interaction with stakeholders, understand perceptions of stakeholders, consider available knowledge on all aspects of the farming system, including social dimensions, and perform a good basis for developing and parameterizing quantitative models. Quantitative methods allow quantifying the consequences of mental models, operationalizing the impact of stresses and strategies to tackle them and help to unveil unintended consequences, but are limited in their reach. Both are needed to assess resilience of farming systems and suggest strategies for improvement and to help stakeholders to wider their views regarding potential challenges and ways to tackle them.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

1. ASSESSING FUTURE RESILIENCE

Francesco Accatino, Wim Paas, Hugo Herrera, Franziska Appel, Pytrik Reidsma

1.1 Introduction

Farming systems in Europe face a number of challenges of different types, economic, environmental, social, and institutional, in the form of sudden shocks or gradual stresses. These challenges occurred in the past, are occurring in the present, and are likely to occur also in the future. The SURE-Farm project aims to investigate the resilience and the sustainability of European farming systems. Resilience refers to the capacity of farming systems to face challenges while maintaining the provision of private and public goods, whereas sustainability refers to a balanced provision of these goods

A framework was developed in the project to assess the resilience of farming systems (Meuwissen et al., 2019). The framework guides through the definition of the main aspects of resilience assessment, i.e., the resilience "*of what", "to what*", and "*for which purpose*". The "*of what*" corresponds to the definition of the system, the "*to what*" corresponds to the inventory of the challenges relevant for the system, the "*for which purpose*" corresponds to the inventory of the relevant functions provided by the system. In addition to that, the framework guides through the assessment of three resilience capacities (robustness, adaptability and transformability) and of resilience attributes (i.e., characteristics of the system that increase the likelihood that the system is resilient). Resilience attributes contribute to the "generic resilience", i.e., the capacity of the system to withstand both known and un-known challenges.

Among the most important purposes of WP5 are the operationalization of the resilience framework and the assessment of the provision of private and public goods in 11 case studies (see the overview of the SURE-Farm case studies in D1.3 (Unay-Gailhard et al., 2018). A toolbox for Integrated Assessment (IA) was selected and presented in D5.1 (Herrera et al., 2018). This toolbox includes a set of qualitative and quantitative methods for investigating the resilience of farming systems under different angles, including the response of systems to challenges and their provision of functions.

An integrated assessment of the current resilience and provision of functions for the 11 SURE-Farm case studies was done in D5.3 (Reidsma et al., 2019). The core of the methods used for the assessment were selected from the IA toolbox and included specifically FoPIA- SURE-Farm 1 (see D5.2, Paas et al., 2019), ecosystem services assessment (see D5.3, Chapter 15), and stochastic and statistical modelling (see the Appendices of D5.3). The analysis was also complemented with insights gained from other SURE-Farm work packages, specifically farm surveys (D2.1 Spiegel et

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

al., 2019), learning capacity interviews (D2.3, Urquhart et al., 2019), risk management focus groups (D2.6, Soriano et al., 2020), demographic interviews (D3.2, Coopmans et al., 2019), AgriPoliS focus groups (Pitson et al., 2019), and the ResAT policy analysis (D4.1 Termeer et al., 2018).

The purpose of the current deliverable is to assess the resilience of farming systems and their provision of private and public goods in the future. Compared to the assessment of the present resilience, assessing future resilience requires a different operationalization of the SURE-Farm resilience framework as well as a selection of different tools, both quantitative and qualitative. The need for a different operationalization of resilience is mainly grounded in the consideration that different scenarios and alternative states are possible for the future. The models selected from the IA toolbox are needed for making projections of the behavior of farming systems in possible futures. The models and methods considered are ecosystem services modelling, system dynamics, AgriPoliS, and FoPIA-SURE-Farm 2.

The rest of this introductory chapter is structured as follows. First, (section 1.2) we give an overview of the methods selected from the IA toolbox (D5.1; Herrera et al., 2018; more in-depth details will be given in dedicated chapters). Second we explain how we operationalize the resilience framework for future resilience assessment. Third, we describe how different elements of the resilience framework are addressed by the different selected methods of the IA toolbox. Fourth, we provide an overall consideration about possible differences and complementarities between qualitative and quantitative methods for resilience assessment. In the rest of the deliverable, Chapter 2, 3, 4, and 5 are dedicated to the application of and FoPIA-SURE-Farm 2, ecosystem service modelling, system dynamics, AgriPoliS, respectively, to different case studies; Chapter 6 is dedicated to a comparison of the results obtained from different methods for some case studies; and Chapter 7 provides overall conclusions.

1.2 Modelling tools used for the integrated assessment in future scenarios

We selected a number of tools from the IA toolbox for the assessment of private and public functions and of resilience in future scenarios in the SURE-Farm case studies. Each of the method of the IA toolbox has a specific aim and was developed for a specific research question. Therefore a multiplicity of methods made it possible to gain insights on different aspects of the farming systems: as stated in D5.1 (Herrera et al., 2018), the insights gained from the application of different methods can be compared, discussed, and integrated into narratives. The methods selected for this deliverable from the IA toolbox are the Ecosystem services modelling, the System Dynamics, AgriPoliS, and the FoPIA-SURE-Farm 2. Ecosystem services modelling and AgriPoliS are more targeted on specific aspects of the system, being the biophysical part for ecosystem service modelling and the demographic, economic and institutional (policy) part for

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

AgriPoliS. System Dynamics and FoPIA-SURE-Farm 2 make it possible to have a more holistic view on the system, with the difference that System Dynamics uses modelling to explore system's behavior over time and FoPIA-SURE-Farm 2 is entirely based on a participatory approach with stakeholders.

Due to differences in the data requirements, the application of the tools to the different case studies was done to different extents (see the summary in Table 1.1). Ecosystem service modelling could rely on data accessible for all the case studies, therefore could be applied to all the case studies. Concerning FoPIA-SURE-Farm 2, participatory workshops could be done for 9 case studies between December 2019 and February 2020; for two case studies (France and Belgium) a participatory workshop could not be done due to the COVID-19 crisis and therefore it was substituted by an expert-based study. System Dynamics could be used to develop a generic qualitative model, which provided insights relevant across some case studies (Germany, France, Spain, Italy, The Netherlands). The development of a quantitative System Dynamics model and AgriPoliS had very high data requirements and therefore could be applied only to a limited number of case studies (The Netherlands and France for System Dynamics, and Germany for AgriPoliS). Other tools of the toolbox (FSSIM, statistical modelling, and the stochastic model) are not included in this deliverable for different reasons. FSSIM is a farm level model with high data requirements. As the type of farming systems in the case studies vary widely, and the focus in SURE-Farm is on the farming system level, and not the farm level, the efforts to employ FSSIM would not do justice to the insights expected regarding resilience and sustainability. Instead, the ecosystem modelling largely covers the aims as expressed in the proposal, i.e. to assess synergies and trade-offs among the performance of different functions. Statistical modelling has been applied, but largely focuses on current resilience and delivery of private and public goods, not on future scenarios, and is therefore not presented here. Results of the stochastic modelling in the Italian case study were included in D5.3, and as far as future scenarios are considered, results will be compared with other methods.

Overall, the application of the different modelling tools to the different case studies made it possible to have an insightful overview of resilience in future scenarios, as well as on complementarities and synergies between different methods. The rest of this section gives an overview of the methods, highlighting the different aims for which they are conceived and therefore the particular aspects in the farming systems investigated. More details in the description of the methods are given in the dedicated chapters of this deliverable.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 1.1 – Application of the different tools of the SURE-Farm IA toolbox to the SURE-Farm case studies for this deliverable. For the FoPIA-SURE-Farm 2, the (X) indicates that the method was applied as a desk study and not as a participatory assessment with stakeholders.

	Case studies										
Method	BE	BG	DE	ES	FR	IT	NL	PL	RO	SE	UK
E.S. modelling	X	X	X	X	X	X	X	X	X	X	X
System Dynamics Qual.			X	X	X	X	X				
System Dynamics Quant.					X		X				
AgriPoliS			X								
FoPIA-SURE-Farm 2	(X)	X	X	X	(X)	X	X	X	X	X	X

1.2.1 Overview of Ecosystem Services assessments

The Ecosystem Service assessments consists of two models focused on the biophysical components of the farming systems. The first model is a land use optimization model, the second is a nitrogen fluxes dynamic simulation model. The two Ecosystem Service models consist of specific models that need to be calibrated or parameterized according to the different farming systems.

The land use optimization model is static (i.e., the time component is not considered) and consists of statistical relationships linking land use and climate variables to the provision of two ecosystem services (crop production and carbon sequestration). This model is used for applying a multi-criteria analysis for studying the trade-off between the two ecosystem services. The output of the model is a set of "possible future system configurations" characterized by different provisions of the two ecosystem services. The method does not provide the "best" future system configuration, but provides the set of alternatives within which a political choice has to be made.

The Nitrogen Fluxes model is focused on the fluxes of nitrogen between compartments of the farming system, i.e., the soil, the vegetal compartment (crops and grasslands), and the animal compartment. The model can provide time trajectories of private functions (related to food production) and public functions (soil organic nitrogen). By running the model it is possible to simulate the impact of certain challenges testing the robustness of the system.

1.2.2 Overview of System Dynamics

The System Dynamics approach provides a holistic but high-level view on the farming system. System dynamics focuses on identifying feedback loop mechanisms and resources that drive system response to shocks and disturbances. Using system dynamics it is possible to model approach many aspects of the farming system (e.g., biophysical, social, economic), as well as

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

their reciprocal interactions. The description of the system is done via a relational causal loop diagrams describing interactions between system components. Analysing these diagrams it is possible, from a qualitative perspective, to identify the feedback loops driving system's behaviour over time). Causal loop diagrams can be transformed into fully fleshed simulation models by operationalizing the interactions between components through mathematical equations. Simulation models can be used to generate trajectories of relevant variables and provision functions over time. The System Dynamics is not a specific model but a modelling approach, and specific models can be formulated and thereafter calibrated/parameterized for the different SURE-Farm case studies.

1.2.3 Overview of AgriPoliS

AgriPoliS (Agricultural Policy Simulator) is an agent-based model that focuses on evolution of agricultural structures based on the (economic) development of individual farms. Its aim is to understand the effects of stresses and policy changes on farm structures and to capture potential emergent phenomena which arise from these interactions (see Balmann, 1997; Happe, 2004; Kellermann et al., 2008).

1.2.4 Overview of FoPIA-SURE-Farm 2

The FoPIA-SURE-Farm 2 approach is a semi-qualitative approach that consists of a series of participatory activities done with stakeholders. Whereas FoPIA-SURE-Farm 1 focused on the past and present situation, FoPIA-SURE-Farm 2 addresses future resilience and delivery of private and public goods. It aims to discuss the functioning of the farming system, the impact of possible future challenges on the system, and to identify alternative systems that improve resilience and sustainability (along with the possible trajectories to get there). Via discussion with stakeholders, it is specifically possible to (i) identify critical thresholds in the system, (ii) discuss alternative system configurations and link them with possible future scenarios already conceived for European agriculture (i.e., the Eur-Agri-SSP scenarios), (iii) assess expected performance of farming systems under maintenance of the status quo, system decline and alternative systems, (iv) expose some of the system mechanism that explains system dynamics.

1.3 SURE-Farm resilience framework in future scenarios

The SURE-Farm resilience framework consists of five steps aimed at defining resilience and sustainability of farming systems (Figure 1.1). The first three steps include the definition of the system, the inventory of the relevant challenges, and the inventory of the most relevant functions along with their performance. The fourth step is the assessment of the resilience capacities, i.e., robustness, adaptability, and transformability. Robustness is defined as the capacity to withstand stresses and shocks; adaptability is defined as the capacity to make

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

adjustment in the configuration in response to stresses and shocks without changing the structures and feedbacks mechanisms of the faring system; and transformability is the capacity to significantly change the internal structure and feedback mechanisms of the farming system in response to stresses and shocks. The fifth step refers to the identification of the resilience attributes based on observed resilience capacities. These resilience attributes are defined as characteristics of the system that enhance the likelihood of the system to be resilient. In SURE-Farm, resilience capacities attributes relate to the resilience principles of openness, modularity, diversity, tightness of feedback and system reserves. In SURE-Farm, resilience attributes (Step 5) are also used vice versa to determine resilience capacities (Step 4), e.g. in FoPIA-SURE-Farm 2. Here we define a set of concepts useful for future resilience assessment: the concepts of future challenges, scenarios, and alternative systems. Then, we describe how the different methods selected are conceptually differently related to the elements of the resilience framework.

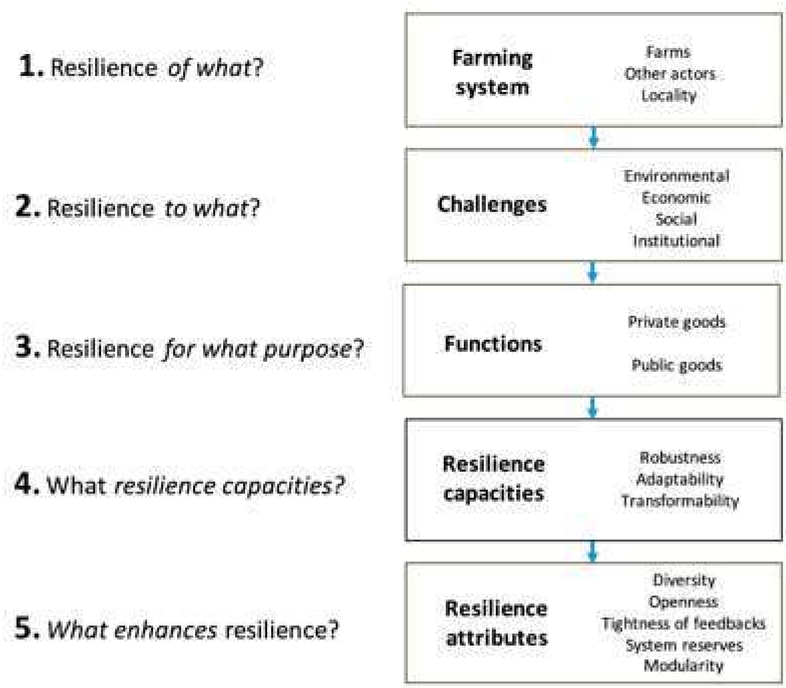


Figure 1.1 – Resilience assessment framework from Meuwissen et al. (2019)

1.3.1 Future challenges, alternative systems, scenarios

Future challenges are challenges that might occur in the future. While the past and current assessment is an inventory of challenges occurred in the system, future challenges can be many

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

and different according to projections. They can be completely new challenges, or existing challenges that increase in magnitude and push the system beyond certain limits

Alternative systems are configurations of the system alternative to the current one that have more or less likelihood to occur in the future. The notion of alternative system does not simply denote the current system providing different levels of functions, it rather denotes a system with different feedbacks, elements, and inter-relationships.

Scenarios are possible contexts and narratives in which the system can be embedded in the future. They are not simply limited to future challenges but describe a wider context. They might constitute additional challenges but also opportunities that enhance characteristics of the systems or mitigate possible challenges. For example, a scenario that envisages progressive decline in livestock production is a challenge for the farming systems specialized in dairy production; on the contrary, a scenario that envisages the increment in livestock production at the European level provides an opportunity for the same system. In this deliverable we often refer to the five Eur-Agri-SSP scenarios developed for Europe (Mitter et al., under review). Future challenges can be either enhanced or mitigated in different scenarios. Alternative systems can be compared with the scenarios and their compatibility can be evaluated.

1.3.2 Approaches to resilience assessment in future scenarios with modelling tools

The modelling tools used in this deliverable belong to two families: on the one hand there are quantitative simulation models (i.e., ecosystem service modelling, system dynamics, and AgriPoliS) and on the other hand we have a participatory assessment (FoPIA-SURE-Farm 2). These two families of methods approach the different elements of the resilience assessment of future system stages (including scenarios and alternative systems) in different ways.

In simulation modelling, future challenges as well as future scenarios are imposed by the modeler by means of given trajectories of input variables or parameters. The model then is able to simulate the provision of *future functions* under the given *future scenarios* and *future challenges*. By elaborating on the results it is possible to define metrics of resilience capacities and discuss resilience attributes.

In the participatory assessment, communicating future scenarios and challenges to participants would be unnecessarily complicating things. Instead, future challenges are an outcome of the methods as participants can indicate the most likely and relevant challenges for the future according to their view. In addition, proposed alternative systems can be compared with the Eur-Agri-SSP scenarios by researchers in the evaluation phase after the workshop.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

1.4 Steps of the resilience assessment frameworks with the different methodologies

This section provides a compared overview of how the different methods taken from the IA toolbox for this deliverable address the different elements of the SURE-Farm resilience framework. This section does not go into details, but details are given in the chapters dedicated to the application of the methods (i.e., Chapters 2, 3, 4, 5). The models can be used following the SURE-Farm resilience framework, this means that they can be used for both specific and generic resilience. In particular, steps 1, 2, and 3 regard the application of the models to specific aspects of the system (system definition), specific challenges and functions that can be simulated. Direct results obtained by following the first three steps related to specific resilience to given functions, future challenges and context. Steps 4 and 5 are more about general insights that can be withdrawn from the model results and therefore can be used for considerations about generic resilience. The application of FoPIA-SURE-Farm 2 largely addresses specific resilience (defining the challenges, indicators and closeness to thresholds), however some insights can be derived about general resilience, by discussing the direction of resilience attributes and by discussing the compatibility of alternative systems to Eur-Agri-SSP scenarios.

1.4.1 System definition

The definition of the farming system is a very important step because it sets the limits of what can be considered and investigated in the other steps of the resilience framework. The FoPIA-SURE-Farm 2 approach is based on discussions with stakeholders; therefore the representation of the farming system can be holistic and defined as in Meuwissen et al. (2019). However, for quantitative models, there are some methodological differences. Because quantitative models are conceived and built with specific purposes, they focus on specific components of the farming system and are based on assumptions. What can be done with the model should therefore be coherent with the model assumptions. Thus, the definition of the system corresponds, with its particular conceptualization for the model considered.

The land use optimization model considers the NUTS3 region in which the farming system is embedded. Such region is divided into spatial units (squares of 10 km x 10 km) and the different land cover fractions in each spatial units are considered. In the nitrogen fluxes model, the farming system is represented by the compartments composing a farming system from the agronomic point of view (i.e., soil, crops/grasslands, livestock). In the System Dynamics approach, the system is represented as a causal loop diagram between components of the farming system. All components of the system can be potentially included in the representation. The representation of the system can be therefore very complete and holistic, however the results will not be strictly predictive but will constitute more a projection of possible trends. In

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

AgriPolis, the farming system is defined based on the farm types and regional specifics that are representative for the farming system.

1.4.2 Functions

The SURE-Farm project identified eight main functions provided by farming systems. These functions can be identified by different measurable indicators. One function can be represented by several indicators. In FoPIA-SURE-Farm 2 all eight functions can be potentially considered. The functions and the indicators considered are those that are deemed relevant by the stakeholders. For models, indicators of functions are mainly output variables (but in some cases that can also be inputs) and the functions considered correspond only to those that can be simulated and are included in the structure of the model itself.

An overview of the function indicators calculated by the models used in this deliverable is given in Table 1.2. Indicators assessed in FoPIA-SURE-Farm 2 are not included, as the method can potentially cover all functions, and the selected indicators differ per case study. However, in general, the indicators perceived as most important by the stakeholders and therefore selected, include ones related to 'food production', 'economic viability' and 'maintenance of natural resources' (FoPIA-SURE-Farm 1; Paas et al., 2019). These are also the functions most prominent in the quantitative methods. The System Dynamics approach can be ideally adapted to simulate a wide range of functions. For the application of System Dynamics for this deliverable, it was possible to simulate food production (starch potato production and beef production for the Dutch and French case study, respectively), the farmers' income and the return on investments (for the function "economic viability") and the jobs in rural areas (for the function "quality of life"). AgriPoliS can simulate a number of functions. As AgriPoliS is an agent-based model, functions can be simulated at the level of farms. The output variables are provided on farm level as well as aggregated on the regional level. It is possible to assess the effects of future scenarios on crop, livestock and biogas production for "food production" and "other bio-based products". In the context of economic viability, AgriPoliS can simulate a number of different indicators (Table 1.2 provides only examples), such as profits per farm, regional profits, family farm income, long-term and short-term interest, revenue from rented land. AgriPoliS provides output on the use of hired labor, which could be an indicator for job opportunities in the context of quality of life in rural areas. Despite not done for this deliverable, AgriPoliS could also be used to calculate indicators related to "Natural Resources", "Biodiversity and Habitat" (see Hristov et al., 2020) and "Animal Health and Welfare" Emissions, carbon sequestration, nitrogen levels in the soil, and land use intensity (proxy for "Biodiversity and Habitat") can be simulated, and animal welfare can be accounted for by posing restrictions by the modeler.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Concerning the land use optimization model, the functions considered are crop production (for the function "food production") and carbon storage (for the function "natural resources"). Concerning the nitrogen fluxes models, the functions considered are food production (can be either expressed in tons of dry matter or in tons of nitrogen) and soil organic nitrogen (for the function "natural resources"). Not all functions can be calculated by the quantitative models considered in this deliverable. In some cases, functions are a priori difficult to be captured with quantitative models (e.g., "Animal health and welfare"). Complementarity of methods will be discussed also in this sense.

Table 1.2 – Indicators quantified for the SURE-Farm farming system functions with the different models. The unit "tonsDM" stands for 'tons of dry matter", the unit "tonsN" stands for "tons of nitrogen. FoPIA-SURE-Farm is not considered in the table as all 8 functions can be potentially considered and the choice of the indicators is case-study-specific; therefore details for this method are provided in the dedicated chapter. For "Economic Viability" in AgriPoliS only some examples are given.

	System Dynamics (in D5.5)	AgriPoliS	Land use optimization model	Nitrogen fluxes model
Food production	• Starch potato production (NL case study) • Beef production (FR case study)	• Crop production • Livestock production	• Crop production (includes fodder and bioenergy) in [tonsDM / ha]	• Crop production for human consumption [tonsDM] • Animal-source food production [tonsN] • Total food production [tonsN]
Other bio-based products	-	• Biogas production	-	-
Economic viability	• Farm income • Return on investment	• Profits per farm • Farm family income • …	-	-
Quality of life	• Jobs in rural areas	• Amount of hired labour needed • Wages	-	-
Natural resources			• Carbon	• Organic

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

			storage in [tonsC/ha]	nitrogen in the soil [tonsN]
Biodiversity and habitat	-	-	-	-
Attractiveness of the area	-	-	-	-
Animal health and welfare	-	-	-	-

1.4.3 Challenges

Challenges are a number of possible disturbances (in the form of sudden shocks or long-term stresses) that undermine the provision of the functions by the farming systems. In the FoPIA-SURE-Farm 2 approach a large number of challenges can be potentially considered and, in particular, the challenges deemed relevant by stakeholders are taken in account with detail, especially if they are considered critical for pushing the system towards a tipping point. By means of a causal loop diagram, specific challenges are then linked with relevant indicators and resilience attributes.

Concerning quantitative models, the challenges that can be considered are those that can be simulated by the models. For example, the ecosystem service models cannot simulate (in not indirectly) the impact of frequent changes in policies. In addition, this deliverable provides a specific application of the modelling tools: therefore, among all the specific challenges that can be potentially be simulated, a specific challenge is picked and simulated for this deliverable.

With quantitative models, challenges are simulated via imposing a change in the input variables or in the model parameters. With the application of System Dynamics the challenges simulated include social (e.g. aging of the farmers population), environmental (e.g. increase of droughts), and economic (e.g. increase in the production costs) challenges. These were selected, as they were among the most important challenges in the case studies considered. With the application of AgriPoliS, the challenge simulated was a change in the policy, in particular the capping and complete abolishment of direct payment. Also this challenge was selected as it relates to an important challenge in the case study. Concerning the land use optimization model, the purpose was to address the conflict between a public and a private function via land use changes, therefore the challenge considered is the land use conflict in a context of limited land availability. In many case studies, the reduction in the delivery of public goods, while maintaining production was seen as a challenge. With the application of the nitrogen fluxes model, the challenge simulated is the progressive decrease in availability of synthetic fertilizer and feed for import. While the focus of stakeholders was more on challenges affecting

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

economic viability, and the reduction of synthetic fertilizer and feed for import was not mentioned as challenge in any of the case studies, this is a challenge that can have an impact on the long-term, and it allows to assess the environmental resilience of the farming systems.

1.4.4 Resilience capacities

In all the methods applied for this deliverable, results can provide insights about the resilience capacities. For all the methods, resilience capacities can be defined by specific metrics that can be calculated with the results. It is also possible to discuss the resilience capacities qualitatively, although the qualitative discussion prevails for FoPIA-SURE-Farm 2, while for models it is more about defining quantitative metrics.

Assessment of robustness

For FoPIA-SURE-Farm 2, robustness is assessed with the closeness of the system to tipping points (i.e., critical thresholds as defined by the stakeholders) and with the presence of interacting thresholds. With the System Dynamics approach, for this deliverable, recover rapidity is understood as an indication of robustness of the system. With AgriPoliS robustness was assessed by analyzing the extent to which the region can withstand shocks and stresses and continue to produce the same amount, with the same amount of people, and without loss of farms. In the nitrogen fluxes model the robustness is assessed as the percentage decrease in food production with respect to the initial state. Such metric is calculated at different time steps of the simulation (for detecting difference in short-term *vs* long-term robustness). Robustness is not assessed with the land use optimization model.

Assessment of adaptability

In the FoPIA-SURE-Farm 2 approach, alternative systems are generated. Considering the alternative systems that represent an adaptation of the current state (i.e., there are no substantial changes in the configuration and the in feedback mechanisms) the adaptability of the current system can be discussed considering the strategies suggested by stakeholders to get to the alternative system. In the application of AgriPoliS adaptability is assessed by analyzing how the farms and the region change their structure in response to the scenarios and input variables (for example, change in sizes and numbers of farms in response to a capping of direct payments). A change in the regional structure is interpreted as an adaptation in response to political changes. The land use optimization model is based on the concept of multi-criteria optimization and Pareto frontier. In this context, the adaptability can be considered as the capacity of the system to increase both functions considered (i.e., crop production and carbon storage) and the distance of the current situation to the Pareto frontier. Adaptability is not

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

defined with a metric in the nitrogen fluxes model but can be discussed based on the results according to how the system changes some variables in relation to the initial state.

Assessment of transformability

In the FoPIA-SURE-Farm 2 methods, alternative systems are proposed by participants. Considering the alternative systems that represent a transformation of the current state (i.e., there are substantial changes in the configuration and the in feedback mechanisms) the transformability of the current system can be discussed considering the strategies suggested by stakeholders to get to the alternative system.

Assessing transformability with models is quite challenging. Models, by definition, represent a framework of assumptions, elements, and conceptual relationships. The results of the model will always be coherent with such a framework. A transformation is defined as a change in settings and feedback mechanisms and thus a change in the framework of assumptions, elements, and conceptual relationships upon which the model itself is based. In alternative, if the state variables and the configuration change too much along a simulation, it could be argued that the simulated system undergoes a transformation. However, in this case, the threshold is arbitrary to distinguish an "adaptation" from a real "transformation.

However, transformability regards a substantial change from the initial conditions, for example a system can be considered "transformed" if it reaches a different steady state following a disturbance. In System Dynamics it is not possible to provide major insights about transformability, but it is possible to identify the thresholds beyond which transformation could be expected. In the land use optimization model, it can be argued that if a point of the Pareto frontier is very "far" from the current configuration, it constitutes a transformation. However, the threshold limiting "not far" by 'far" is very arbitrary. It depends on the underlying land use changes that determine this point. Overall, we can say that transformability can be discussed (in a participatory approach, for example FoPIA-SURE-Farm 2) but not clearly measured with a metric in the methods applied.

1.4.5 Resilience Attributes

According to assumptions of the models and the way the farming system is represented, a number of resilience attributes can be discussed and/or assessed. Here we give an overview of the resilience attributes that can be addressed in the different methods (Table 1.3), but details are provided in the dedicated chapters. As in D5.2 (Paas et al., 2019), resilience attributes are adapted from Cabell and Oelofse (2012) and are linked to five generic resilience principles (Resilience Alliance, 2010), i.e., diversity, modularity, openness, tightness of feedbacks, system reserves. In this deliverable we also addressed two attributes linked to one of the resilience

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

principle (system reserves) but that could not fit into any of the resilience attributes previously identified. In the land use optimization model we found that some land can be used as "buffer" for expansion of crops and forest; in the nitrogen fluxes model we found that the excess of organic nitrogen in a system can constitute a system reserve and enhance robustness in case of progressive diminution of synthetic fertilizer availability. We added the resilience attribute "excess of resources" that could be referred to both excess of land and excess of organic fertilizer available.

Table 1.3 – Resilience attributes that can be assessed and/or discussed with the different models used in this deliverables. Models/methods considered are System Dynamics (SD), AgriPoliS (A), Land use optimization model (LUO), Nitrogen fluxes model (NF). Resilience attributes are linked to resilience principles (Resilience Alliance, 2010): diversity (DI), modularity (MO), openness (OP), tightness of feedbacks (TF), system reserves (SR). Lines in italics refer to resilience attributes not fitting into the ones derived by Cabell & Oelofse (2012) in D5.2, but could fit into a resilience principle.

Resilience principle	Resilience attribute	SD	A	LUO	NF
SR	Reasonably profitable	X	X		
SR, TF	Coupled with local and natural capital			X	X
DI	Functional diversity		X	X	X
DI	Response diversity	X	X		X
OP	Exposed to disturbance	X	X		X
MO, DI	Spatial and temporal heterogeneity		X		X
MO	Optimally redundant (farms)		X		
SR	Supports rural life	X			
TF, SR	Socially self-organized	X			
TF	Appropriately connected with actors outside the farming system				X
SR	Coupled with local and natural capital (legislation)	X			
OP, SR	Infrastructures for innovation		X		
DI	Diverse policies				
TF	Ecologically self-regulated				
MO	Optimally redundant (crops)				
MO	Optimally reduntant (nutrient and water)			X	
MO, DI	Spatial and temporal heterogeneity		X		
MO	Optimally redundant (labor)	X			
OP, TF	Globally autonomous and locally interdependent	X			X
OP	Reflective and shared learning				
SR	Honors legacy				
SR	Builds on human capital	X			
SR	*Excess of resources*	X		X	X

1.4.6 Future scenarios

The narrative of future scenarios can be considered as contexts into which future challenges can be embedded and alternative systems can fit or not. In this deliverable we consider the five Eur-Agri-SSP scenarios developed in D1.2 (Mathijs et al., 2018) and further developed (Mitter et al., 2019; under review). In FoPIA-SURE-Farm 2, the alternative systems formulated by the stakeholders are evaluated by researchers regarding their overall (in)compatibility with the Eur-

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Agri-SSP scenarios. For each scenario, the average of the compatibilities of all the alternative systems can be then considered as the compatibility of the current system to the scenario. In the modelling methods, scenarios are simulated via assigning trajectories of input variables or changing parameter values; details are given in the different chapters. Concerning the System Dynamics, it is important to identify the main loops that can be triggered by different challenges. Each of these loops can be discussed in terms of its suitability with the different Eur-Agri-SSP scenarios.

1.5 Qualitative and quantitative methods: methodological differences

The use of different qualitative and quantitative methods is at the core of the integrated assessment of the resilience of farming system (D5.1), both for past and present resilience (D5.3) and for future resilience. We deemed it relevant to discuss the differences and complementarities between the two families of methods.

Representation of the system

Each modelling tool is usually specifically developed to address some specific questions and to describe a certain aspect of the system. For this reason, quantitative models might be very specific on certain aspects of the system (for example, ecosystem service modelling is focused on the biophysical component of the system). Instead, qualitative models can have a holistic view on the system, having a representation that makes it possible to involve all the components. It is to be noted however, that also some quantitative models can have a holistic view on the farming system, which is the case for System Dynamics.

Transparency

Models formalize some aspects of reality, making them objective and transparent. This makes it possible to have a common view for all the users that work around the same model. With qualitative methods, the definition of the system is less rigorous and less formalized. However, objectivity and transparency are not a guarantee of scientific soundness. Indeed, models can be wrong, with non-adapted assumptions or relying on poor data. For this reason, qualitative methods can be used as a support to validate the objective reality described by quantitative models.

Coherence

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Quantitative models make it possible to simulate future scenarios maintaining coherence with the set of rules constituting them. The coherence is guaranteed through the consistent application of rules and mathematical equations. In other words, if the model constitutes a conceptual transparent representation of reality, the use of the model extends the reach of our mind following the assigned rules and quantifies the consequences of the representation of the reality. It should be said that coherence obtained with mathematical relationships does not mean full predictability. In fact, if mathematical relationships are sufficiently complex and non-linear (even being them deterministic), the capacity of predicting the results without the model can be low even for those having a good knowledge of the model hypotheses. With qualitative models, it is more difficult to maintain the same kind of coherence and it might happen that the consequences of a given scenario fall in contradiction with the definition of the system. It is however to be noted that some tools and protocols are developed for maintaining coherence within participatory methods (see e.g., Mitter et al., 2019; under review), and tools like causal loop diagrams help in this purpose. In any case, when developing future scenarios, participatory methods indicate direction of changes (e.g., improvement or worsening); on the contrary quantitative models have the added value of providing quantifications of consequences of future scenarios.

A drawback of the coherence of quantitative models is the impossibility to conceive new systems and to develop "out-of-the-box" scenarios. For a quantitative model it is impossible, by definition, to suggest new configurations that go beyond what is represented by the models themselves. On the contrary, in participatory methods, it is possible to brainstorm "out-of-the-box" scenarios, i.e., to imagine future alternative systems completely different from the current configuration.

Metrics for resilience

Quantitative models give the possibility to provide clear definitions and metrics of resilience or of some aspects related to it. Examples of these metrics are the return time to equilibrium, the maximum disturbance that can be absorbed by the system without losing some assigned properties. It is possible to quantify these metrics for the past analyzing time series or for the future analyzing simulated trajectories (if models are well calibrated). Resilience and resilience capacities can be objectively defined also with qualitative methods, however without objective quantifications.

Coupling with mathematical frameworks

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Mathematical models can be embedded in other mathematical techniques able to provide additional insights about resilience and resilience capacities. Those techniques are, for example multi-criteria analysis (Dodgson et al., 2009), the application of the viability theory (Aubin, 1991), and the application of information theory (Ulanowicz et al., 2009). These techniques make it possible to investigate resilience by providing answers to question such as "which parameter is mostly affecting the output?", "How many strategies can be put in place in order to maintain the system in a desired state in face of random disturbances?', "how much time is needed to bring a system back to a viable state after perturbation?". All these types of questions are directly or indirectly related to resilience and to their capacities, i.e., robustness, adaptability, and transformability.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

2 FoPIA-SURE-Farm 2 ASSESSMENT

Wim Paas, Francesco Accatino, Franziska Appel, Jo Bijttebier, Jasmine Black, Camelia Gavrilescu, Vitaliy Krupin, Gordana Manevska-Tasevska, Franziska Ollendorf, Mariya Peneva, Jens Rommel, Carolina San Martín, Simone Severini, Bárbara Soriano, Stela Valchovska, Mauro Vigani, Erwin Wauters, Katarzyna Zawalińska, Cinzia Zinnanti, Miranda Meuwissen, Pytrik Reidsma

2.1 Introduction[1]

This chapter extends the FoPIA-SURE-Farm approach by providing results of participatory assessments on future resilience of EU farming systems (FoPIA-SURE-Farm 2). In a previous deliverable of SURE-Farm, current sustainability and resilience was assessed (D5.2; Paas *et al.*, 2019), using the Framework of Participatory Impact Assessment for Sustainable and Resilient EU farming systems (FoPIA-SURE-Farm 1; Reidsma *et al.*, 2019). FoPIA-SURE-Farm 1 included the five steps of the SURE-Farm resilience framework (Meuwissen et al., 2019): 1) defining the system, 2) identifying main challenges, 3) assessing current farming system functions, 4) assessing resilience capacities (robustness, adaptability and transformability), and 5) assessing resilience attributes (system characteristics that supposedly convey resilience to a system). While continuing being embedded in the theoretical resilience framework of SURE-Farm (Meuwissen et al., 2019), FoPIA-SURE-Farm 2 aims to include resilience concepts as critical thresholds or tipping points, cascading scales (e.g. Kinzig *et al.*, 2006), and regime shifts (e.g. Biggs et al., 2018), which were not explicitly taken into account in FoPIA-SURE-Farm 1.

System resilience relates to system dynamics and hence changes over time. As a consequence, not only the past and current, but also the future needs to be considered. Scenario research shows that there are different pathways of development towards the future (e.g. D1.2; Mathijs *et al.*, 2018). Along these future pathways, systems' functioning can change, and critical thresholds could be trespassed, possibly initiating cascading scales (Kinzig et al., 2006). This could lead to a different system with a changed identity, dependent on the scenario. Consequently, for future resilience, different futures need to be explored.

In general, extrapolations of statistical models to explore the future only show a limited part of all possible futures, based on patterns from the past. Systems dynamics modelling (e.g. Herrera, 2017; Chapter 4) can take into account multiple pathways towards the future, but is dependent on input from other methods for parameterization and structuring of the model(s). Moreover, currently available models are not excelling in modelling transformative change, e.g. simulating

[1] This introduction is into a great extent a copy of the introduction of the FoPIA-SURE-Farm guidelines as presented in the Supplementary Materials A of this report.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

trajectories to alternative desired systems. Participatory methods can integrate multiple future pathways (Delmotte et al., 2013; Walker et al., 2002) and to a limited extent can also include resilience concepts such as critical thresholds (Resilience Alliance, 2010; Walker et al., 2002).

Stakeholders may provide empirical knowledge about their system (Delmotte et al., 2013) that can fill in knowledge gaps (Vaidya and Mayer, 2014). Stakeholder input will be influenced by stakeholder's perceptions, which partly can also explain or drive system dynamics as stakeholders are important components of socio-ecological systems (Walker et al., 2002). However, it should be kept in mind that stakeholder inputs are based on different perceptions than for instance researchers' perceptions, indicating that both perceptions should be used in complementary ways (e.g. Sieber et al., 2018). Hence, participatory methods can provide a first exploration of farming system resilience in possible futures. Participatory methods also provide an opportunity to assess whether current strategies for more sustainability and resilience make sense in the light of expected future developments.

2.2 Methodology[2]

2.2.1 Structure and expected outcomes

FoPIA-SURE-Farm 2 includes a preparation phase, the workshop and an evaluation phase. The preparation and evaluation phase were conducted by the research team. In the preparation phase, research teams made use of SURE-Farm previous deliverables and (grey) literature. We considered scenarios and adaptive cycles too complicated and too time-consuming to be communicated during a workshop. Hence, we designed the main research questions that we thought of as being easy to understand and directly relevant for participants in the workshops. So, while the full approach of FoPIA-SURE-Farm 2 covers the complexity of resilience (including causal loop diagrams, cascading scales, future scenarios), this complexity is largely covered by the research teams. The stakeholder workshops were set up in such a way that they contributed to understanding complexity by researchers, while the participating stakeholders were not tired out by this complexity.

It is generally difficult to assess transformation and transformability with quantitative models (D5.1; Herrera *et al.*, 2018). FoPIA-SURE-Farm 2 allows to improve understanding on transformation and transformability. It should, however, be noted that towards the stakeholders a neutral approach was taken regarding their current farming system, i.e. it was not suggested by researchers to participants that systems should transform. The workshop was designed to

[2] This method section is into a great extent a copy of the text describing the main research questions and general structure of FoPIA-SURE-Farm as presented in the guidelines for FoPIA-SURE-Farm 2 (Supplementary Materials A; these also contain a detailed explanation of all research questions and steps to perform FoPIA-SURE-Farm 2)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

assist stakeholders to better understand the challenges affecting their current system, and strategies to improve the current system, or if desired, to transform into an alternative system.

2.2.2 Research questions

As the point of departure, the case study research teams conducted an assessment of the current performance levels and trends in the farming systems. This assessment was based on FoPIA-SURE-Farm 1 (Paas et al., 2019), other SURE-Farm deliverables and (grey) literature. Under RQ2, the boundary conditions were assessed to keep the current system as desired in the future (maintaining status quo). This included taking into account current trends and required improvements in function performance. Under RQ2, critical thresholds of important system indicators, resilience attributes and challenges were assessed by workshop participants. System's closeness to thresholds was consequently evaluated by the research team based on participant's comments and (grey) literature, e.g. based on ongoing trends identified under RQ1. Third, farming system performance was assessed when critical thresholds of main challenges would be exceeded (RQ3; system decline). Under RQ3, possibilities of cascading effects could be discussed. After discussing the conditions for maintaining the status quo and system decline, RQ4 addressed possible desired transformations of the farming system towards the future. Under RQ4, it was discussed what alternatives are possible when challenges would become more severe, and when certain functions would need more improvement than possible with the current system configuration. RQ5 aimed to gain information on whether the right investments were currently made and the possibilities of no regret options, regardless the direction of future pathways.

Main Research Questions (RQ):

1. What are the current performance levels and trends of main indicators, resilience attributes and challenges of the farming system?
2. What is required to keep the current farming system in the future? (i.e. what boundary conditions need to be in place and what critical thresholds should be avoided to maintain the status quo?)
3. What will happen if the essential requirements are not met? (system decline)
4. What are possible desired transformations of the farming system? (alternative systems)
5. Given the likelihood of future states, are current strategies dedicated to the right issues?
6. What are underlying mechanisms causing farming system dynamics?
7. Are maintaining the status quo and proposed alternative systems compatible with Eur-Agri-SSPs?

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Based on the information acquired in RQ1-RQ5, research teams aimed to expose the underlying mechanisms that cause farming system dynamics (RQ6). This approach was inspired by the work of Kinzig *et al.* (2006) and Biggs et al. (2018). Both sources have in common that they aim to present evidence for (potential) system transformation in a narrative way, with support of a visualization of interactions between important system parameters.

Biggs et al. (2018) mainly elaborate on transformations of the ecological part of social-ecological systems. Biggs et al. (2018) use a causal loop diagram (CLD) to support narratives of system transformations. In a CLD, system parameters, such as main indicators, resilience attributes, challenges and strategies, are presented by boxes that are connected with each other by arrows that represent interactions. A '+' or '-' indicates whether an interaction is seen as positive or negative, i.e. whether an increase in one parameter results in an increase or decrease of another parameter. Thus the relation between indicators, attributes, challenges and possible strategies can be exposed and presented. In a CLD, multiple interactions can form closed loops that provide either reinforcing (positive) or balancing (negative) feedbacks. The increase of a certain challenge may increase emphasis on certain feedback loops, explaining a change in system performance and identity (Brzezina et al., 2016).

Kinzig et al. (2006) specifically assess critical thresholds and cascading scales for alternative future states of agricultural regions. Kinzig et al. (2006) distinguish the ecological, as well as the economic and social/cultural domain across the patch, farm and region scale. Thresholds of systems parameters can interact across domains and levels of integration (Kinzig *et al.*, 2006; Figure 2). This might result in cascading effects and ultimately in alternative system states. The framework of Kinzig et al. (2006) can be seen as an abstract of a usually information richer CLD. The advantage of the framework of Kinzig et al. (2006) is that main thresholds and changes can be well qualified and visualized, where in a CLD it is not directly clear where and in which direction system changes occur. In FoPIA-SURE-Farm 2, the possibility of cascading scales was evaluated.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

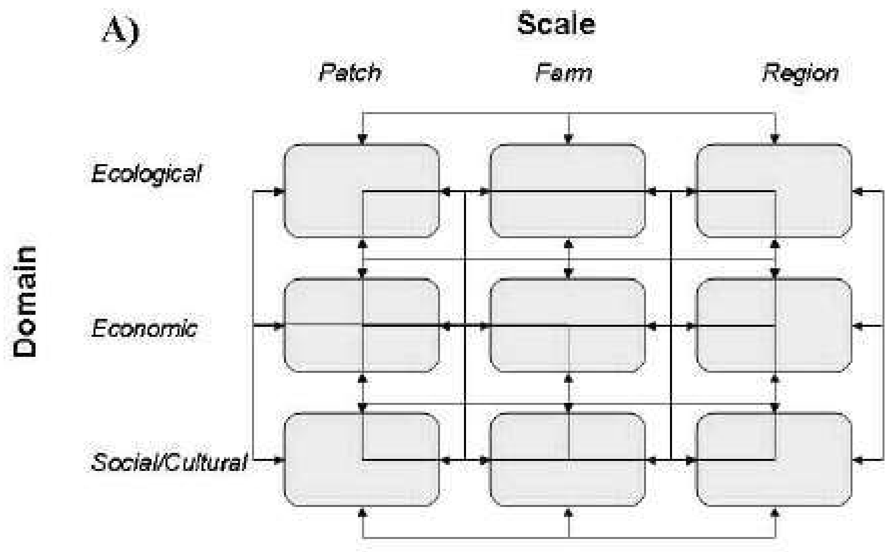


Figure 2.1. A visualization of possible threshold interactions between domains and scales leading to a system change. Source: Kinzig et al. (2006).

Under RQ7, proposed alternative systems were evaluated for compatibility with Shared Socio-economic Pathways (SSPs; O'Neill *et al.*, 2014, 2017) for European agricultural systems (Eur-Agri-SSPs; Mitter et al. (under review); see Supplementary Materials A for more details).

Although the complete adaptation or transformation process of farming systems may take longer, 2030 was taken as the time horizon for all research questions. In Supplementary Materials A, main research questions and sub-questions are explained in more detail, including linkages to the resilience framework of Meuwissen et al. (2019).

2.2.3 Stakeholder workshops

Stakeholder workshops were conducted in nine SURE-Farm case studies between November 2019 and February 2020 (Table 2.1). In BE-Dairy and FR-Beef, desk studies were performed, because planned workshops had to be cancelled due to measures that were put in place in the context of the COVID-19 outbreak. Participants from the agricultural community, government, (processing) industry, NGO's, agricultural advisors and researchers were invited and present (Table 2.1). The stakeholder workshops took about half a day. A detailed program of the workshop is provided in the Supplementary Materials A. The workshops mainly consisted of plenary and small group discussions. Individual workshop reports are presented in Supplementary Materials B-L.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.1. Stakeholder workshop timing and number of participants.

CS	Date	Total	Farmer	Govern-ment	Industry	NGO	Agricultural advice	Research	Finance	Other
BG-Arable	16/01/2020	19	8	5	1	2	3			
DE-Arable&Mixed	06/02/2020	15	5	4	1	1	1	1		
ES-Sheep	14/02/2020	18	7	4	1		3	3		
PL-Horticulture	29/11/2019	12	7	1		1	3			
IT-Hazelnut	21/01/2020	14	5	2	1	2	3	1		
NL-Arable	10/12/2019	22	8	3	2	2		3	2	2
RO-Mixed	12/03/2020	16	6	2	3			5		
SE-Poultry (eggs)	31/01/2020	7	5		1					1
SE-Poultry (broilers)	03/02/2020	2			2					
UK-Arable	15/01/2020	5		1		2	2			
BE-Dairy	Desk study	-								
FR-Beef	Desk study	-								

2.3 Cross case study comparison

2.3.1 Introduction

This sub-chapter synthesizes results from nine case study workshops. Where possible, results from the desk studies in BE-Dairy and FR-Beef are integrated in the text.

2.3.2 Main indicators per system

Taking FoPIA-SURE-Farm 1 results as a basis, a pre-selection was made of most important system indicators and resilience attributes.

Common across most case studies are indicators related to the function “Economic viability” and “Food production” (Table 2.2). For the function “Natural resources”, indicators that represent this function were mainly discussed in the arable systems. Indicators for “Attractiveness of the area” were discussed in case studies in which actors experienced a certain degree of isolation and/or outmigration (BG-Arable, DE-Arable&Mixed, IT-Hazelnut). In ES-Sheep, the number of farms in the region was used as an indicator for “Quality of life”, but also related to “Attractiveness of the area”. In UK-Arable, the happiness-index-of-farmers as an indicator for the function “Quality of life” also partly relates to the social isolation actors experience, but this indicator also relates to the acknowledgement and acceptance to farmers by consumers and society at large.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.2. Number of indicators discussed per system function per case study workshop.

System functions	BG-Arable	NL-Arable	UK-Arable	DE-Arable& Mixed	RO-Mixed	ES-Sheep	SE-Poultry	IT-Hazelnut	PL-Horticulture	Total[1]
Food production	2	1	1	1	1	1	1		1	9
Bio-based resources					1					1
Economic Viability	1	1	1	1	1	1	1	2	3	12
Quality of life			1			1				2
Natural Resources		2	1	3			1	1		8
Biodiversity & habitat	2		1		1					4
Attractiveness of the area	1			2				1		4
Animal health & welfare			1				1			2
Total	**6**	**4**	**6**	**7**	**4**	**3**	**4**	**4**	**4**	**42**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Resilience attributes most commonly discussed across case studies were "Infrastructure for innovation", "Production coupled with local and natural capital", "Socially self-organized" and "Reasonable profitable" (Table 2.3). Resilience attributes related to diversity were discussed in less case studies. SE-Poultry and PL-Horticulture emphasized both, the functional and response diversity. "Support rural life", a resilience attribute related to the interplay between the farming system and the rural population was discussed in DE-Arable&Mixed, IT-Hazelnut and RO-Mixed, where worries about isolation and/or outmigration exist (see also previous paragraph). In ES-Sheep and IT-Hazelnut, the resilience attribute "Diverse policies" was discussed. Both mentioned that case studies experience pressure from regulations that are aimed at improving the maintenance of natural resources, which brings extra production costs. These extra costs can currently not be easily compensated with increased product prices without losing a competitive advantage. Regulations seem not balanced in these case studies, in the sense that adaptability towards more environmental production is not well enough supported.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.3. Resilience attributes discussed per case study.

Resilience attributes	BG-Arable	NL-Arable	UK-Arable	DE-Arable& Mixed	RO-Mixed	ES-Sheep	SE-Poultry	IT-Hazelnut	PL-Horti-culture	Total[1]
Reasonably profitable		V	V				V		V	4
Production coupled with local and natural capital	V	V	V			V		V	V	6
Functional diversity							V		V	2
Response diversity				V			V		V	3
Exposed to disturbances	V						V			2
Heterogeneity of farm types			V		V					2
Support rural life				V	V			V		3
Socially self-organized	V	V	V					V		4
Appropriately connected with actors outside the farming system			V		V					2
Legislation coupled with local and natural capital					V					1
Infrastructure for innovation	V	V	V	V			V	V		6
Diverse policies						V		V		2
Total	4	4	6	3	4	2	5	5	4	37

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Challenges varied widely across case studies (Table 2.4). Low prices and price fluctuations or high production costs were perceived as main challenges in all studied systems, except in SE-Poultry. Although high production costs were not identified as a challenge as such in SE-Poultry, this challenge is experienced as a follow-up from other challenges: the high standards/ strict regulation and the need for changes in the technology. Challenges related to (continuous change of) laws and legislation were experienced as the main challenges in all studied systems, except for ES-Sheep. In ES-Sheep, low economic viability is directly related to reduced payments due to policy changes; policy issues in ES-Sheep were further addressed via the resilience attribute “Diverse policies”. Pressure from environmental laws and regulations were always experienced as the main challenge in combination with challenges from economic laws and regulations (UK-Arable, SE-Poultry and IT-Hazelnut). In BE-Dairy, challenges from environmental laws and regulations were experienced in combination with low prices and price fluctuations. Extreme weather was experienced as a main challenge in the studied arable, perennial and mixed systems, but not in the participatory studies on livestock systems. However, although not seen as a main challenge in ES-Sheep, extreme weather does play a role in this case study. In the desk study on BE-Dairy and FR-Beef, extreme weather was perceived by researchers to be a main challenge. When extreme weather was mentioned, the occurrence of drought was defined as the most important extreme event. In DE-Arable&Mixed, lack of infrastructure and low attractiveness of the area were specifically experienced as challenges. In ES-Sheep and BG-Arable, low attractiveness of the area was also perceived as a problem. During the workshop in ES-Sheep low attractiveness of the area was primarily perceived through the low availability of labor. Low availability of labor was also experienced in BG-Arable, PL-Horticulture and BE-Dairy. In SE-Poultry, changes in technology and consumer preferences were specifically experienced as challenges. Pest & diseases were very specific to case studies: plant parasitic nematodes (NL-Arable), wildlife attacks (ES-Sheep) and diverse yield and quality reducing pests (IT-Hazelnut). In BE-Dairy, low land availability was also a main challenge.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.4. The main challenges discussed per case study.

Challenges	Domain	BG	NL	UK	DE	RO	ES	SE	IT	PL	Total[1]
Change in technology	Agronomic							V			1
Low prices and price fluctuations	Economic	V		V	V	V			V	V	6
High production costs	Economic		V	V			V				3
Extreme weather	Environmental	V	V		V	V			V	V	6
Pests & diseases	Environmental		V						V		2
Wildlife attacks	Environmental						V				1
Continuous change of laws and regulations	Institutional	V	V		V	V				V	5
Economic laws & regulations	Institutional			V		V		V	V		4
Environmental laws & regulations	Institutional			V				V	V		3
Lack of infrastructure	Social				V						1
Low attractiveness	Social				V						1
Low labor availability	Social	V					V			V	3
Changes in consumer preferences	Social						V	V			2
Total		**4**	**4**	**4**	**5**	**4**	**4**	**4**	**5**	**4**	**38**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

2.3.3 Status quo

Current developments

Based on earlier work in SURE-Farm (e.g. D5.2; Paas et al., 2019) and (grey) literature, research teams assessed current developments of main indicators. Most of the farming system main indicators of system functions are currently not static according to the judgment of research teams in the preparation phase. Overall there is a slight decrease in main system indicators and resilience attributes. In IT-Hazelnut, SE-Poultry and NL-Starch potato, all perceived to be moderate to well performing systems (FoPIA-SURE-Farm 1), overall moderate positive indicator developments were expected. Overall moderate decrease of indicator performance was expected in ES-Sheep (mainly due to expected lower food production and lower attractiveness of the area), PL-Horticulture (expected lower "Economic viability") and UK-Arable (expected lower "Quality of life", maintenance of "Natural resources" and "Biodiversity & habitats"). ES-Sheep and PL-Horticulture were perceived to be already low performing farming systems (FoPIA-SURE-Farm 1). In BE-Dairy increased greenhouse gas emissions are expected, coinciding with increased milk production, while income is expected to stay fluctuating.

Boundary conditions

Boundary conditions were mentioned for maintaining the status quo. For the economic, environmental, institutional and social domains, on average equal numbers of boundary conditions were mentioned (about one to three boundary conditions per domain per case study). Agronomic boundary conditions were amongst others related to productivity levels (BG-Arable) and availability of new technology (ES-Sheep). Economic boundary conditions were amongst others related to access to new markets (ES-Sheep, IT-Hazelnut, NL-Arable), payments for the delivery of public goods (NL-Arable, ES-Sheep), balance between input prices and farm gate prices (SE-Poultry, RO-Mixed, PL-Horticulture, NL-Arable, IT-Hazelnut). Environmental boundary conditions were amongst other related to the limited occurrence of extreme weather events (BG-Arable, IT-Hazelnut, NL-Arable, PL-Horticulture, RO-Mixed), improved soil quality (NL-Arable, UK-Arable) and ecological regulations (IT-Hazelnut, RO-Mixed). Institutional boundary conditions were amongst others related to good governance (BG-Arable, DE-Arable&Mixed, ES-Sheep, NL-Arable, PL-Horticulture, RO-Mixed, SE-Poultry) and access to knowledge, finance and/or land (BG-Arable, DE-Arable&Mixed, PL-Horticulture, RO-Mixed). Social boundaries were amongst others related to rural demographics and/or availability of labour (BG-Arable, IT-Hazelnut, PL-Horticulture, RO-Mixed, SE-Poultry) and more cooperation and social self-organization (BG-Arable, ES-Sheep, PL-Horticulture, RO-Mixed, UK-Arable).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

In some case studies, emphasis was put on specific domains. In BG-Arable and RO-Mixed for instance, six, respectively five boundary conditions were defined for the institutional and social domain. In UK-Arable, four boundary conditions were mentioned for the environmental domain. Boundary conditions for maintaining the status quo in the future were least defined for the agronomic domain and only mentioned in BG-Arable, NL-Arable and ES-Sheep.

2.3.4 Critical thresholds

Closeness to critical thresholds

Introduction

Participants evaluated the existence of critical thresholds related to function indicators, resilience attributes and challenges. In plenary discussions, participants did sometimes discuss the relative closeness to critical thresholds. In case closeness to critical thresholds was not indicated by participants, the research team evaluated closeness based on the current performance levels, and magnitude of variation and/or trends.

Not close	It is unlikely that the distance to critical thresholds will be trespassed in the coming ten years, based on knowledge on possible variation and/or trends.
Somewhat close	It is somewhat likely that the distance to critical thresholds will be trespassed in the coming ten years, based on knowledge on possible variation and/or trends.
Close	It is likely that the distance to critical thresholds will be trespassed in the coming ten years, based on knowledge on possible variation and/or trends.
At threshold or beyond	Current levels are at or beyond the critical threshold

Function indicators

For most system indicators that were discussed, critical thresholds were defined (Table 2.5). Critical thresholds were defined mostly for system indicators that represented the functions “Food production”, “Economic viability”, “Natural resources” and “Attractiveness of the area”. Systems were evaluated to be mostly close to critical thresholds for “Food production” and “Economic viability” and somewhat close to critical thresholds for “Natural resources” and “Attractiveness of the area”. Participants in PL-Horticulture and ES-Sheep, lower performing systems according to participants in FoPIA-SURE-Farm 1, indicated that for some indicators, levels were at the threshold or beyond. Participants in UK-Arable and NL-Arable were worried that regarding soil quality, an indicator for “Natural Resources”, the system was at a threshold

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

or beyond and that keeping current levels already needed adaptation. In BE-Dairy, water quality and greenhouse gas emissions are beyond acceptable thresholds set by European and regional policy makers. In SE-Poultry, DE-Arable&Mixed and NL-Arable, participants remarked that critical thresholds for food production and economic viability differ from farm to farm. Hence, exceeding thresholds in these case studies may actually imply the disappearance of economically less competitive farms from the farming system.

Table 2.5. Number of function indicators per position relative to the perceived critical threshold (aggregated results across 9 case studies).

	Position relative to perceived critical threshold				No threshold defined	Not discussed	Total[1] (n)
Functions	Not close	Somewhat close	Close	At threshold or beyond			
Food production		1	4	3		1	9
Bio-based resources				1			1
Economic Viability		3	7	1		1	12
Quality of life	1			1			2
Natural Resources		4	1	2		1	8
Biodiversity & habitat	1		1		2		4
Attractiveness of the area		3			1		4
Animal health & welfare			1			1	2
Total (n)	**2**	**11**	**14**	**8**	**3**	**4**	**42**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Resilience attributes

Participants could define much less critical thresholds for the resilience attributes than for functions (Table 2.6). When critical thresholds were defined, they were often not quantified. The two times thresholds were defined for “Diverse policies” (in ES-Sheep and IT-Hazelnut), participants indicated that the system was at or beyond a critical threshold and that policies need to be adapted to the needs of the system. In IT-Hazelnut and DE-Arable&Mixed, the system is perceived to be close to a critical threshold regarding “Infrastructure for innovation”.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

For “Reasonable profitable”, when discussed and a critical threshold was defined, systems were perceived to be close to a critical threshold, similar to “Economic viability” in the previous section. For other resilience attributes, which are related to environmental and social dimensions, the system is perceived to be somewhat close to critical thresholds. This resonates with the perception of closeness to critical thresholds for environmental and social system functions in the previous section.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.6. Number of resilience attributes per position relative to the perceived critical threshold (aggregated results across 9 case studies).

	Position relative to perceived critical threshold				No threshold defined	Not discussed	Total[1] (n)
Row Labels	Not close	Somewhat close	Close	At threshold or beyond			
Reasonably profitable			3			1	4
Production coupled with local and natural capital		2	1		2	1	6
Functional diversity					1	1	2
Response diversity		1			1	1	3
Exposed to disturbances			1			1	2
Heterogeneity of farm types			1		1		2
Support rural life		2	1				3
Socially self-organized	1	1	1		1		4
Appropriately connected with actors outside the farming system	1				1		2
Legislation coupled with local and natural capital		1					1
Infrastructure for innovation			2	1	3		6

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Diverse policies				2			2
Total (n)	2	7	10	3	10	5	37

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Challenges

For many challenges, critical thresholds seem to be (or about to be) reached (Table 2.7). Occurrence of extreme weather is somewhat close to perceived critical thresholds in NL-Arable, IT-Hazelnut, PL-Horticulture, “close to” for DE-Arable&Mixed and BG-Arable and “at or beyond” the perceived critical thresholds in RO-Mixed. Pest & diseases (NL-Arable, IT-Hazelnut), an environmental challenge, are perceived to be somewhat close to critical thresholds. For other challenges in the social, economic and institutional domain, more often critical thresholds seem to be reached. In ES-Sheep, all challenges are perceived to have reached critical thresholds, except for wildlife attacks, for which no threshold was defined. For DE-Arable, challenges related to infrastructure and low attractiveness are perceived to have reached a critical threshold. In SE-Poultry, the challenges of economic and environmental regulations and requirements are perceived to have reached critical thresholds, mainly because of a mismatch between these requirements. Continuous change of these laws and regulations is seen as one of the primary challenges of multiple arable farming systems. For instance in NL-Arable, UK-Arable as well as BG-Arable, prohibition of certain crop protection products before replacements would become available was seen as a critical threshold.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.7. Number of challenges per position relative to the perceived critical threshold (aggregated results across 9 case studies).

		Position relative to perceived critical threshold				No threshold defined	Not discussed	Total[1] (n)
Challenge	Domain	Not close	Somewhat close	Close	At threshold or beyond			
Change in technology	Agronomic			1				1
Low prices and price fluctuations	Economic	1	2	2	1			6
High production costs	Economic			2	1			3
Extreme weather	Environmental	1	2	2	1			6
Pests & diseases	Environmental		2					2
Wildlife attacks	Environmental					1		1
Continuous change of laws and regulations	Institutional		3	2				5
Economic laws & regulations	Institutional	1	1		2			4
Environmental laws & regulations	Institutional		1	1	1			3
Lack of infrastructure	Social				1			1
Low attractiveness	Social				1			1
Low labor availability	Social		1	1	1			3
Changes in consumer	Social				1		1	2

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

preferences							
Total (n)	3	12	11	10	1	1	38

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

In DE-Arable&Mixed, PL-Horticulture, SE-Poultry and RO-Mixed, inadequate alignment of national and EU policies and regulations regarding production quality standards were seen as an important problem. Higher production quality standards involve usually higher production costs. Due to free trade between EU-countries, import of lower quality, and thus usually cheaper, products consequently reduces the competitive advantage of these farming systems.

It is worth noting that challenges are perceived to be more often at or beyond perceived critical thresholds than thresholds for functions, and functions are more often perceived at or beyond critical thresholds than resilience attributes. This could suggest that the studied farming system have some buffering capacity to deal with challenges and/or that challenges have a delayed effect on farming system function performance and resilience attributes.

Interacting thresholds

In all case studies, interacting thresholds across level-domain were observed (Table 2.8). Common interactions between thresholds occur from field-environmental to field-economic, from field-economic to farm-economic, from farm-economic to farm-social, from farm-social to farming system-social, and from farming system-social to farm social. Generally, an environmental issue at field level, for instance, decreasing soil quality (NL-Arable, UK-Arable), pest, diseases (NL-Arable, IT-Hazelnut), wildlife attacks (ES-Sheep), or drought (DE-Arable&Mixed, PL-Horticulture, RO-Mixed, BG-Arable) is too much a shock or stress that it leads to yields that are too low to sustain an adequate level of farm income. Too low farm level incomes were in most case studies resulting in farmers exiting or the lack of finding a successor for the farm. In UK-Arable, also reduced farmer happiness due to lack of recognition was mentioned as a reason for farm exit. Farmers exiting their farm without having a successor was in multiple case studies also considered to lead in the long-term at the farming system level to a smaller rural population (NL-Arable, FR-Beef, ES-Sheep, RO-Mixed, BG-Arable) and/or a less attractive countryside (ES-Sheep, FR-Beef). However, in farming systems where access to land is an issue (e.g. BE-Dairy, PL-Horticulture), disappearance of farmers may in the short-term be desired. In ES-Sheep, disappearance of farms was experienced as a serious issue. In IT-Hazelnut, the retention of young people at the farms was specifically mentioned as something that could support the rural life and vice versa. Both low economic viability at farm level and low

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

attractiveness of the countryside due to depopulation were considered to reduce the access to labor at farm or farming system level in SE-Poultry, PL-Horticulture, DE-Arable&Mixed and RO-Mixed. Access to labor in these systems was important for the continuation of activities on farms to keep them economically viable. Hence, rural depopulation and an unattractive countryside seem to be part of a vicious circle with low economic viability, farms quitting and low access to labor.

Table 2.8. Number of interactions of thresholds between domains and levels leading to system decline in the studied case studies (results aggregated from nine case studies[1]).

	Level	Field		Farm			Farming system		
Level	**Domain**	Eco.	Env.	Econ.	Env.	Soc.	Econ.	Env.	Soc.
Field	Economic	0	0	7	1	0	1	0	0
	Environmental	5	0	1	2	0	0	0	0
Farm	Economic	0	1	2	1	8	2	1	4
	Environmental	1	1	1	0	1	2	1	1
	Social	1	0	1	0	3	0	0	10
Farming system	Economic	1	0	2	1	2	1	0	1
	Environmental	0	0	0	0	0	0	0	1
	Social	0	0	3	0	5	1	1	3

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

2.3.5 Future systems

Description and categorization of future systems

Alternative systems can be categorized according to the main direction that they take, e.g. intensification, organic / nature friendly production, product valorization (Table 2.9). These categories are not mutually exclusive, e.g. organic / nature friendly could be combined with a change towards diversification (NL-Arable) or specialization (PL-Horticulture). In most case studies, alternative systems were perceived as compatible with one another at the same time at farm and/or farming system level (DE-Arable&Mixed, NL-Arable, SE-Poultry, IT-Hazelnut, ES-Sheep), and/or over time at the farming system level (UK-Arable, NL-Arable). In the majority of case studies, technology-driven alternatives are perceived to provide feasible farming systems. For most arable systems in this study and for IT-hazelnut, alternatives that are driven by

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

improved product valorization are compatible with a shift towards more nature-friendly and/or organic agriculture (DE-Arable&Mixed, NL-Arable, IT-Hazelnut). Interestingly, more nature-friendly and/or organic agriculture was not mentioned in SE-Poultry, while actors in this system see intensification and/or technology driven alternatives as feasible. In ES-Sheep, in the high-tech extensive alternative system, technology is oriented to the improvement of pastures management and maintenance of the landscape. Where ES-Sheep is dependent on extensive feed production on land in the region, farms in SE-Poultry are already intensive and import the majority of their feed. In DE-Arable&Mixed, a semi-intensive farming system, participants also perceived possibilities for intensification. In RO-mixed and PL-Horticulture, both smallholder systems with a variety of products, perceived possibilities for specialization driven alternatives. In BG-Arable, with large scale, specialized cereal production, there seems room for diversification. In BG-Arable, NL-Arable and RO-Mixed, alternatives driven by increased collaboration between farming system actors were seen as possibilities for the future.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.9. Alternative systems per category per case study. Categories are based on the most important direction that an alternative system is taking, according to the interpretation of the research team in each case study. Categories are hence not mutually exclusive and alternative systems can have elements of multiple categories.

	Case studies									
Alternative system	BG-Arable	NL-Arable	UK-Arable	DE-Arable&Mixed	RO-Mixed	ES-Sheep	SE-Poultry	PL-Horti-culture	IT-Hazelnut	Total[1] (n)
Intensifica-tion				Intensifi-cation		Semi-intensive alternative system	Large farms			3
Specializa-tion					Commercial specialization of family mixed farms			Horti-culture farming		2
Diversifica-tion	Crop diversifi-cation	Alternative crops	Likely system		Alternative crops / livestock		Self-sufficiency fodder			3
Technology	Innovation and technology	Precision agriculture				Hi-tech extensive alternative system	Robots	Shelter farming	Technolo-gical innovation	6
Collabora-tion	Collaboration	Collaboration & water			Cooperation / multi-functio-nality					3

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Product valorization	Processing and increasing added value								Product valorization	2
Organic / nature friendly		Nature-inclusive	Desirable system	Organic farming	Organic agriculture			Local organic farming	Eco-friendly agriculture	6
Attractive countryside				Better societal appreciation					Sustained demand (high and stable prices)	4
Total (n)	**4**	**4**	**2**	**3**	**3**	**2**	**3**	**3**	**4**	**28**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Expected developments

When critical thresholds of challenges are exceeded, participants in all case studies expected on average that current positive-to-moderately-negative developments would turn into moderate-to strong negative developments for main system indicators (Table 2.10). For resilience attributes, exceedance of critical thresholds of challenges has a similar effect, except for BG-Arable and SE-Poultry. In these case studies, presence of resilience attributes is expected to increase. When selecting the biggest and smallest expected effects of all alternative systems per case study, one could argue that the maximum and minimum potential for change can be assessed (Table 2.10). Alternative systems are perceived to lead to 1) at most moderate positive developments for all system indicators and moderate to strong improvements for resilience attributes, and 2) at least to on average a reduction of negative developments of system indicators in a few case studies (BG-Arable, UK-Arable) and on average have led to small to moderate positive developments in other case studies. For resilience attributes, somewhat stronger positive developments are expected to be achieved.

Functions for which many representative indicators were discussed, showed on average across case studies for the status quo no to weak increases (“Food production” and “Natural resources”) or weak to moderate negative developments (“Economic Viability) (Table 2.11). Under system decline, when critical thresholds are exceeded, these functions could start to show moderate negative developments. Similar effects could be experienced for resilience attributes.

Under alternative systems, “Food production” is perceived to at least not to change and at most moderately improve. For “Economic viability” negative developments are expected to at least be countered by alternative systems and at most be turned into moderate positive developments. For “Natural resources”, current overall stability across case studies is expected to become at least slightly improved and at most moderately improved by alternative systems. In UK-Arable, negative developments for indicators representing “Quality of life” and “Biodiversity & habitat” were expected to be kept going in the least radical alternative system, which was also considered to be the most likely one. In three case studies, some alternative systems resulted in less positive developments for food production (BG-Arable), economic viability (BG-Arable and SE-Poultry) and natural resources (SE-Poultry, NL-Arable, less positive), implying a trade-off as overall performance of main indicators was expected to improve.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 1.10. Average developments of system indicators and resilience attributes per case study for the status quo, system decline and maximum and minimum developments in alternative systems. Scores close to -2 imply strong negative, -1 moderate negative, 1 moderate positive, 2 strong positive developments. Scores close to 0 imply no to weak positive or negative developments.

			Expected average developments in future systems			
Indicator / resilience attribute	Case study[1]	Indicators/ resilience attributes [#]	Status quo	System decline	Maximum in alternative systems	Minimum in alternative systems
Indicators	BG-Arable	5	-0.2	-1.1	1.2	0.2
	NL-Arable	4	0.8	-1.5	1.3	0.8
	UK-Arable	4	-0.8	-1.5	1.8	-0.5
	DE-Arable&Mixed	7	-0.6	-1.3	1.1	0.4
	RO-Mixed	4	0.3	0.3	2.0	0.3
	ES-Sheep	3	-1.3	-1.8	1.3	1.2
	SE-Poultry	4	0.8	-0.1	0.4	0.1
	IT-Hazelnut	4	0.8	-0.4	1.3	0.3
	PL-Horticulture	4	-0.8	-1.5	1.0	0.3
	Average case studies		**-0.0**	**-0.6**	**1.3**	**0.5**
Resilience attributes	BG-Arable	4	0.0	0.5	1.5	0.3
	NL-Arable	6	0.0	-0.8	1.5	0.4
	UK-Arable	4	-0.5	-1.5	1.8	0.0
	DE-Arable&Mixed	3	0.0	-1.5	1.7	0.7
	RO-Mixed	4	0.5	0.5	1.3	0.3
	ES-Sheep	6	-0.7	-1.5	1.3	1.3
	SE-Poultry	5	0.4	0.9	0.5	0.5
	IT-Hazelnut	5	0.6	-0.3	1.8	1.0
	PL-Horticulture	4	-0.5	-1.5	0.6	0.0

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Average case studies	**0.0**	**-0.8**	**1.3**	**0.4**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Minimum and maximum positive developments of farming system functions indicate that for most functions at most moderate improvements are expected. For "Quality of life" (discussed once) and "Biodiversity & habitat" (discussed four times), on average at most strong positive developments are expected and on average at least weak to moderate negative developments are expected. This indicates that for these functions, alternative systems seem to take different directions which in some cases has a negative impact.

Minimum and maximum positive developments are expected to be stronger for resilience attributes than for system indicators. In particular, "Production coupled with local and natural capital", "Infrastructure for innovation" were often discussed and expected to show moderate to strong positive developments in proposed alternative systems. For resilience attributes also trade-offs were observed for some alternative systems compared to the current developments. In SE-Poultry, "Reasonably profitable" was expected to become negative, similar to the function "Economic viability". However, this was expected to be a problem for only the actors that will not be able to keep pace with developments in the system, while other actors are expected to improve. In PL-horticulture, the alternative system "local organic production" was expected to turn positive developments for "Response diversity" into a negative development, as this alternative was seen as a reduction of possibilities to react to developments in different markets. In NL-Arable, although not discussed with participants, the research team expected that the attribute "Exposed to disturbance" would deteriorate in multiple alternative systems, as these systems could result in further opening system borders, thus potentially exposing the system to bigger shocks and stresses. In UK-Arable, "Diversity of farm types" and "Social self-organization" were expected to deteriorate in the "likely system", but obviously less in the desirable system. In the "likely system" in UK-Arable, farm area scale enlargement is expected to continue, thus reducing diversity of farms and the number and closeness of farming system actors in the system on which social self-organization is partly dependent.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 2.11. Developments of system indicators per function and resilience attributes for the status quo, system decline and maximum and minimum developments alternative systems. Scores close to -2 imply strong negative, -1 moderate negative, 1 moderate positive, 2 strong positive developments. Scores close to 0 imply no to weak positive or negative developments.

			Expected average developments in future systems			
Indicator / resilience attribute	Name	Indicators / resilience attributes [#]	Status quo	System decline	Maximum in alternative systems	Minimum in alternative systems
Indicator	Food production	8	0.1	-0.9	1.1	0.2
	Bio-based resources	2	0.0	-0.9	1.0	0.5
	Economic viability	11	-0.4	-1.2	1.1	0.6
	Quality of life	1	-1.0	-2.0	2.0	-1.0
	Natural resources	7	0.0	-1.2	1.1	0.2
	Biodiversity & habitat	4	0.3	-0.3	2.0	-0.3
	Attractiveness of the area	4	-0.5	-1.4	1.3	0.6
	Animal health & welfare	2	0.5	0.0	1.0	0.5
	Average functions[1]		**0.0**	**-0.6**	**1.3**	**0.5**
Resilience attribute	Reasonable profitable	4	-0.5	-1.2	0.5	0.4
	Production coupled with local and natural capital	5	-0.2	-1.5	1.7	1.0
	Functional diversity	3	0.0	-0.3	0.7	0.2
	Response diversity	3	0.0	-1.5	0.8	0.2
	Exposed to disturbance	3	0.3	0.8	0.7	0.2
	Heterogeneity of farm types	2	0.5	0.5	1.0	-1.0
	Support rural life	4	0.3	-0.8	1.3	0.5
	Socially self-organized	5	0.0	-0.9	2.0	0.4
	Appropriately connected	2	-0.5	-0.6	2.0	0.4

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	with actors outside the farming system					
	Legislation coupled with local and natural capital	1	0.0	0.0	1.0	1.0
	Infrastructure for innovation	7	0.0	-0.4	1.7	1.1
	Diverse policies	2	0.0	-0.8	1.5	1.0
	Average resilience attributes[1]		**-0.1**	**-0.8**	**1.3**	**0.4**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Boundary conditions

To realize alternative systems, participants indicated that overall more enabling boundary conditions need to be present compared to maintaining the status quo (Table 2.12). All boundary conditions mentioned for maintaining the status quo in the future are relevant for at least one proposed alternative system. Boundary conditions for different domains can differ between proposed alternative systems per case study. It is striking that institutional and social boundary conditions are mentioned across most case studies. Economic boundary conditions were mentioned in all case studies, except for UK-Arable. On average, farming systems have increased attention for economic and institutional boundary conditions, implying that these domains are especially important across multiple alternative systems per case study. Economic boundary conditions included amongst others better cost profit ratios (PL-Horticulture, SE-Poultry, NL-Arable, RO-Mixed), access to new markets (ES-Sheep, IT-Hazelnuts, NL-Arable), access to land (PL-Horticulture, SE-Poultry), compensation for the delivery of public goods (ES-Sheep, NL-Arable). Institutional boundary conditions included amongst others improvements on access to knowledge (DE-Arable&Mixed, BG-Arable, RO-Mixed), more effective bureaucracy (DE-Arable, ES-Sheep, SE-Poultry, RO-Mixed), improving (consistency and transparency of) policies and regulations (DE-Arable, PL-Horticulture, NL-Arable, BG-Arable, RO-Mixed).

Table 2.12. Number of boundary conditions mentioned per domain for future systems.

	Sum of boundary conditions across all case studies for

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Domain	Status quo	Alternative systems (sum of all mentioned boundary conditions)	Alternative systems (sum of average number of boundary conditions mentioned per alternative per case study)
Agronomic	4	12	7
Economic	15	27	16
Environmental	15	19	11
Institutional	18	32	20
Social	18	26	17
Total[1]	**70**	**116**	**72**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

On average, there was no increased attention for the social domain and decreasing attention for the environmental domain. However, in general there was attention for improving the environmental and social domain by increasing indicator and resilience attribute levels. Boundary conditions to improve these levels are perceived to mostly lie in the economic and institutional domain. It has to be noted that for specific alternative systems in specific case studies, boundary conditions in the environmental and social domains were perceived as important (Appendix B). For instance, for alternative systems primarily focused on becoming organic or producing more environmental friendly, generally more environmental boundary conditions were mentioned. However, interestingly, there were less boundary conditions mentioned for the social domain for alternative systems primarily driven by increased collaboration. Environmental boundary conditions included amongst others a limited number of extreme weather events (IT-Hazelnut, PL-Horticulture, NL-Arable, BG-Arable, RO-Mixed, UK-Arable), improvement of soil condition (UK-Arable, NL-Arable) and (demand for) sustainable management of land and resources (ES-Sheep, IT-Hazelnut, UK-Arable, BG-Arable). Social boundary conditions include amongst others a populated countryside with sufficient available (qualified) labor (IT-Hazelnut, PL-Horticulture, SE-Poultry, BG-Arable, RO-Mixed), improved

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

public awareness/perception of the contribution of agriculture to society (DE-Arable, ES-Sheep, PL-Horticulture, UK-Arable), improved access to knowledge and knowledge sharing (IT-Hazelnut, SE-Poultry, BG-Arable, RO-Mixed, UK-Arable), and improved cooperation and self-organization (ES-Sheep, PL-Horticulture, UK-Arable, BG-Arable, RO-Mixed). Increased attention for agronomic boundary conditions was only the case for ES-Sheep, NL-Arable and DE-Arable&Mixed. Boundary conditions for the agronomic domain ranged from the availability of technology (ES-Sheep), adequate production levels (BG-Arable) and presence/absence of certain crops or farm types (NL-Arable).

Strategies

Strategies, as proposed by participants, had different degrees of specificity: some strategies were overarching multiple specific strategies and covered multiple domains, e.g. social and institutional, while other strategies were very specific and linked to one domain. In this report, the degree of specificity of strategies is not taken into account when providing summary statistics on strategies. In this report, strategies are categorized per domain by the research teams of case studies (Table 2.13). Strategies are categorized according to the primary domain they operate in. In this report, strategies are not categorized by the actors that need to be involved.

During the evaluation of critical thresholds (section 2.3.4), participants already came up with strategies that were perceived necessary to avoid critical thresholds. In further discussions, participants also sometimes indicated that current strategies were not effective anymore. We used this participant input to update the list of strategies to maintain the status quo in the future. It seems that fewer strategies are perceived to be necessary, compared to the strategies implemented up till now to maintain stability and performance levels of main indicators. However, to realize alternative systems, more strategies are perceived necessary. This is especially the case for strategies in the institutional domain. To a certain extent this reflects the increased attention for boundary conditions in the institutional domain, but also reflects the perceived interaction of the institutional domain with other domains, e.g. the social and environmental domain. For instance, suggested strategies from the institutional domain in some case studies are expected to improve environmental indicators. Typical suggested strategies in the institutional domain are better cooperation with actors inside and outside the farming system (BG-Arable, UK-Arable, RO-Mixed), regulations specified for the farming system to avoid mismatches (DE-Arable&Mixed, ES-Sheep, NL-Arable, RO-Mixed), strategies regarding the protection and promotion of its products (ES-Sheep, De-Arable&Mixed, PL-Horticulture, IT-Hazelnut), simplification and/or relaxation of regulations (PL-Horticulture, DE-Arable&Mixed,

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

NL-Arable), rewarding the delivery of public goods (NL-Arable, ES-Sheep) or financial support in general (PL-Horticulture, IT-Hazelnut, RO-Mixed).

Table 2.13. Number of strategies mentioned per domain for future systems.

Domain	Sum of strategies implemented up till now	Sum of strategies to maintain the status quo	Sum of all mentioned strategies	Sum of average number of mentioned strategies per alternative system per case study
Agronomic	17	16	35	24
Economic	29	20	33	21
Environmental	7	6	17	10
Institutional	17	13	46	31
Social	15	12	26	17
Total[1]	**85**	**67**	**157**	**103**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Contrary to strategies in the institutional domain, the number of strategies related to the economic domain is reduced. However, there are exceptions: in SE-Poultry and ES-Sheep, current strategies in the economic domain are maintained in all alternative systems. Moreover, in ES-Sheep some economic strategies are added for alternative systems. In NL-Arable, three out of four alternative systems maintain a focus on economic strategies, but the nature of the strategies shifts from scaling up production and cost reduction towards developing a new business model.

Agronomic strategies include amongst others improved knowledge and research on crops and livestock (NL-Arable, ES-Sheep, SE-Poultry, DE-Arable&Mixed, RO-Mixed), implementation of more technology (all case studies, for most alternative system categories, except PL-Horticulture; Appendix B). In PL-Horticulture, strategies were more oriented towards the economic and institutional domain, which were expected to reduce primarily the impact of change of laws and regulations, low and fluctuating prices and the lack of labor availability.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Strategies primarily aimed at the social domain were mentioned in all case studies, except for SE-Poultry. Strategies in the social domain included amongst others cooperation and/or knowledge sharing among farming system actors (in a value chain and/or cooperative) (all case studies having socially oriented strategies), learning, education and/or awareness raising strategies for actors inside the farming system (UK-Arable, NL-Arable, IT-Hazelnut, BG-Arable, RO-Mixed) or aimed at producer-consumer connections (PL-Horticulture, NL-Arable, ES-Sheep). Environmental strategies were only proposed in the arable systems, ES-Sheep, the perennial system IT-Hazelnut and RO-Mixed for most of the proposed alternative systems (Appendix B).

Compatibility with Eur-Agri-SSPs

After the workshops, research teams evaluated the compatibility of possible future systems with Eur-Agri-SSP scenarios (Mitter et al., under review) (Table 2.14 and Table 2.15). Requirements of future systems, regarding indicator improvement, avoidance of thresholds, presence of boundary conditions and implementation of strategies were compared to developments of indicators in Eur-Agri-SSPs related to population, economy, policies & institutions, technology and environment & natural resources. Eur-Agri-SSPs are not downscaled to the level of individual farming systems. Still, compatibility of future systems with multiple scenarios indicates flexibility of such systems and may reveal what future system is “the safest bet” or for what scenario, no feasible future system was proposed.

Most future systems, including maintaining the status quo, seem to be most compatible with SSP1 “Sustainability pathways”. This is mainly due to favorable developments regarding policies and institutions and technology, corresponding with boundary conditions and strategies in most future systems. Also, developments in the population may increase compatibility as citizen environmental awareness is expected to increase and the rural-urban linkages to be strengthened. This is however not important for all alternative systems. For instance, alternative systems that focus on specialization in PL-Horticulture and RO-Mixed depend less on developments related to population. For most arable systems, developments regarding the environment and natural resources are also favorable and help to avoid further degradation beyond critical thresholds, e.g. regarding soil quality. The need for improving soil quality also explains lesser compatibility with other SSPs for arable systems compared to other studied farming systems. It should be noted that too much attention for environmental performance might threaten certain crops that under conventional cultivation depend on crop protection products, e.g. potato. Alternative systems primarily driven by organic/nature friendly production, product valorization, but also intensification seem to be most compatible with SSP1.

With regard to environmental developments needed for at least maintaining the status quo, it becomes clear that SSP2 “Status quo” will not bring the developments that are needed to avoid

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

exceeding environmental thresholds in the arable systems. Still, supported by generally positive developments in the economy, policies and institutions and technology, most case studies are weakly compatible with SSP2. However, for case studies where scaling and further intensification was seen as a possibility for the future (ES-Sheep, SE-Poultry, RO-Mixed, BE-Dairy), SSP2 seems to be moderately compatible.

In SSP3 “Regional rivalry” most rural-urban linkages, infrastructure, export, trade agreements, institutions, technology levels and maintenance of natural resources are expected to decline, which is only expected to be compensated by increased commodity prices and direct payments. SSP3 seems, therefore, most incompatible with most future systems in all case studies, especially because of the exporting nature of many case studies and/or the need for technology and maintenance of remaining natural resources. SE-Poultry is an exception to this, because of the current experienced mismatch of Swedish national food production quality requirements and EU free trade agreements. SE-Poultry is mainly producing for its own national market. Closing borders and decreased trade agreements would consequently imply an increase in a competitive advantage over cheaper produced, lower quality products from importing countries. Loss of competitive advantage because of mismatches between regulations was also mentioned by participants in DE-Arable&Mixed and PL-Horticulture, but only to a limited extent.

SSP4 “Inequality pathways” shows a mix of positive and negative developments. Population indicators, such as rural-urban linkages are expected to decrease while technology levels are expected to go up. Indicators related to economy and policies and institutions are showing both positive and negative developments. In SSP4, further depletion of natural resources is expected, but probably at a slower rate due to increased resource use efficiency. Altogether, future systems are weakly compatible with the developments in SSP4. Alternative systems primarily driven by intensification, specialization or technology seem to be most compatible with this SSP.

Alternative systems seem only weakly compatible with SSP5 “Technology pathways”. In SSP5, technology levels will generally increase, but not necessarily made available to agriculture, which is partly why alternative systems primarily driven by technology are not the most compatible alternatives.

Table 2.14. Average compatibility of alternative system categories with Eur-Agri-SSPs. Where values -1 to -0.66: strong incompatibility, -0.66 to -0.33: moderate incompatibility, -0.33 – 0: weak incompatibility, 0-0.33 weak compatibility, 0.33-0.66: moderate compatibility, and 0.66-1: strong compatibility. Colors reflect compatibility categories. Aggregated results from nine case studies.

		Average compatibility score				
Category future	Future	SSP1	SSP2	SSP3	SSP4	SSP5

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

systems	systems [#]	"Sustain-ability"	"Status quo"	"Regional rivalry"	"Inequality"	"Technology"
Status quo	9	0.55	0.31	-0.59	0.15	0.29
Intensification	3	0.67	0.48	-0.29	0.21	0.28
Specialization	2	0.50	0.36	-0.67	0.24	0.37
Diversification	6	0.63	0.30	-0.48	0.17	0.25
Organic / nature friendly	6	0.72	0.37	-0.74	0.11	0.21
Product valorization	2	0.68	0.26	-0.80	0.01	0.22
Technology	6	0.63	0.32	-0.50	0.22	0.26
Collaboration	3	0.63	0.26	-0.76	0.16	0.24
Other	1	0.81	0.36	-0.69	-0.09	0.24
Average[1]		**0.63**	**0.33**	**-0.59**	**0.15**	**0.26**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

Table 2.15. Average compatibility of case studies' future systems with Eur-Agri-SSPs. Where values -1 to -0.66: strong incompatibility, -0.66 to -0.33: moderate incompatibility, -0.33 – 0: weak incompatibility, 0-0.33 weak compatibility, 0.33-0.66: moderate compatibility, and 0.66-1: strong compatibility. Colors reflect compatibility categories.

		Average compatibility score				
Case Study[1]	Future systems [#]	SSP1 "Sustain-ability"	SSP2 "Status quo"	SSP3 "Regional rivalry"	SSP4 "Inequality"	SSP5 "Techno-logy"
BG-Arable	5	0.65	0.21	-0.77	0.20	0.21
DE-Arable&Mixed	4	0.80	0.34	-0.74	0.06	0.32
NL-Arable	5	0.72	0.22	-0.79	0.13	0.19
UK-Arable	3	0.69	0.20	-0.78	0.02	0.10
RO-Mixed	4	0.54	0.41	-0.64	0.23	0.37
ES-Sheep	3	0.62	0.47	-0.71	0.19	0.25
SE-Poultry	4	0.63	0.48	0.54	0.18	0.23
IT-Hazelnut	5	0.50	0.34	-0.65	0.13	0.31
PL-Horticulture	4	0.51	0.33	-0.70	0.21	0.34
Average		**0.63**	**0.33**	**-0.59**	**0.15**	**0.26**

[1]For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from these case studies are hence not included in this table.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

2.3.6 Causal mechanisms

Causal loop diagrams have provided an integration of workshop results and their interpretation per case study. Primarily to expose the connection between indicators, resilience attributes, boundary conditions and strategies (system elements) in the social, economic, environmental and institutional domain. Secondly, the identification of reinforcing and balancing feedback loops were useful for interpretation of results. Reinforcing feedback loops were for instance loops in which higher income leads to more investment aimed at further increasing income, e.g. through higher yields or better valorization of products. Balancing feedback loops were for instance loops that included yield and/or income reducing effects imposed by natural limits of the system, e.g. increased nematode pressure when crop rotations become too tight (NL-Arable), or consumer preferences that changed when environmental standards are (not) met, leading to lower/higher demand, lower/higher prices and lower/higher farm income (e.g. SE-Poultry, BE-Dairy, FR-Beef). Interesting in NL-Arable is the role of the cooperative in a reinforcing feedback loop of co-dependency between cooperative and farmers. As a minimum volume is required for the cooperative to be profitable, low yields have a double effect in the sense that prices of product also go down. This is interesting for other case studies where local processing and vertical integration is mentioned as an important strategy (PL-Horticulture, RO-Mixed, IT-Hazelnut).

The interconnectivity of system elements and the identification of feedback loops also helped to understand why participant's emphasized the importance of boundary conditions and strategies in the institutional domain for improving economic and environmental functions. Indeed, strategies in the institutional domain seem to affect many important system indicators and resilience attributes and can stimulate reinforcing feedback loops in a positive way (see e.g. the CLD for DE-Arable&Mixed; Appendix D).

Arable systems and PL-Horticulture typically have feedback loops including many elements that include natural resources, yield as well as profitability, indicating a directly perceivable feedback from for instance soil quality to yields. For instance, droughts were mentioned to be aggravated by low soil quality in NL-Arable, DE-Arable&Mixed, BG-Arable and PL-Horticulture. Sensitivity to drought (a feedback signal from low soil quality) provides an intrinsic motivation to take care of natural resources, e.g. soils and water retention capacities. Besides this intrinsic motivation, these systems are also externally incentivized by regulations. Continuous change of these laws and regulations is seen as one of the primary challenges of these farming systems for which a critical threshold was defined (see section 2.3.2).

The feedback from natural resources to yield and profitability seems less perceivable by system actors in IT-hazelnut, SE-Poultry, FR-Beef and BE-Dairy. In contrast, in these case studies, the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

improvement of natural resources is primarily incentivized by regulations that aim at preserving these resources. In addition, a connection with consumer awareness was made in SE-Poultry, FR-Beef and BE-Dairy, which can both influence policies and regulations, but also strengthen competitive advantage through improved producer-consumer interactions.

2.4 Discussion

2.4.1 Closeness to thresholds

All studied farming systems are perceived to be close to, at or beyond multiple critical thresholds. For the systems that are perceived to be at or beyond critical thresholds, it is not necessarily too late to transform: the real (not perceived) threshold might be at a different level than perceived. Moreover, resilience studies on the impact of climate change on natural and social systems suggest that late reversal (i.e., coming back to a desired state after exceeding a critical threshold) is possible, provided the disturbance causing the exceedance does not last too long (Van Der Bolt et al., 2018). Arable systems, in need for soil improvement to avoid critical thresholds, are at most weakly compatible with SSP2-5 where there is no increased attention for the maintenance of natural resources. In that regard, arable systems seem especially close to critical thresholds.

Defining critical thresholds seemed most difficult for resilience attributes. This could be an indication of the perceived redundancy of these attributes for system functioning: in the growth phase in a relatively stable environment, improving efficiency is more important than increasing presence of resilience attributes. However, when the system is forced to adapt/transform, attributes become more important, as they provide a basis for adaptation/transformation (Cabell and Oelofse, 2012; Gunderson and Holling, 2002). Indeed, participants often could indicate what needed to improve for the resilience attributes. Moreover, proposed strategies and boundary conditions in multiple case studies reflected resilience attributes, e.g. collaboration and cooperatives as well as policies enabling these strategies reflect the resilience attribute “social self-organization”. Suggesting improvements for resilience attributes can hence be seen as an implicit acknowledgment that adaptation or transformation is required.

Interactions between critical thresholds across domains and levels of integration are to be expected. Farming system challenges (in)directly affect the economic viability at farm level, a central critical threshold observed in all farming systems. In most farming systems, exceeding this threshold affects the availability of (qualified) laborers and farm successors, which in turn leads to depopulation, low attractiveness and low self-organization of the farming system, thus reinforcing low economic viability and lack of labor. As low economic performance seems to be preceding the long-term process of depopulation, dropping food production levels and low economic performance can be seen as the driver as well as an early warning signal for critical transitions (see e.g. Van Der Bolt et al., 2018). In that respect, focus on food production and economic viability (FoPIA-SURE-Farm 1), rather than social functions by farming system actors seems reasonable. However, improving economic viability through area expansion might lead to less farms and depopulation. In the more remote case studies, e.g. DE-Arable and BG-Arable, attractiveness of the area seems low anyways. Consequently, improving prices may not prevent further depopulation and lack of labor.

2.4.2 Status quo and system decline

Maintaining the status quo in the future implies a stagnation at moderate levels for most system functions and resilience attributes. The likely exceedance of a critical (and interacting) threshold in the coming ten years is expected to lead to moderately negative developments for most system functions and resilience attributes. The consistent developments for functions and resilience attributes in both situations (status quo and decline), suggests a perceived interaction between them. One could argue that to react to shocks and stresses, a system needs resources, especially for adaptation and transformation. These resources can only be adequately realized when system functions are performing well. The other way round, resilience attributes can be seen as "resources" to improve system functions, e.g. existing diversity of activities and farm types makes visible what works in a specific situation, openness of a system helps to timely introduce improved technologies and connection with actors outside the farming system may help to create the enabling environment for innovations in general to improve system functioning.

Decline as a result of challenges is primarily experienced at the farm level, resulting in the disappearance of (certain) farms from the farming system. In multiple case studies (SE-Poultry, DE-Arable&Mixed, NL-Arable), participants indicated that identified thresholds would differ among farmers. Farms disappearing and depopulation or the countryside becoming less attractive is hence a long-term process that is currently not a key issue in most studied farming systems. The farmer population may currently serve as a buffer resource, explaining that challenges are more often perceived to be at or beyond critical thresholds than main indicators, and main indicators more often than resilience attributes (section 2.3.4). The real effect of farmers disappearing from the farming system may only be reached when a critical minimum of farms is left, e.g. when no proper quality of life and self-organization is possible anymore. This also suggests a delay in the cause (challenge) and effect (indicator/resilience attribute performance) relation, aligning as well with the observations in section 2.3.4. Overall, the reinforcing negative nature of depopulation, and possibility of delayed effects, seems serious enough to consider the possibility of depopulation in all case studies.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Increasing farm size could be seen as a solution to compensate for the loss of farmers in the farming system, especially when one of the main reasons for disappearance is low economic viability. Increasing the farm size is often associated with the advantage of economies of scale. For multiple farming systems in our study (NL-Arable, UK-Arable, SE-Poultry, BE-Dairy), production margins are low, which could further stimulate this thinking. However, strategies for future alternative states are not unanimously pointing in that direction. From the farm level perspective, this can be explained that beyond a certain size, further economies of scale are not realized, i.e. there probably is a most optimal size dependent on the context of farm demographics. At the farming system level, such a context is provided, which becomes clearly visible in ES-Sheep, where further reduction of the farmer population is perceived to be harming the farming system, e.g. through reduction of facilities such as farmer networks, agricultural research, etc., but also hospitals, schools, etc. In DE-Arable&Mixed, reduced availability of infrastructure and facilities is primarily perceived through the lack of a skilled labor force in the farming system. Such threats at farming system level as experienced in ES-Sheep and DE-Arable&Mixed is not completely unlikely for other farming systems either as has been pointed out in the respective case study reports and literature (Kinzig et al., 2006). The context that determines optimal farm size hence is dependent on the social and professional activities and facilities that can be maintained, a farming system function ("Attractiveness of the area" Meuwissen et al., 2019), by a certain farmer population size. Allowing low margins to persist in combination with unchecked farm level economical thinking might result in the exceedance of a critical threshold at farming system level in the social domain. Although the number of farmers is a concern in a few of our case studies, there still seem time and options available to react. In IT-Hazelnut for instance, introduction of new machinery in the past has made farming more attractive for the younger generation, thus avoiding depopulation. Further developments in IT-Hazelnut, regarding local value chain activities, are aimed to further stimulate the retention of young people in the area. Another promising sign is the reduced attention for scale enlargement in future situations. In PL-Horticulture, a case study relative close to Poland's capital Warsaw, participants aim at increasing the economic viability, which probably will re-attract seasonal laborers to the region. Technology intensive scale enlargement in some alternative systems in ES-Sheep, DE-Arable&Mixed, SE-Poultry and BG-Arable could be seen as a last resort to compensate for what seems the irrevocable process of depopulation in relatively remote areas. It should be noted that to acquire the necessary (financial) means to achieve alternative systems, mainly for improved economic and environmental performance, scale enlargements and perceived economies of scale might still be tempting if no help from outside the farming system is provided.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

FoPIA-SURE-Farm 1 and 2 have been able to detect the issue of farm size in relation to the minimum farmer population that is necessary to maintain attractiveness of the countryside. This was mainly due to the fact that there are farming systems present in our palette of case studies in which participants perceived issues regarding this problem. In other farming systems, the issue of depopulation seems less present, probably because of the high population density (e.g. NL-Arable, BE-Dairy). Farming system actors are probably biased regarding depopulation and a loss of attractiveness of the rural area, as it is related to farm closure. Considering the possibility that farm exit could be good for farming system performance and resilience might go beyond the mental models of some farming system actors.

The continuing low margins as perceived in multiple case studies might be addressed with alternative systems and strategies that stem from incentives for improved economic performance primarily at farm level and environmental performance primarily at farming system level. Social performance is not one of the primary incentives, which could be a reason to worry as social performance is key for economic and environmental viability in the long-run. However, social performance is acknowledged as a boundary condition in all case studies. It is hence a bit unclear whose responsibility it is to ensure quality of life and attractiveness of rural areas: of actors inside and/or outside the farming system? Based on FoPIA-SURE-Farm 1, the current low allocated importance for social farming system functions suggest that these should become higher on the list of objectives of farming system actors. Based on this study, farming system actors indicate that they are willing to improve the social functioning, but that they depend on actors outside the farming system as well. Moreover, farmers and other farming system actors comprise often only a small part of the population in rural areas. Hence, a shared responsibility for social functions for actors inside and outside the farming system seems justified. Concretely the reflections above can be translated into research questions that are worth investigating more:

- What is the minimum number of farmers (and other stakeholders) in a farming system to ensure the delivery of private and public goods?
- How attractive does the countryside need to be to keep the current (or a minimum) number of farmers (and other stakeholders)?

2.4.3 Alternative systems and strategies

Alternative systems

Most alternative systems are considered by the research teams to be adaptations from the current system, i.e. no big change in performance and/or identity is expected. This could have been different if participants would have been asked to re-imagine the farming system without any of the current limitations. Also consideration of participants for other participants could be a

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

reason. In NL-arable, for instance the starch potato production that identifies the system stayed as most important crop in all alternative systems. Participating farmers and persons from the starch processing cooperative are dependent on the cultivation of these potatoes for their livelihood. Suggesting a radical alternative could in that regard be seen as a disregard for the main activities of those participants. In Work Package 4 (WP4) of SURE-Farm, researchers worked with "critical friends" rather than the more mainstream farming system actors that were participating in FoPIA-SURE-Farm 2. As a result, participants in WP4 seemed less bounded to the current situation (Buitenhuis et al., submitted).

Boundary conditions

The perception of participants that all boundary conditions for maintaining the status quo should be kept in place for at least one alternative system in each case study, suggests that participants have taken the current situation into account when proposing alternative systems. This could indicate path-dependent thinking of participants, which could also explain why most alternative systems are considered by researchers to be adaptations to the current system.

Boundary conditions for maintaining the status quo are supposed to be enabling conditions to: 1) stop at least slightly negative current developments of main indicators and resilience attributes, and 2) to avoid the imminent threat of exceeding a critical threshold, resulting in the decline of studied farming systems. For realizing alternative futures, studied farming systems are dependent on even more enabling conditions. Dependent on the alternative system, emphasis may be put on a specific domain. Most common is an increased emphasis on boundary conditions in the economic and institutional domain. For instance, for better access to markets and better prices, improved risk management strategies, improved efficacy of bureaucracy and more transparent, consistent, farming system specific policies are required. This indicates that for further adaptation, farming systems are dependent on actors outside the farming system. "Connected with stakeholders outside the farming system" and "Policies adapted to local and natural capital" are regarded as hardly present and less important resilience attribute for current resilience in most case studies (FoPIA-SURE-Farm 1). The perceived less importance is contrasting with the need for boundary conditions in the social and institutional domains.

Boundary conditions seem to hold across different alternative systems per case study. Boundary conditions were not mutually exclusive, suggesting that in this respect, multiple alternative systems can co-develop and co-exist. Occurrence of boundary conditions across types of alternative system was not studied in-depth, leaving space for further analyses.

Strategies

In alternative systems, strategies are increasingly in the social and institutional domain, but are still aimed to mainly improve economic and environmental functions. The strategies seem to

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

differ more across different alternative systems per case study, compared to boundary conditions. Common for different types of alternative systems (e.g. technology, collaboration, or organic /nature friendly driven) is the role of technology and stakeholder interaction, for instance for improving agronomic practices, local processing by cooperatives and knowledge exchange. Occurrence of strategies across types of alternative system was not studied in-depth, leaving space for further analyses.

Strategies were in most cases not mutually exclusive, suggesting that in this respect, multiple alternative systems can co-develop and co-exist. However, strategies may compete over the same resources, thus enforcing system actors to prioritize. Although alternative systems may be compatible, presence of boundary conditions may in the end determine what strategies can most effectively be implemented by farming system actors. The relation between boundary conditions and strategies was not discussed at a one to one level in the workshop. Still, possible importance of boundary conditions for determining effectiveness of strategies, also emphasizes the role of actors outside the farming system for providing the enabling environment for change into the desired direction. This provides opportunities for actors outside the farming system, in cooperation with actors inside the farming system, to address social functions of the farming system that are currently often neglected to a certain extent in most case studies (FoPIA-SURE-Farm 1), but important for economic and environmental system functions.

Compatibility with Eur-Agri-SSPs

Alternatives are probably at most moderately compatible with one or two alternative scenarios (often SSP1 "Sustainable pathways" and SSP2 "Status quo") and at most weakly compatible with two to three other systems (often SSP2, SSP4 "Inequality pathways" and SSP5 "Technology pathways). This suggests that maintaining the status quo and realizing alternative systems is never expected to result in thriving farming systems. This might reflect the path-dependent alternatives participants have proposed. In order to achieve higher compatibility, more radical re-designs that break with current trajectories will be necessary for some scenarios. In other scenarios, expected improvements for functions and resilience attributes my create enough resources and momentum for further improving compatibility with scenario developments. Improved profitability, social self-organization and infrastructure for innovation, foreseen in most alternative systems, are for instance all perceived to contribute to adaptability and transformability (FoPIA-SURE-Farm 1).

In most cases, moderate to strong incompatibility with SSP3 "Regional Rivalry" is expected. SSP3 partly reflects the current COVID-19 crisis in which borders are closed, transport of goods is limited and at national and EU-level direct (emergency) payments are provided to some agricultural sectors. Reduced solidarity among EU member states regarding joint health and

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

restoration plans could be a further step into the direction of SSP3. In the second stage after the outbreak of COVID-19 in Europe, after an initial reaction of reduced solidarity, joint plans for health, environment and economy are developed, suggesting any scenario, except SSP3. At the level of the European Union it has for instance been suggested to see the COVID-19 crisis as a wake-up call to further push the Green Deal and its Farm to Fork strategy (https://ec.europa.eu/food/farm2fork_en), which is more in line with SSP1. The reasoning for this is that the origin of the crisis (a zoonosis) is directly related to how we co-exist with animals and the natural environment. The exception of SE-Poultry, where all future systems seem compatible with SSP3, is a critique towards the mismatch of national and EU policies and regulations.

Methodological issues

Basing FoPIA-SURE-Farm 2 on the results of FoPIA-SURE-Farm 1 has resulted in a focus on mainly food production and economic function indicators. To a lesser extent, also environmental function indicators were included. Social functions were hardly represented. However, with regard to resilience attributes, social self-organization was assessed as an important attribute in most case studies in FoPIA-SURE-Farm 1 and therefore included in FoPIA-SURE-Farm 2. Besides, food production and economic performance in some case studies turned out to be influenced by social functions such as the quality of life in rural areas and the attractiveness of rural areas. The more top down approach of FoPIA-SURE-Farm 1 narrowed down the system functioning to the economic and environmental domain, according to stakeholders' perspectives. FoPIA-SURE-Farm 2 combined a semi top-down approach (introducing function indicators from FoPIA-SURE-Farm 1 but letting participants decide and discuss on thresholds and interactions) with a bottom up approach (letting participants come up with alternative systems). The discussions on interactions between thresholds and on alternative systems both introduced opportunities to put the social domain back on the agenda. In conclusion it could be argued that building FoPIA-SURE-Farm 2 on FoPIA-SURE-Farm 1 on the one hand created path-dependency, risking that certain dimensions of farming system sustainability and resilience would not be addressed. On the other hand, the path-dependency helped to fit the challenging topic of future resilience of farming systems in a workshop format with a duration of only four hours. Finally, having results from workshops from multiple case studies provided an extra opportunity to reflect on the presence / absence of certain sustainability and resilience dimensions.

Asking stakeholders for input has the advantage that social indicators can be assessed that are otherwise difficult to measure. For ecological indicators this is different: although perceptions on performance levels of ecological indicators may influence stakeholder behavior and are hence important to take into account, these perceptions are not necessarily reflecting reality. It could therefore be argued that for instance ecological indicators should also be assessed by

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

experts. Although stakeholders are expected to have a good knowledge of the study area, they have a specific perspective depending on the organization they are from. This implies that stakeholders have in some cases different priorities (FoPIA-SURE-Farm 1) and are probably not completely informed about all dynamics in a farming system. By inviting multiple types of stakeholders (e.g. farmers, industry, government), a more complete picture could be realized compared to an approach where only one type of stakeholders would be consulted. Still, the identified alternative systems, strategies and boundary conditions are probably not complete. Also the lack of a shared vision, for instance mentioned in NL-Arable, is indicative for the challenge of a multi-stakeholder process, i.e. even though all possible strategies are known, it is still not clear what strategies should be prioritized and emphasized. Expert opinions from outside the system on for instance the causal loop diagram and outcomes from quantitative modelling (Chapter 3 and Chapter 4) are expected to provide a more complete overview.

Participation of stakeholder groups differed across case studies (Table 2.1). Moreover, in some case studies key actors were missing, e.g. farmers in UK-Arable and people from the government in SE-Poultry. Power relations among stakeholders also might have played a role, making that some participants did not feel free enough to express themselves. However, this was not mentioned in the case study reports.

In FoPIA-SURE-Farm 1, participants mentioned strategies that were implemented to deal with experienced shocks and stresses in the past in order to maintain desired levels of function importance. In FoPIA-SURE-Farm 2, participants were asked to come up with strategies to realize alternative systems in order to maintain or achieve desired function performance. This makes that strategies from both workshops are slightly different, i.e. the strategies in FoPIA-SURE-Farm are not necessarily fit to deal with unexpected shocks and stresses on the pathway to higher performance. However, expected improvement of resilience attributes suggest that farming systems are becoming more resilient towards the future in the alternative systems. Linking strategies to resilience attributes, as is also done in FoPIA-SURE-Farm 1, is a way to make the strategies from both FoPIA-SURE-Farm workshops more comparable. In addition, a better insight in increased robustness, adaptability and transformability might be achieved.

Grouping boundary conditions and strategies by domains helped to see what is needed for maintaining the status quo in the future or to realize what is needed to realize alternative systems. However, boundary conditions and strategies may be at the cross-section of multiple domains. This is, for instance, pointed out by Finger et al. (2019) for the introduction of precision farming. Precision farming is a typical example of an overarching strategy that encompasses multiple, smaller strategies that interact with each other, which partly explains how strategies can cover multiple domains. Dependent per case study, overarching and/or

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

detailed strategies were mentioned, e.g. IT-hazelnut with a few overarching strategies and NL-Arable with some overarching and many smaller strategies. Taking into account hierarchic structures with regard to strategies, simply counting strategies per domain, as is done in this report, comes with limitations. Moreover, strategies could be categorized by the actors that need to be involved, for instance, to make sure that change is realized by all actors and not just a few. Regarding that, also the availability of resources for strategies and the actors that manage those resources could be recorded (Mathijs and Wauters, submitted). More refinement in categorization, taking into account multiple domains, level of detail and actors involved would bring us closer to more definite conclusions on the domain(s) in which most improvement for sustainability and resilience can be achieved. We aim to provide such an analysis in our next SURE-Farm deliverable, D5.6.

Causal loop diagrams represented the overall understanding of researchers of their case study. Although important feedback loops were identified, there is still room for further refinement and exploration. For instance, reflections on stocks (resources) and delayed reactions in the system could be taken into account. The evaluation of resource availability under different scenarios for some case studies as presented in Chapter 4 of this report could serve as an example. Another thing to do would be to verify whether the possibility of depopulation through farmers exiting the farming system is processed well in all CLDs. The basic structure for including this could be derived from the stock and flow models as presented in Chapter 4 of this report. Another thing would be the incorporation of very specific strategies for improved sustainability and resilience. In line with this, further exploration would be a qualitative impact assessment of these strategies as is foreseen for D5.6.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

2.5 Conclusion

All studied farming systems are close to, at or beyond at least one, but often multiple critical thresholds, according to judgments from the participants and/or research teams. In addition, interactions between critical thresholds across domains and levels of integration are to be expected. While current trends of system performance are on average perceived as slightly positive, exceeding any of the identified thresholds is expected to lead to a decline in performance of most main system indicators and resilience attributes. Farming system challenges (in)directly affect the economic viability at farm level, a central critical threshold observed in all farming systems. In most farming systems, exceeding this threshold affects the availability of (qualified) laborers and farm successors, which in turn leads to depopulation, low attractiveness and low self-organization of the farming system, thus reinforcing low economic viability and lack of labor. Closeness to critical, interacting thresholds suggests that robustness of farming systems in the future seems low.

To avoid critical thresholds and improve system (mainly economic and environmental) functions, workshop participants came up with alternative systems that are mainly adaptations from the status quo. This could suggest a low level of acknowledgement that transformation is needed, which could negatively influence the transformability of the system. Incompatibility with SSP3 and low to moderate compatibility with other SSPs suggest that more radical alternatives for farming systems need to be explored. Expected increased performance of resilience attributes in alternative systems such as social self-organization and infrastructure for innovation could be the result of alternative systems as well as the preconditions for having enough adaptability for improving system functions. This would suggest that improving system functions also leads to higher resilience and vice versa, and that in case of low function performance or low adaptability/transformability, farming systems need to be stimulated by actors inside and outside the farming system. This was confirmed by the increased number of mentioned boundary conditions and strategies in the social and institutional domain that is needed for realizing these alternatives. Strategies differed more per domain across alternative systems per case study than boundary conditions. Dependent on the boundary conditions, some strategies can be more effectively implemented than others, thus shaping the future of farming systems. This provides opportunities for actors outside the farming system to address functions that are currently less addressed. For instance the current lack of attention for social functions of farming systems.

Current lack of allocated importance to social system functions and resilience attributes by farming system actors (FoPIA-SURE-Farm 1) is understandable, but not reasonable in the long-term. Neither is the current disregard for the resilience attributes "connected with actors outside the farming system", "policies coupled with local and natural capital" and "diverse policies" (FoPIA-SURE-Farm 2), all being related to social and institutional capital. And yet, in all case studies, boundary conditions in the institutional domain were present and were perceived to be very important. To improve sustainability and resilience, a more balanced attention for the economic, environmental as well as the social and institutional domain is key for all actors involved inside and outside the studied EU farming systems.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3 ECOSYSTEM SERVICE MODELLING ASSESSMENT

Francesco Accatino, Corentin Pinsard, Yong Shi, Franziska Appel, Katarzyna Bańkowska, Jo Bijttebier, Camelia Gavrilescu, Mariya Peneva, Simone Severini, Bárbara Soriano, Gordana Manevska-Tasevska, Mauro Vigani, Cinzia Zinnanti, Pytrik Reidsma

3.1 Methology for ecosystem services assessment

3.1.1 Background

What is considered "ecosystem service modelling" in the SURE-Farm project, corresponds to a set of analyses or modelling techniques envisaged to assess current or future ecosystem services provision by the SURE-Farm case studies. Ecosystem services are the benefits that humans can get from nature (Daily, 1997). Farming systems provide a certain amount of ecosystem services (Power, 2010): provisioning services are the most important (e.g., crop and animal production) but, according to the practices, agriculture provides also regulating services (e.g., pollination and carbon sequestration), and cultural services (e.g., landscape aesthetic qualities). At the same time, farming systems are embedded in a wider regional context in which they compete with other land uses and land covers. For example the expansion of the farming system over forest might be a cause of carbon storage decrease.

For D5.3 (Reidsma et al., 2019) the ecosystem services assessment was a quantitative analysis of available ecosystem services data in the case study regions completed with expert assessment. For the current deliverable, the purpose is to assess and discuss future ecosystem services provision under different scenarios. For this purpose, the ecosystem service modelling consists in the soft coupling of two different modelling approaches looking at the farming systems under different angles and modelling the provision of different services. The available tools did not make it possible to simulate all the ecosystem services considered in D5.3, but only a subset of them, constituted by crop production, animal production, carbon storage, and organic matter in the soil. Other ecosystem services (e.g., pollination or cultural services) could not be simulated in future scenarios for lack of data or for unavailable modelling tools.

The ecosystem service models are exclusively focused on the biophysical component of the system, i.e., no considerations are included about other functions related to social dynamics and preferences and economic viability. While other modelling approaches include also these functions (see System Dynamics and AgriPoliS), the ecosystem services modelling approach is more focused on the biophysical and agronomic description of the farming system.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The description of the tools follows the SURE-farm resilience assessment framework (Meuwissen et al., 2019). In the system definition and functions section, we give a description of how the system is conceived in the models and how the main components of the system are translated into mathematical or statistical equations; we also specify the outputs of the models. In the challenge section we describe the scenarios simulated by the systems and we give details the time trajectories of model inputs. In the resilience capacities section we describe the metrics we use in order to assess aspects of robustness and adaptability of the system with the modelling tools used (transformability is not assessed).

3.1.2 System definition

Figure 3.1.1 depicts the way in which ecosystem service modelling tools conceive the system, i.e., the wider regional context (Figure 3.1.1A) for the first modelling tool and the farming system nitrogen fluxes and pools (Figure 3.1.1B) for the second modelling tool. The first modelling framework (hereafter, "land use optimization model") is focused on the land cover and land use conflicts as a basis of the trade-offs between ecosystem services. Land use and land cover are among the main determinants of ecosystem services (Metzger et al., 2006). Indeed, being the land a scarce resource, the expansion of a particular land cover determines a reduction of the ecosystem services provided by it (Fischer et al., 2013). Possible solutions for softening conflicts might come from land covers promoting the provision of multiple ecosystem services (Accatino et al., 2019). For example, grasslands enhance the provision of carbon storage and animal production (Soussana and Lemaire, 2014), and mixes of crops cultivation and forestry enhance at the same time the provision of crops and carbon sequestration (Fagerholm et al., 2016; Pantera et al., 2018). The land use optimization model is based on the conflict between different land covers (seasonal crops, permanent crops, heterogeneous agriculture, grassland, and forest) for managing the conflict between two ecosystem services: crop production and carbon storage. In this context, the model considers the region as a whole system in which the land occupied by the farming system competes with other land uses more favorable to carbon storage (and other ecosystem services related to natural land covers).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

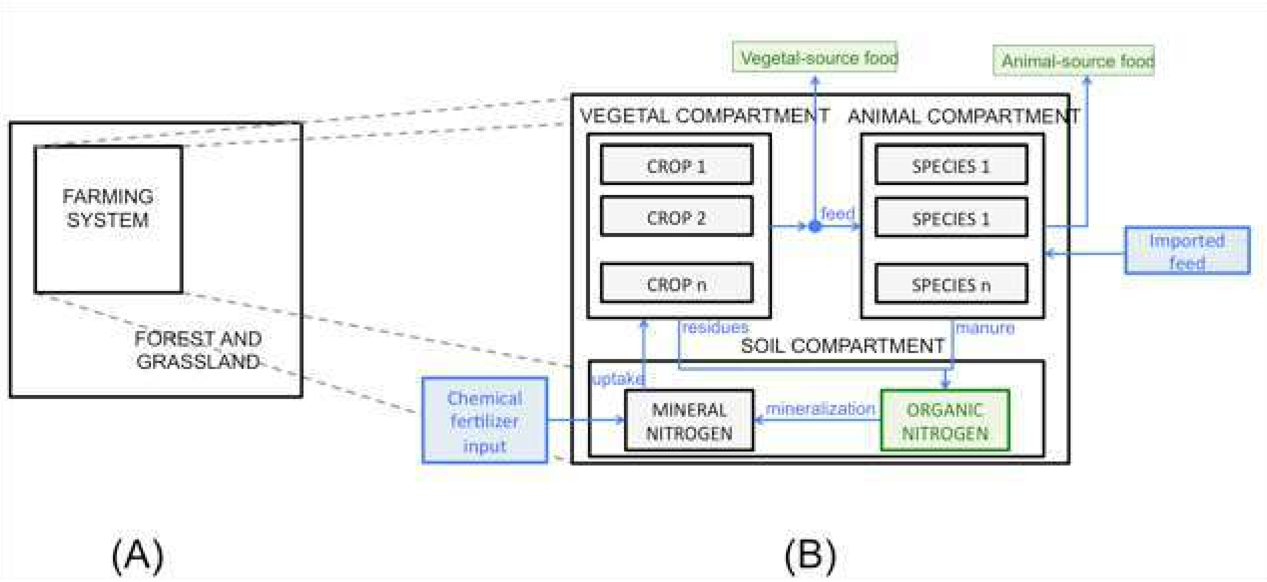


Figure 3.1.1 – Scheme depicting how system are conceived in the land use optimization model (Panel A) and in the nitrogen fluxes simulation model (Panel B). Panel A is referred to a whole region (NUTS3) containing a farming system among other land covers, Panel B is referred to the agricultural system of the region.

The second modelling framework (hereafter "nitrogen fluxes model") considers the internal functioning of the farming system from the point of view of nitrogen fluxes. The farming system is modeled as composed by a crop/grassland compartment, an animal compartment and a soil compartment. The crop/grassland compartment is composed by land cover fractions cultivated with different crops or occupied by grasslands. The animal compartment is composed by different livestock species. Within the soil compartment a dynamic nitrogen balance is implemented. The model considers the nitrogen fluxes between compartments. Harvested crops might go to direct human consumption, to animal as feed, or can undergo transformation (e.g., soy) and arrive in part to human consumption and in part to animal consumption as co-products. In the soil compartment the organic nitrogen balance (a proxy of the organic matter in the soil), is increased by organic nitrogen inputs (manure from the animal compartment and crop residues from the crop compartment) and decreased by mineralization. The amount of available mineral nitrogen in the soil determines the yield of the crops.

As a consideration, the ecosystem service analysis and modelling is not strictly focused on the farming systems as defined in D5.3. Rather they are extended to a wider area, ranging to the agricultural context to the whole NUTS3 region(s). The first reason for this is practical: the data for making an analysis of the ecosystem services possible are usually available at larger scales and with resolutions too broad for the farming systems defined. The second reason is conceptual: in order to analyze tradeoffs and synergies between ecosystem services it is important to take into account the wider context in which the farming system is embedded. In

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

the region, the farming system competes for land with other farming systems or other land uses dedicated to conservation. To give an example, the French case study is defined as a grassland-based beef cattle system, however, crops and fodder are present in neighboring territories. The analysis of ecosystem services should also include those land covers as they are in conflict with grasslands and their balance regulates the provision of multiple ecosystem services, e.g., crops, animal products and carbon storage.

Land use optimization model

The land use optimization model is based on statistical, data-based relationships between determinants and ecosystem services, following the methodology put in place by Accatino et al. (2019). The NUTS3 regions containing SURE-Farm case studies were divided into spatial units consisting of 10 km x 10 km squares (an overview of the location of the considered NUTS3 regions per case study is given in Figure 3.1.2). Determinants consisted of variables characterizing spatial units, i.e., land cover fractions, land use and climate variables. For the land cover fractions, we considered the fraction occupied by seasonal crops, permanent crops, heterogeneous agriculture, grassland and forest. Fractions were computed starting with the Corine Land Cover data of 2012 following the classification given in Table 3.1.1. The land use variable was energy input, which was based on the energy input in MJ/ha for producing agricultural goods, including labour, machinery, fertilizer and irrigation (Péres-Soba et al., 2012).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

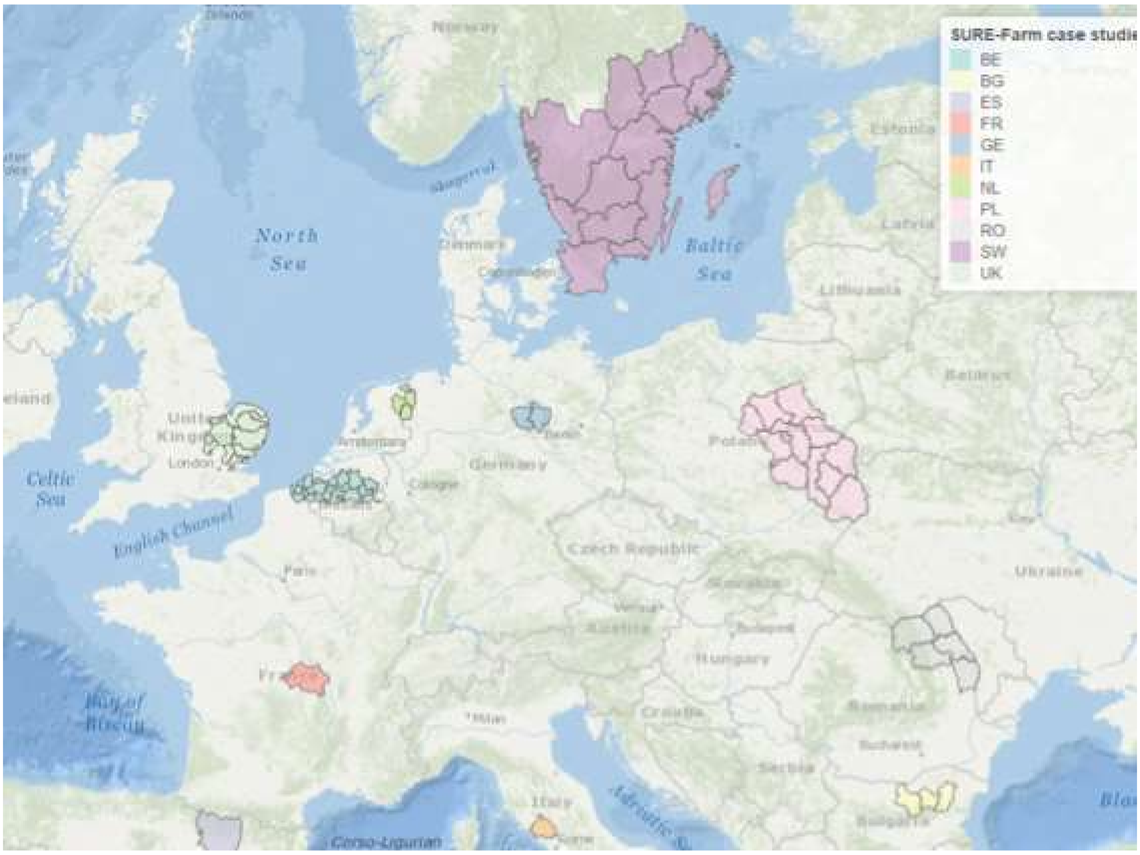


Figure 3.1.2 – Location of the NUTS3 regions considered for the different SURE-Farm case studies for the land use optimization model for ecosystem services.

Table 3.1.1 – Corine Land Cover (CLC) categories used for the land use optimization model and their grouping into categories for the model

Land cover	CLC category code	CLC category descriptions
Annual crops	2.1.1	Non-irrigated arable land
	2.1.2	Permanently irrigated land
	2.1.3	Rice fields
Permanent crops	2.2.1	Vineyards
	2.2.2	Fruit trees and berry plantations
	2.2.3	Olive groves

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Heterogeneous agricultural areas	2.4.1	Annual crops associated with permanent crops
	2.4.2	Complex cultivation patterns
	2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation
	2.4.4	Agro-forestry areas
Grassland	3.2.1	Natural grasslands
	3.2.2	Moors and heathland
	3.2.3	Sclerophyllous vegetation
	3.2.4	Transitional woodland-shrub
	2.3.1	Pastures, meadows and other permanent grasslands
Forests	3.1.1	Broad-leaved forest
	3.1.2	Coniferous forest
	3.1.3	Mixed forest

The model for calculating an ecosystem service (*ES*) is a descriptive model in the sense that the shape of the relationship is assigned, but does not fully have a mechanistic interpretation. The model is based on the assumption that that each land cover fraction LC_i provides a given quantity of ecosystem services. Such quantity is partially dependent on intrinsic properties of the land cover types and partially dependent on other factors, such as land use and climate.

$$ES = \sum_i \alpha_i LC_i \cdot f(\theta_1, \theta_2, \theta_3, \dots) \qquad \text{Eq. (3.1.1)}$$

Where α_i is a coefficient of provision of the ecosystem service by the land cover type *i* and $f(\theta_1, \theta_2, \theta_3, \dots)$ is a function of climate and land use variables (θ_j). For such factors we used a Cobb-Douglas function, being it a weighted product of the different factors. The choice of the weighted products instead of linear combination comes from the assumption of non-substitutability between the factors (Accatino et al., 2019). The equation 3.1.1 becomes then

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

$$ES = \sum_i \alpha_i LC_i \cdot \prod_j \theta_j^{\gamma_{i,j}} \qquad \text{Eq. (3.1.2)}$$

where the exponents $\gamma_{i,j}$ are specific to the land cover type *i* and the land use or climatic variable *j*.

The ecosystem services considered were crop production (from either seasonal or perennial crops) and carbon storage. Because of the type of modelling, we focused on those ecosystem services, which are based exclusively on land cover without spatially explicit interactions. Other ecosystem services were not adapted to this modelling: for example, animal production is not always strictly linked to land cover as it might be intensive and dependent on imports of external feed; pollination depends on spatial interactions between pollinator habitats and cultivated fields at finer scales.

Values of parameters (α_i and $\gamma_{i,j}$) are calibrated so that the differences between the predicted values of ecosystem services and the measured values are minimized. Values of parameters are given in Appendix C. The calibration was done for each case study, therefore the parameter sets change from case study to case study even with the same model: this reflects the specific conditions within each case study region. Once the models are calibrated, a two-objectives optimization is run for each case study in order to compute the Pareto frontier whose shape shows the trade-off between crop production and carbon storage. The two objectives optimization is run with an evolutionary technique implemented with NSGA II (Deb et al., 2002)

The optimization model is completely based on conflicts between different land covers: those more suitable for crop production (e.g., seasonal crops) and those more suitable for carbon storage (e.g., forest), with some land covers in between, providing a certain level of both ecosystem services (e.g., heterogeneous agriculture). Even though cropland contributes at a certain extent to carbon storage, grassland and forest contribute to it at a major extend. Although changes in management and technology may change crop production and carbon storage for a given land cover, this is not included in the assessment. Therefore we expect that the conflict between agriculture and forest/grasslands drives the tradeoff at the regional scale. However, the strength of the tradeoff is different from case study to another depending on the parameters calibrated.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Nitrogen fluxes model

As depicted in Figure 3.1.1B, the model conceives the farming system as composed by three compartments: a soil, crop/grassland compartment and animal compartment.

Nitrogen in the soil. The soil compartment is composed by the mineral nitrogen N^{MIN}(immediately available for plant uptake) pool and the organic nitrogen pool N^{ORG} (mineralizing at a slower pace and therefore not immediately available for the plant). The sources of fertilization are the following: atmospheric deposition, residues from cultures, effluents from the livestock compartment, and the synthetic fertilizer. The atmospheric deposition is fixed and obtained from EMEP database. The residues of cultures are constituted by the aerial residues and the roots: the aerial residues are calculated by means of the harvest index HI (characteristic of each crop see the IPCC guidelines for National Greenhouse Gas Inventories or (Le Noë et al., 2017)) whereas the root biomass is calculated by means of the shoot-to-root ratio SR (characteristic of each crop, see the IPCC guidelines for National Greenhouse Gas Inventories or (Le Noë et al., 2017)). Effluents are estimated as outputs of the livestock compartment and constitute a fraction of the animal nitrogen intake. Synthetic fertilizer input varies as scenario simulated. All the nitrogen inputs to the soil are composed by an organic and a mineral part, filling the two pools respectively. For crop residues and effluents from the livestock compartment the organic fraction is given by the humification coefficient (Le Noë et al., 2017). The mineralization M constitutes a flux from the organic to the mineral compartment and is proportional to the nitrogen in the organic pool $M = k \cdot N^{ORG}$ by means of a coefficient *k* called mineralization rate. The mineralization rate is calculated with the equation from the AMG model (Clivot et al., 2019), based on averaged biophysical values (data from the Joint Research Center).

Simulation of harvested crops. The mineral nitrogen available after emissions is taken up by the plants and the harvest for each crop is modeled with a piecewise linear function that saturates at a maximum yield (see Appendix C). The underlying assumption is that the biomass produced grows linearly with nitrogen availability when nitrogen is limiting, but the nitrogen uptake stops once the potential yield is reached or when other factors become limiting.

Repartition of harvested crops. The harvested quantity of crops is then partitioned by means of coefficients to be conveyed to the different compartments. A part goes to direct human consumption, a part goes to animal consumption (feed), a part undergoes industrial transformation; of this last part, a fraction becomes plant-source human consumption and a part goes to animal consumption as by-product. Coefficients of repartition are specific from each case study and, where not available, were assigned default values.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Dynamics of livestock population. Livestock population x_t changes following a dynamic population model :

$$x_{t+1} = x_t\left(1 + \tau_B + \tau_d(\varphi_t)\right) \qquad \text{Eq. (3.1.3)}$$

The growth rate τ_B corresponds to the willingness of farmers to increase the stock, the loss rate τ_d corresponds to the willingness of farmers to destock due to scarcity of feed available. The variable φ_t corresponds to the feed scarcity. In order to calculate the feed scarcity, the feed available (formed by the feed produced in the region and the imported feed) is compared with the feed demand of the livestock. The comparison is done component by component and the feed composition need is assigned to the different case studies following Hou et al. (2016).

3.1.3 Functions simulated

Table 3.1.2 indicates the ecosystem services analyzed in D5.3 and simulated with the two ecosystem services models of this deliverable. The analysis of D5.3 was based on data and expert assessment and could be done for a wide range of (biophysical-based) private and public goods. The D5.5 is centered around simulations of future scenarios and, for this purpose, the modelling was possible for a subset of the ecosystem services considered in D5.3.

Table 3.1.2 – Ecosystem services addressed within D5.3 and simulated with the two models used in this deliverable.

	Ecosystem services	Analysis in D5.3	Land use optimization model	Nitrogen flux simulation model
Private goods	Food crop production	X	Merged together as “crop production”	X
	Fodder crop production	X		X
	Energy crop production	X		X
	Grazing livestock density	X		
	Animal source food production			X
Public goods	Timber removal	X		
	Carbon storage	X	X	
	Habitat quality index	X		

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

NOx deposition	X	
Organic matter soil concentration	X	X
Relative pollination potential	X	
Recreation potential	X	
Water retention index	X	

The land use optimization model is focused on crop production and carbon storage. In this model, what is labeled as "crop production" encompasses food crop production, fodder crop production, and energy crop production. A distinction was not possible because in the Corine Land Cover classification no internal distinctions were available. Among other ecosystem services, timber growth and NOx deposition could not be assessed, however, they are strictly based on forest, therefore, we can argue, that when forest is increased, those ecosystem services are increased.

The nitrogen flux simulation model can simulate the provision of different private goods: food crops, fodder crops, energy crops, and animal source food. Concerning animal source food, this has to be considered as an addition to D5.3, where only a proxy (grazing livestock density) could be assessed. The public good simulated is the soil organic matter in the soil, as in the model we simulate organic nitrogen dynamics, which is a proxy.

Other ecosystem services could not be simulated due to lack of data or sufficient knowledge about the process. Calibration of the land use optimization for habitat quality, recreation potential, relative pollination potential, and water retention index did not provide satisfactory results.

3.1.4 Future challenges and scenarios

Future challenges description

The application of the ES models is embedded in the Eur-Agri-SSP scenarios (see Mitter et al., under review, and D2.1, Mathijs et al. (2018)). Those scenarios correspond to specific changes in land cover and land use or in changes in the proportion between livestock and crops in the regions. Those kind of changes are not the only elements envisaged by the scenarios (as indeed, other things related to economy, society, and institutions are considered), however, for our modelling, we consider only the part of the scenarios related to land use, nitrogen input, feed availability, and livestock. We consider the scenarios Eur-Agri-SSP1 (sustainability), Eur-Agri-SSP2

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

(business as usual), Eur-Agri-SSP3 (regional rivalry), and Eur-AgriSSP5 (fossil-fuel development). Briefly, the scenario Eur-Agri-SSP1 describes a reduction of land dedicated to agriculture for enhancing the land dedicated to conservation, a reduction in meat consumption compensated with increased production of vegetal proteins; the scenario Eur-Agri-SSP2 relates to business as usual (not significant modifications are done); the scenario Eur-Agri-SSP3 and Eur-Agri-SSP5 include an increase in land dedicated to agriculture as well as an increase in the livestock sector for boosting the production of vegetal and animal goods.

Concerning the land use optimization model, we believe that using the multi-criteria analysis for addressing the tradeoff between crop production and carbon storage fits with the sustainability Eur-Agri-SSP1 scenario, where the aim is to conciliate environmental conservation and agriculture. Animal production is not considered in this model and its increase is not envisaged in this scenario. We expect that this scenario will not be adapted for the case studies too much focused on beef production.

Concerning the nitrogen fluxes model, we decided to consider two challenges to which European farming systems might be confronted in the next decades: a progressive decline in the availability of chemical fertilizer and a progressive decline in the availability of external animal feed for import. As outputs of the participatory workshops, it is evident that the SURE-farm case studies are confronted with specific challenges of different types (environmental, social, economic, institutional). These can however not all be simulated at the same time, and the resilience to resource challenges in the long-term has received limited attention so far. The considered challenges are conceived to test the configuration of the system from the biophysical point of view in face of shortage in inputs to the system. Actual European agriculture is dependent on hydrocarbons, particularly for the synthesis of nitrogenous fertilizers using the Haber Bosch process and then for the import of animal feed, the production and transport of which require respectively gas and oil. However, the International Energy Agency suggests in its 2018 World Energy Outlook that the world's peak oil production could be reached by 2025. This peak would lead to an increase in the fluctuation of hydrocarbon prices (including gas and coal) and, in the long term, their increase. Past dynamics and recent crisis management do not suggest that the agricultural sector in Europe would be totally spared from these future energy and economic disruptions. Thus, it seems reasonable to investigate the production capacity of agricultural systems in Europe considering a decrease in the availability of synthetic fertilizer and animal feed imports that would be linked to the passage of the global oil peak in the coming years.

The chosen challenges should not be considered as predictions or projections; they are rather explorations to provide attention to the biophysical characteristics of the farming systems and

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

their resilience in relation to possible shortages in external inputs. Considering these challenges under the three Eur-Agri-SSP scenarios corresponds to measure the feasibility of the systems subject to those challenges under the scenarios.

Simulation of challenges under scenarios

Concerning the land use optimization model, we applied an evolutionary technique to optimize crop production and carbon storage. Variables in each land unit could vary between -20% and +20% of their original value. This assumption was made in order to avoid complete changes in the land cover of the regions.

Concerning the nitrogen fluxes models, simulations are done as in Table 3.1.3. We simulated scenarios along a time horizon of 30 years setting a decline of chemical nitrogen availability and external feed availability. At the initial time, the chemical fertilizer availability to import is equal to 70% of the initial need in mineral nitrogen by crops (i.e., the quantity that fulfills the plant need taking into account losses) and the feed availability to import is equal to the initial feed import. As for other variables, we simulated their variation according to the Eur-Agri-SSP scenario.

For the Eur-Agri-SSP1 sustainability scenario we simulated a linear increase in the land occupied by oil and protein crops (substitutes for animal products) and at the same time a linear decrease in other cultivated lands. Grasslands are kept constant as they are linked with environmental services. Animal production is decreased and this corresponds to a voluntary destocking in both ruminants and monogastric population. These variables are linked with the overall storyline of the scenario that envisages a decrease in the land dedicated to agriculture, a higher proportion in agriculture for the land dedicated to oil and protein crops, and a decrease in the demand and production of animal source food. Due to its assumptions, the model could not simulate the increase of yield due to technology, considered in this scenario. For the business-as-usual Eur-Agri-SSP2 scenario, all the variables are left unchanged as in the original data. Such scenario serves as a test for the current agronomical configuration of the farming system. For the regional rivalry Eur-Agri-SSP3 scenario, the agricultural system is boosted and expanded over other land cover types as demand for environmental services is declining and environmental standards are declining. We therefore set an increase in the land dedicated to agriculture, except for grassland kept constant, and oil and protein crops that decreases as they do not have to substitute animal products. The livestock population is allowed to grow as long as feed is available.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 3.1.3 – Summary table of the Eur-Agri-SSP scenarios considered in the nitrogen fluxes model. Eur-Agri-SSP scenarios are included by imposing time trajectories of some model inputs and parameters. Arrows indicate the direction of change , i.e., decreasing (↘) or increasing (↗), the final value is represented as a percentage of the initial value (i.v.)

	Eur-Agri-SSP1		Eur-Agri-SSP2		Eur-Agri-SSP3//5	
Parameter/Variable	trend	final value	trend	final value	trend	final value
Feed import	↘	10% of i.v.	↘	10% of i.v.	↘	10% of i.v.
Synthetic fertilizer availability	↘	10% of i.v.	↘	10% of i.v.	↘	10% of i.v.
Oil and protein crops share	↗	120% of i.v.	=	-	↘	80% of i.v.
Cereals share	↘	80% of i.v.	=	-	↗	120% of i.v.
Fodder share	↘	80% of i.v.	=	-	↗	120% of i.v.
Total agricultural land	↗	80% of i.v.	=	-	↗	120% of i.v.
Grassland	=	-	=	-	=	-
Monogastric	↘	-	=	-	↗	-
Ruminants	↘	-	=	-	↗	-

3.1.5 Resilience capacities

The outputs of the models have to be analyzed in relation to the message they can give about the resilience of the system simulated. Of course, models are representative of a certain aspect of reality and therefore the results show only a particular aspect of the resilience of the system. For this reason, it is important to discuss results in relation to the limits of the model, considering also those factors that are not included in the model.

The land use optimization model is aimed at giving an idea about the possibility to conciliate crop production and carbon sequestration in the context of the sustainability scenario Eur-Agri-SSP1. The increase in animal production is not envisaged in this scenario. We analyze the following metrics: (i) percentage of maximum crop production increase in relation to the initial

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

situation, (ii) percentage of maximum increase in carbon storage in relation to the initial situation, (iii), the percentage of points in the Pareto frontier for which it is possible to increase at the same time crop production and carbon storage. We argue that this is a metric of adaptability as it shows how the system is adaptable to land use conflicts in relation to the scenario Eur-Agri-SSP1.

The nitrogen-fluxes model simulates the time trajectories of different variables constituting the functions provided by the system. We observe trajectories of the following functions: (i) crop production for human consumption, (ii) animal production, (iii) total food production, (iv) organic nitrogen in the soil (being it a proxy of the organic matter in the soil). We also track the percentages of decreases in food production at given time steps along the simulation. Those metrics are a measure of robustness; the smaller is the percentage decrease the more robust is the system.

The nitrogen fluxes model requires data about crops (hectares and typical yields), manure and synthetic fertilizer application, livestock composition and production. Animal intake and diet composition is estimated by Hou et al. (2016). For the different case studies, sources are diverse and are provided in Appendix C

3.2 Results of the ecosystem service modelling assessment: French case study

3.2.1 Land use optimization

The land uses considered for the analysis are seasonal crops, permanent crops, heterogeneous agriculture, grassland and forest. The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the French SURE-farm case study region gives the Pareto frontier depicted in Figure 3.2.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

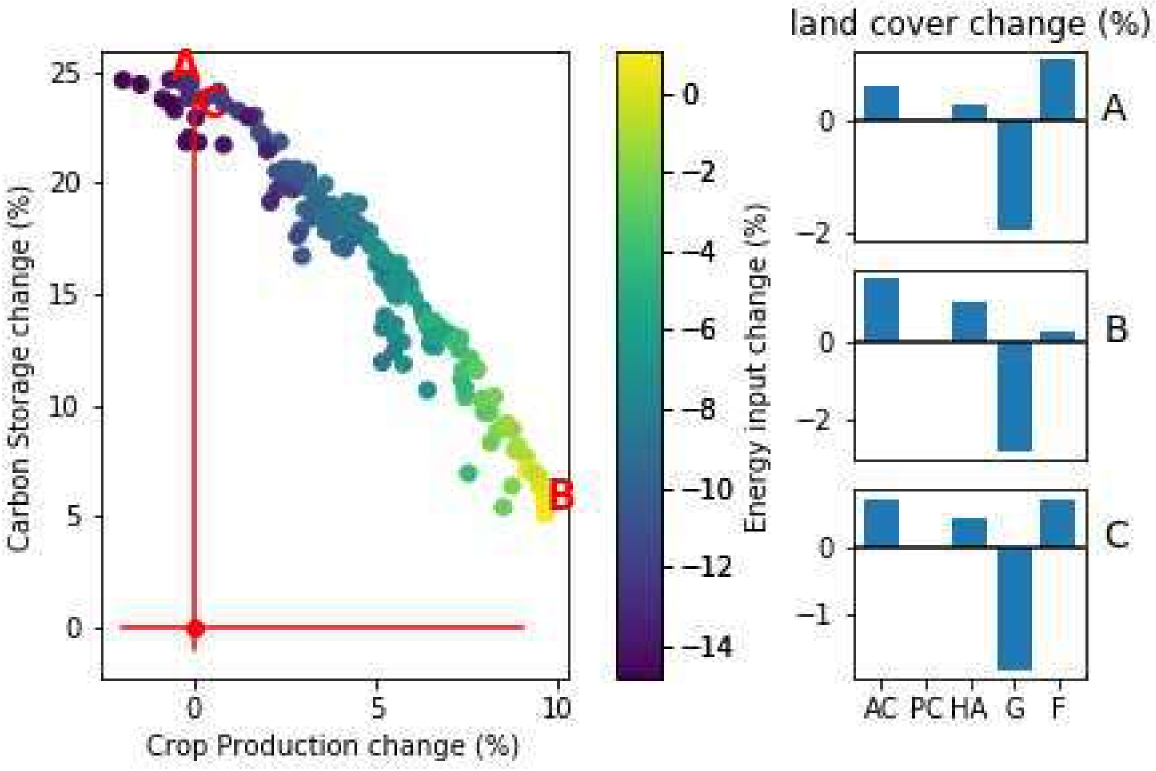


Figure 3.2.1 - Results of the land use optimization model for the French case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The French case study farming corresponds to the region of the Bourbonnais and is mostly focused on the extensive beef production based on permanent grassland. Being the case study centered on the production of beef, it is a priori poorly adapted to the sustainability scenario (Eur-Agri-SSP1) in the way it is defined. The Bourbonnais system is highly specialized in beef production and it is therefore not adapted to a scenario in which the vegetal-source products are preferred over the animal-source products. The grasslands of the Bourbonnais are highly maintained by the grazing livestock. However, cattle receive some supplementary feed also from crops cultivated in the Southern part of the same region. Therefore the land uses characterizing the system (according to this analysis) are “grassland” (as main land cover type) and “annual crops”.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The Pareto frontier shows that the system has a great possibility to improve carbon storage while also improving the crop production. Indeed, all the optimized points increase carbon storage. However, a better look at the results shows that this optimization is not in line with the Bourbonnais identity. The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.2.1) maximizes carbon storage and minimizes crop production and shows that an increment of 24.7% in carbon storage is possible but with a decrease of 5% in crop production. Point B (Figure 3.2.1) maximizes crop production and minimizes carbon storage and shows an increase of 9.7% in crop production without a decrease in carbon sequestration. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Belgian case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 92.9% of the total number of optimized points: this is the highest detected in all the SURE-farm case studies. This indicates that the system has a very high adaptability to the Eur-Agri-SSP1 scenario and has many possibilities to increase both crop production and carbon storage at the same time. A better look at the land use changes in the different points of the Pareto frontier helps to understand how it is possible.

Figure 3.2.1 also shows bar diagrams with the land use changes occurring in the points A , B and C marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). Point C indicates the point on the Pareto front that maximizes carbon storage, while maintaining the same level of crop production. In all the three points, A, B, and C, the directions of land use change are the same: forest, annual crops, and heterogeneous agricultural lands are expanded over grassland. The difference between the three points is given by different extents to which the three land cover fractions are increased. Forest is expanded more than annual crops in Point A, annual crops are expanded more than heterogeneous agriculture and forest in Point B and the increases in the three land covers are more balanced in point C. In this scenario, which considers the optimization of crop production and carbon storage, grassland is the land cover type that the model tends to substitute. Grassland is not productive for crop production, and is less efficient than forest in carbon storage. Among all the Sure-farm case study, the Bourbonnais region is the one with the highest fraction of grassland, this is why there is room for increasing forest and other forms of agriculture to promote the two considered ecosystem services at the same time.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

In the particular situation of the Bourbonnais, grassland can be even a source of carbon emission because of the relatively high density of cattle grazing on it. Therefore, expanding forest over grassland would indeed be a gain on carbon storage and sequestration for the region. But this would lead to a reduction in the livestock sector of the Bourbonnais. Concerning the replacement of grassland with crops, this is a phenomenon already happening in the Bourbonnais, but it was indicated as something undesirable by stakeholders (see D5.3) as it affects negatively the landscape. Sometimes permanent grassland is replaced with cultivated grassland which is more efficient for the dry matter productivity but less efficient for carbon storage and having an effect of lowering biodiversity. It is to be noted, however, that not all the permanent grasslands in the region can be converted because of the underlying morphological and soil characteristics.

Overall, the high system's adaptability in the Eur-Agri-SSP1 scenario is so high because adapting the system in this scenario would correspond to a radical transformation of the system itself, which is not even desirable by the stakeholders. Previous work done with stakeholders indicated the importance of keeping the farming system linked with the natural capital and this happens if the identity of the system (i.e., livestock coupled with grassland) is maintained. Alternative formulations of the scenario Eur-Agri-SSP1 should consider the situation of the systems specialized in the production of animal-source product, stressing on their sustainable linkage with the natural resources.

3.2.2 Nitrogen fluxes model

The land cover of the agricultural context of the French farming system is characterized by a big presence of grassland (30%) with also cereals (27%), some fodder crops (7%), oil and protein crops (5%) and other crops (2%). The livestock sector has a density of 0.92 livestock unit per hectare of agricultural land with 89% ruminants, 55% of which are on pasture

Changes in the agricultural system compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 3.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.2.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.2.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.2.3 shows that the sources of fertilization are mainly coming from mineralization of organic nitrogen, crop residues and animal effluents, showing that the dependency on

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

chemical fertilizer is quite low. The contribution of the fertilization from animal effluents is different in the three scenarios.

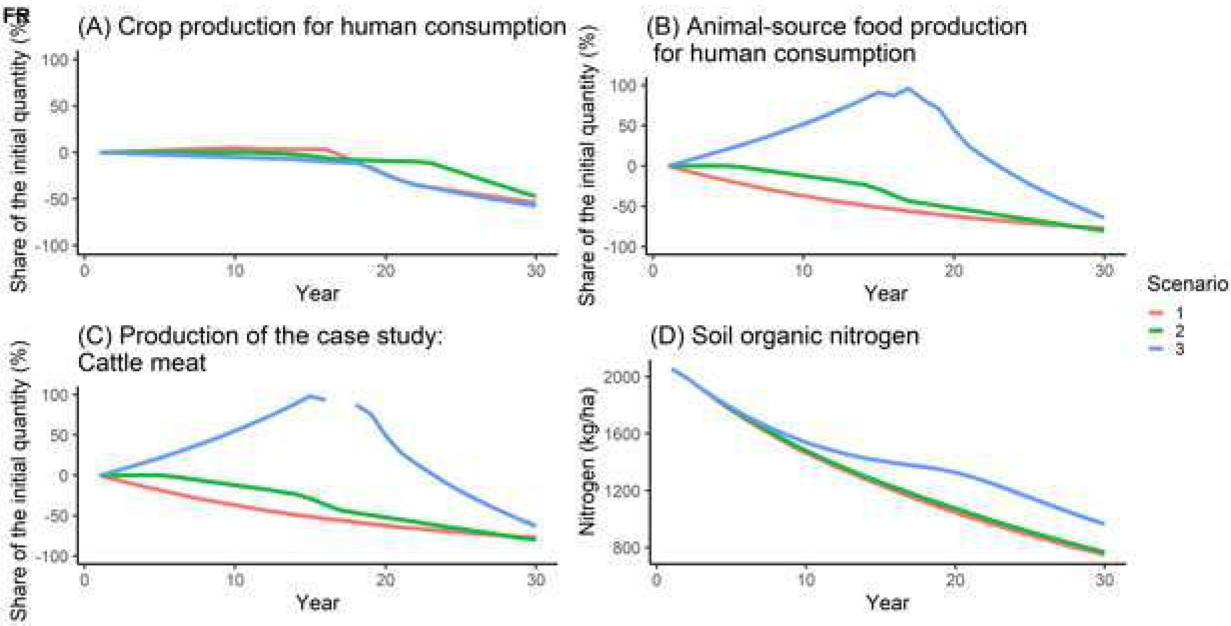


Figure 3.2.2. Simulation results of the nitrogen fluxes model for the French case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), beef production (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

The first scenario (compatible with Eur-Agri-SSP1, sustainability) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. The livestock compartment is destocked in this first scenario and this has a direct consequence on animal production total food production and an indirect consequence on the crop production to humans (Figure 3.2.2). In the first years of the simulation, the vegetal production increases because of reduced feed-food competition. While less land is dedicated to agriculture, more harvested biomass is dedicated to human and not to animal consumption. However, the destocking of the livestock compartment causes a shortage in fertilizer and anticipates the point in which the system starts experiencing shortage in nitrogen fertilizer (Figure 3.2.3). The system is highly characterized by the presence of grazing cattle and its reduction provokes a reduction in fertilizer for crops and in the organic matter in the soil (Figure 3.2.2D).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

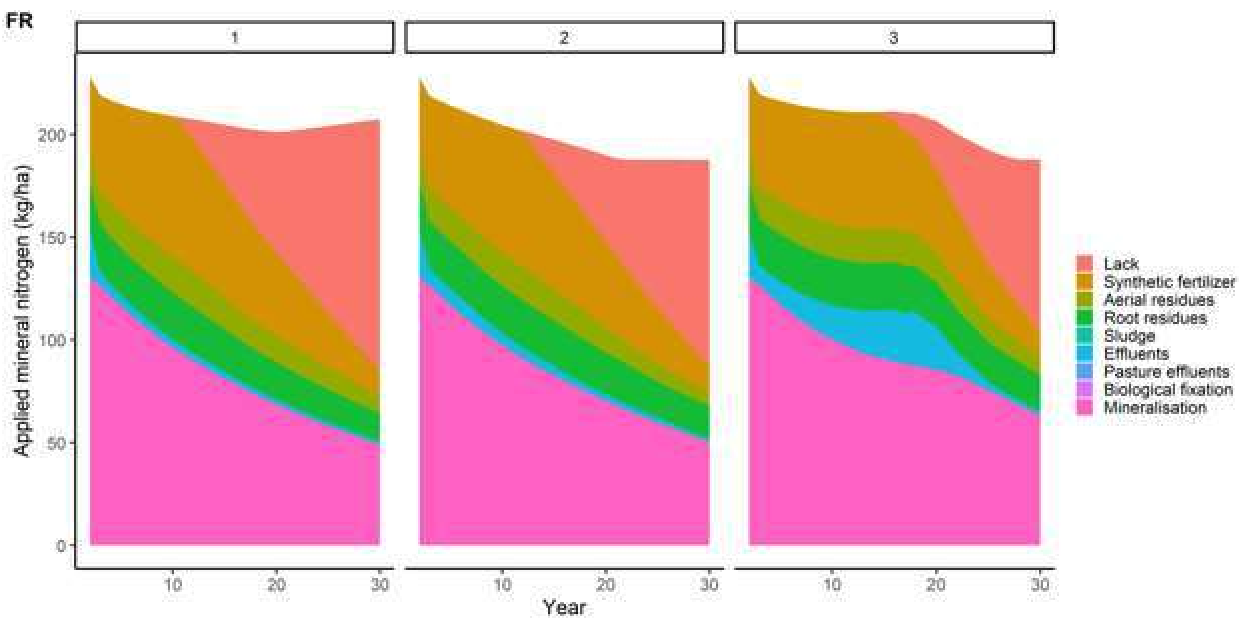


Figure 3.2.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the French case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the second scenario (compatible with Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. The system resists for a longer time (comparing to the other two scenarios) to the decrease of chemical fertilizer and feed import. The configuration of the system based on the presence of grassland, grazing livestock and also crops in the same regions constitutes a good balance between the livestock and the crop compartment. The system is feed self-sufficient and the animal production shows a decline very late in the simulation (after year 20, see Figure 3.2.2B).

In the third scenario (compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. The possibility to increase the livestock compartment makes it possible to have a strong increase in beef production at the beginning (Figure 3.2.2C). Such increase is very high in the first part of the simulation, but then drops in the end of the simulated time horizon. Concerning crop production to humans (Figure 3.2.2A), the production decreases due to increased feed-food competition. The increased presence of cattle increase the availability of animal effluents for fertilization (Figure 3.2.3) and of the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

organic matter in the soil (Figure 3.2.2D), and therefore retards the shortage in fertilizer. The system is then damaged by the lack of imported feed at the end of the simulation.

3.2.3 General considerations

The adaptability of the Bourbonnais region to the Eur-Agri-SSP1 was investigated with the land use optimization model and with the nitrogen flux model. The land use optimization model shows that adapting the system to the scenario would correspond to a transformation of its identity, as grassland would be replaced with other land covers. In addition, among the three scenarios the Eur-Agri-SSP1 model is the one performing the worst as it would remove the livestock compartment and would expose the system to be more dependent on external chemical nitrogen. The Bourbonnais system is totally specialized in extensive beef production coupled to the natural capital, and the grasslands of the region provide a net input to food productions. Therefore, the definition of the sustainability scenario should take this into account; otherwise, in a scenario where animal-source products are replaced by vegetal substitutes, a system like this cannot exist in the current form.

The system performs well in scenario Eur-Agri-SSP2, i.e., the business-as-usual scenario. The system is able to sustain long periods of crop and animal production before going in shortage of fertilizer. The actual configuration is therefore optimal and robust to progressive shortages in fertilizer and in feed import. The scenario Eur-Agri-SSP3/5 leads to a boosting of the livestock sector and an increased in production in the short term. However this leads to a more severe drop in the last part of the simulation when feed shortage arrives.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.3 Results of the ecosystem service modelling assessment: Spanish case study

3.3.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Spanish SURE-farm case study region gives the Pareto frontier depicted in Figure 3.3.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

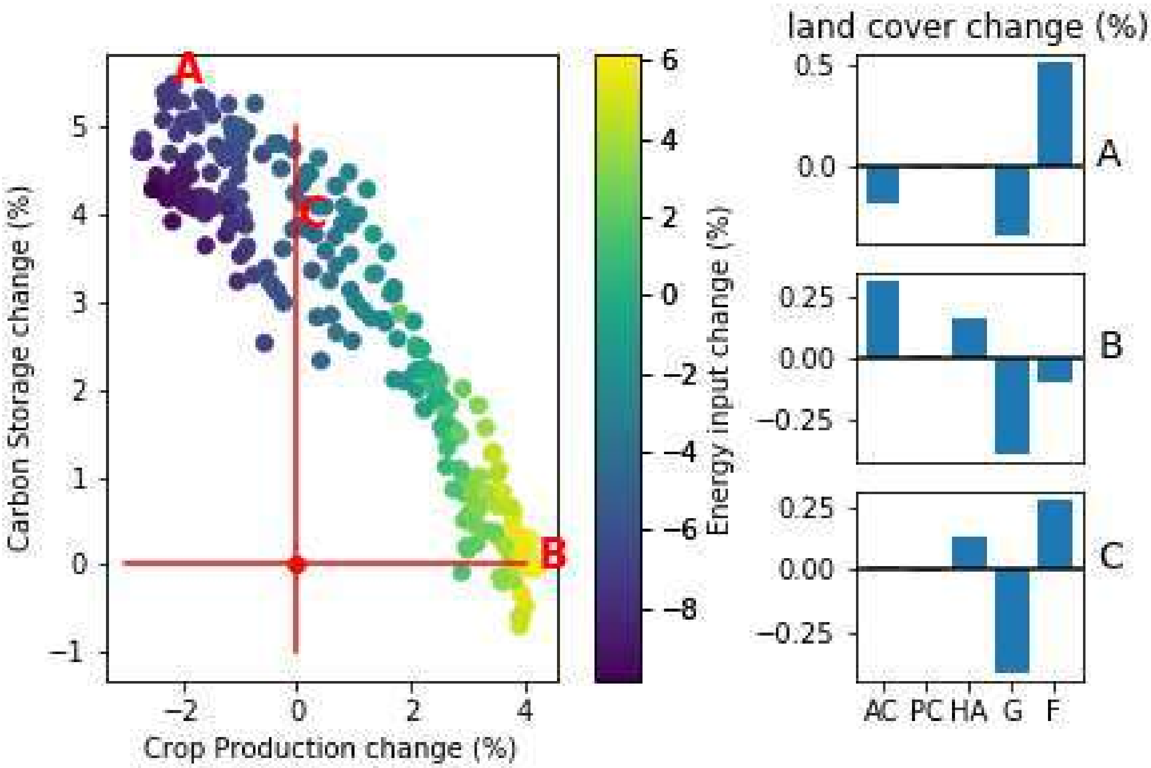


Figure 3.3.1 - Results of the land use optimization model for the Spanish case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The Spanish case study farming system is an extensive grassland-based ovine system. Being the case study centered on the production of meat, it is a priori poorly adapted to the sustainability scenario (Eur-Agri-SSP1) in the way the scenario is defined. The Spanish case study is highly specialized in ovine meat production and it is therefore not adapted to a scenario in which the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

vegetal-source products are preferred over the animal-source products. Although much of the animal rearing is based on pasture, the production relies also on the presence of cultivated land for the forage. According to the terminology of this analysis, the land use categories corresponding to the Spanish case study are "grassland" (most important) and "annual crops". In the rest of the region, the analysis of the Corine Land Cover categories reveals that there are no permanent crops, but some heterogeneous agricultural land is present.

The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.3.1) maximizes carbon storage and minimizes crop production and shows that an increment of 5.8% in carbon storage is possible but with a decrease of 2% in crop production. Point B (Figure 3.3.1) maximizes crop production and minimizes carbon storage and shows an increase of 4.1% in crop production with only a slight (almost negligible) decrease in carbon storage. The configuration of the Pareto frontier shows that almost all the points of the Pareto frontier increase carbon storage. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Spanish case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 53.56% of the total number of optimized points: this is considered average with respect to the other SURE-farm case studies. This indicates that the system has a very high adaptability to the Eur-Agri-SSP1 scenario and has many possibilities to increase both crop production and carbon storage at the same time. A better look at the land use changes in the different points of the Pareto frontier helps to understand how it is possible to increase both ecosystem services at the same time.

Figure 3.3.1 also shows bar diagrams with the land use changes occurring in the points A, B and C marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). Point C indicates the point on the Pareto front that maximizes carbon storage, while maintaining the same level of crop production. In Point A of Figure 3.3.1 (maximization of carbon storage), the increase in carbon storage is obtained by an expansion of forest over grassland and annual crops. In Point B of Figure 3.3.1 (maximization of crop production), annual crops and heterogeneous agricultural land are expanded over grassland and forest. In Point C of Figure 3.3.1 (maximization of carbon sequestration without decreasing crop production), the increase in carbon sequestration occurs with the expansion of the heterogeneous agricultural land and forest over grassland. In each point of the Pareto front, grassland is reduced and occupied by

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

agricultural land or by forest. In the context of the scenario Eur-Agri-SSP1 (where crop production and carbon storage are maximized and meat production is decreased), grassland is decreased because it is not productive for crop and less efficient than forest for carbon storage. As it happens for the French case study, the points of the Pareto frontier lead to a transformation of the identity of the system, reducing grassland and increasing cultivated land. Overall, adapting the system to the scenario Eur-Agri-SSP1 would correspond to a radical transformation of the system itself, as the current configuration of the system is based on a grassland-based meat production.

3.3.2 Nitrogen fluxes model

The land cover of the agricultural context of the Spanish farming system is characterized by presence of fodder (62%) and grassland (13%), with also cereals (21%), oil and protein crops (1%) and other crops (3%). Livestock density is moderate, corresponding to 1.01 livestock unit per hectare of cultivated land. The percentage of ruminant is only 15% with 63% of them on graze. According to the data, even though the Spanish case study is referred to ovine production, it interacts and competes in the region with a well-developed sector of monogastrics (pigs and poultry). This means that, while the ruminant sector might be self-sufficient (ovine sector), feed self-sufficiency might be lower for the monogastric sector.

Changes in the agricultural system compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.3.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.3.3, in which the “lack” term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.3.3 shows that the sources of fertilization are mainly coming from mineralization of organic nitrogen, crop residues and animal effluents, however, the contribution of animal effluents is not very high compared to the nitrogen demand of crops and the system experiences shortage in fertilizer quite early (compared to other case studies) in the three scenarios (between year 9 and 11).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

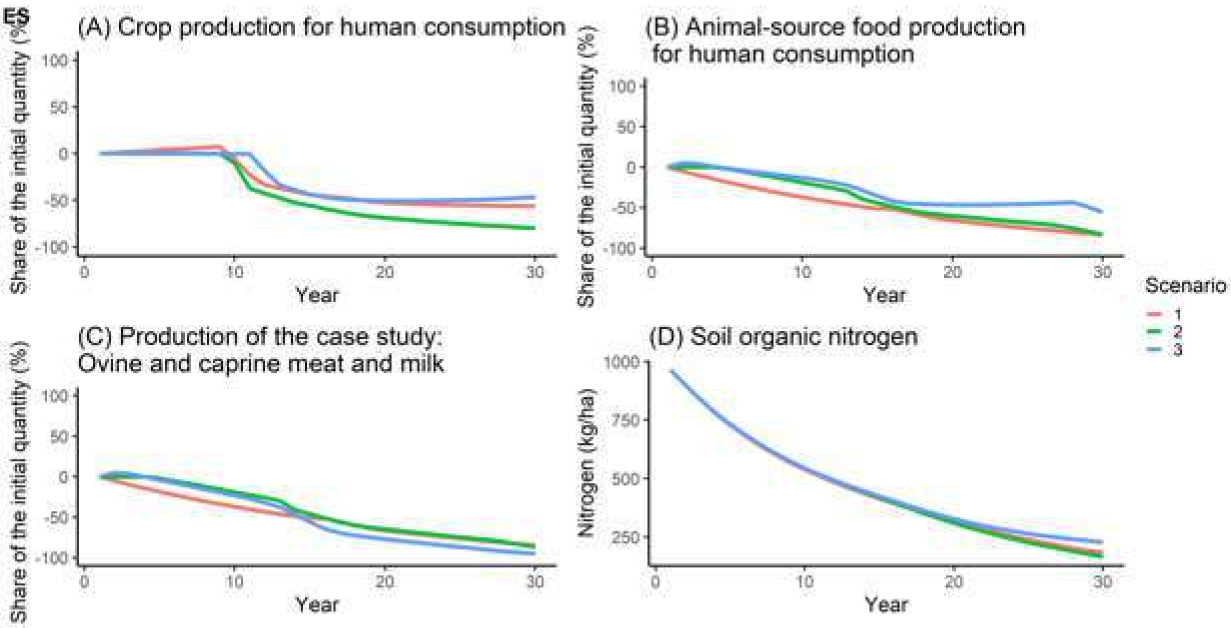


Figure 3.3.2. Simulation results of the nitrogen fluxes model for the Spanish case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), ovine production (meat and milk) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

The first scenario (compatible with the Eur-Agri-SSP1, sustainability) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. Due to the increase in oil and protein crops, less fertilizer is needed for the crop compartment, therefore, even though the land for agriculture is reduced, the crop production for human consumption is slightly increased in the first years of the simulation. However, the crop production drops at year 9 as shortage in fertilizer arrives (Figure 3.3.2A).

In the second scenario (compatible with the Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In the third scenario (compatible with the Eur-Agri-SSP3 and Eur-Agri-SSP5 scenario), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. For both scenarios animal production is maintained or slightly increased for the first 6-7 years, however it then drops because of feed shortage (Figure 3.3.2B). This is mainly due to the presence of the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

monogastric sector, which demands feed importation, however, also the ovine sector demands some feed and decreases (Figure 3.3.2C)

Although the agricultural context of the Spanish case study is characterized by the presence of both livestock and crops, the system does not seem have a strong coupling between the two components. This is mainly explained by the presence of the monogastric sector. The demand for nitrogen by the crop compartment is still very high (and not compensated by the manure provided by the livestock sector) and the demand for feed is very high especially for the presence of the monogastric sector. The extended presence of forage in the region constitutes an important form of feed-food competition (because vegetal-source food is subtracted to humans), but also a competition with the monogastric sector. If the fodder cultivation was replaced by other types of cultivation, for example protein crops, this would increase feed self-sufficiency for the monogastric sector. However, to achieve this, the ovine sector should rely more on pastures.

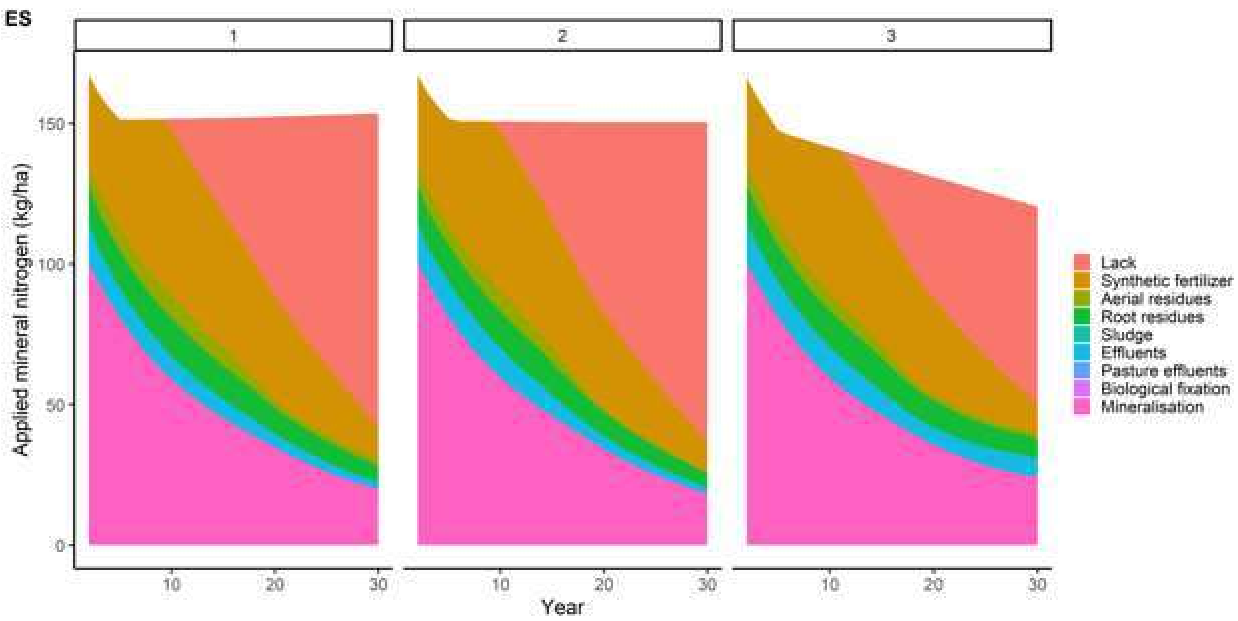


Figure 3.3.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Spanish case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.3.3 General considerations

Concerning the scenario Eur-Agri-SSP1, analyses were done both with the land use optimization model and with the nitrogen fluxes simulation model. The land use simulation model shows that

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

an increase in both carbon storage and crop production can be obtained reducing grasslands and expanding both annual crops and forest. However, as it happens for the French case study, this might constitute a non-desirable transformation of the system. The identity of the system is based on the grassland-based ovine production, therefore it would not be adapted to a scenario in which the decrease in meat production is encouraged. However, the system relies on a big quantity of fodder cultivation. Among the insights coming from the nitrogen fluxes model, we can say that a reduction of the feed-food competition would increase the net contribution of the region to food provision and would valorize the contribution of grassland to food provision. The scenarios Eur-Agri-SSP2 and Eur-Agri-SSP3/5 highlight that the configuration of the system is highly dependent on external inputs and therefore poorly robust to decreases in external inputs, especially for the presence of the monogastric sector in the region.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.4 Results of the ecosystem service modelling assessment: Swedish case study

3.4.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Swedish SURE-farm case study region gives the Pareto frontier depicted in Figure 3.4.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

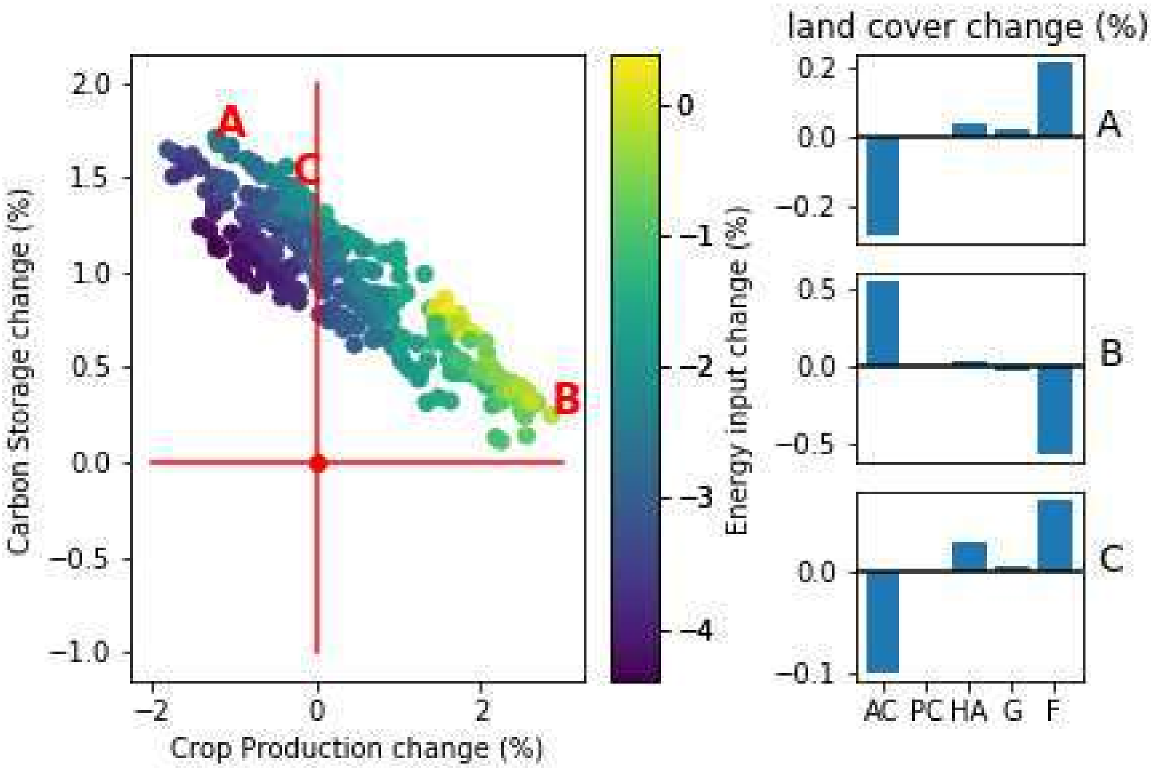


Figure 3.4.1 - Results of the land use optimization model for the Swedish case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The Swedish case study is focused on the production of eggs and broiler. The main impact of the production system on the local land use consists in cereal cultivation. From the analysis done in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

D5.3 (Reidsma, et al., 2019), it is evident that the Swedish case study is in strong contrast with the surrounding landscape and lowers the provision of non-food-related ecosystem services of the region. The analysis of the Corine Land Cover data shows that the region is characterized by a strong presence of forest, a moderate presence of annual crops, a minor presence of grassland and heterogeneous agricultural land, and negligible presence of permanent crops.

The Pareto frontier (Figure 3.4.1), shows that the potential for improvement in both ecosystem services is very low compared to other case studies, meaning that the conflict for land use is very tight and the current land use configuration of the region is already close to the optimal. The extreme points of the Pareto frontier (Points A and B in Figure 3.4.1) show the maximum extent at which crop production and carbon storage can be maximized, as well as the effect of their maximization on the other ecosystem service. Point A maximizes carbon storage and minimizes crop production and shows that an increment of 1.7% in carbon storage is possible but with a decrease of 2% in crop production. Point B (Figure 3.4.1) maximizes crop production and minimizes carbon storage and shows an increase of 2.9% in crop production with a very negligible increase in carbon storage. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Swedish case study region, the points in the Pareto frontier that increase both objectives at the same time represent 57.41% of the total number of optimized points, which is considered average compared to the other case studies. Despite the region has relatively high possibilities to increase both ecosystem services at the same time, the potential for increase in those ecosystem services is very low, showing that the region is very close to an optimized configuration in relation to Eur-Agri-SSP1.

Figure 3.4.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). The different points on the Pareto frontier are characterized by different increases or decreases in annual crops and forest, with a minor role played by heterogeneous agricultural land. However, all the changes in land uses are characterized by very low increases or decreases (not more than 0.5% of land is converted in land use). In Point A of Figure 3.4.1 (maximization of carbon storage), increases in carbon sequestration are obtained by increase of forest and a slight increase of heterogeneous agricultural land over forest. In Point B of Figure 3.4.1 (maximization of crop production), the model suggests an increase of annual crops over forest with a slight increase in

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

heterogeneous agricultural land and a slight de-intensification of annual crops. This would lead to an increase in crop production with no substantial change on carbon sequestration. In Point C of Figure 3.4.1 (maximization of carbon sequestration without decreasing crop production), annual crops are decreased and de-intensified, but forest and heterogeneous agricultural land are increased. The message here is that carbon storage can be increased with increased practices more adapted to increase carbon storage or in mixed configuration (e.g., agro-forestry).

3.4.2 Land use optimization

The land cover of the agricultural context of the Swedish farming system consists in a varied cultivation of different crops that could be used for human and livestock consumption. Specifically, 32% of land is dedicated to cereals, 31% to fodder, 30% to grassland and a minor land is dedicated to oil and protein crops (5%) and other crops (2%). The presence of livestock is quite low, being its density of 0.31 livestock units per hectare of agricultural land, with a 88% of ruminants and most of the cattle on graze (90%). The Swedish case study is based on the egg and broiler production and data show that it is in co-presence with a ruminant sector with which there is some interaction and competition for land.

Progressive decreases in chemical fertilizer availability and feed import availability are simulated in different scenarios. The scenarios consisted in changes in the agricultural system compatible with Eur-Agri-SSP scenarios simulated over a period of 30 years (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.4.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.4.3, in which the “lack” term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants.

In the three simulated scenarios, crop production for human consumption follows more or less the same trend (Figure 3.4.2A) while the animal production trajectories show that the behavior of animal production is substantially different in the third scenario with respect to the other two scenarios. The repartition of the sources of fertilizers (Figure 3.4.3) shows that the system depends on mineralization of organic matter in the soil and crop residues, while in the third scenario there is an increasing contribution of effluents. Note that the trajectories in crop production for human consumption (Figure 3.4.2A) begin to decrease when the system experience lack of fertilizer (Figure 3.4.3).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The first scenario (compatible with Eur-Agri-SSP1) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. Crop production (Figure 3.4.2A) is decreased because of lack in fertilizer and the animal production (Figure 3.4.2B) decreases because of the destocking imposed for scenario.

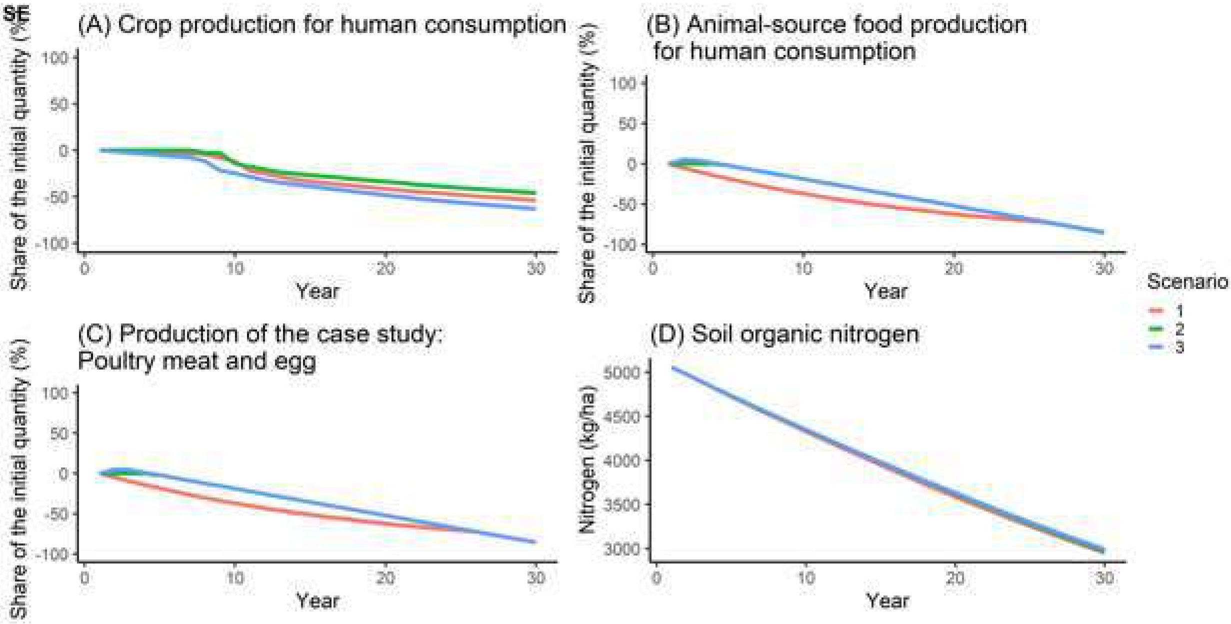


Figure 3.4.2. Simulation results of the nitrogen fluxes model for the Swedish case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), egg and broiler production (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the second scenario (compatible with Eur-Agri-SSP2), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In this scenario, animal production (Figure 3.4.2B) and eggs and broiler production (Figure 3.4.2C) is decreased because of shortage in feed.

In the third scenario (compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. In this case the agricultural production is increased and therefore the livestock sector (mainly the monogastric) can be increased because of the presence of internal resources. However, no differences are detected with the second scenario concerning the animal production (the curves of scenario 2 and 3 are overlapped in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Figure 3.4.2B and Figure 3.4.2C). This is due to the fact that, despite the livestock number is allowed to increase in the third scenario, the region lacks some key feed components.

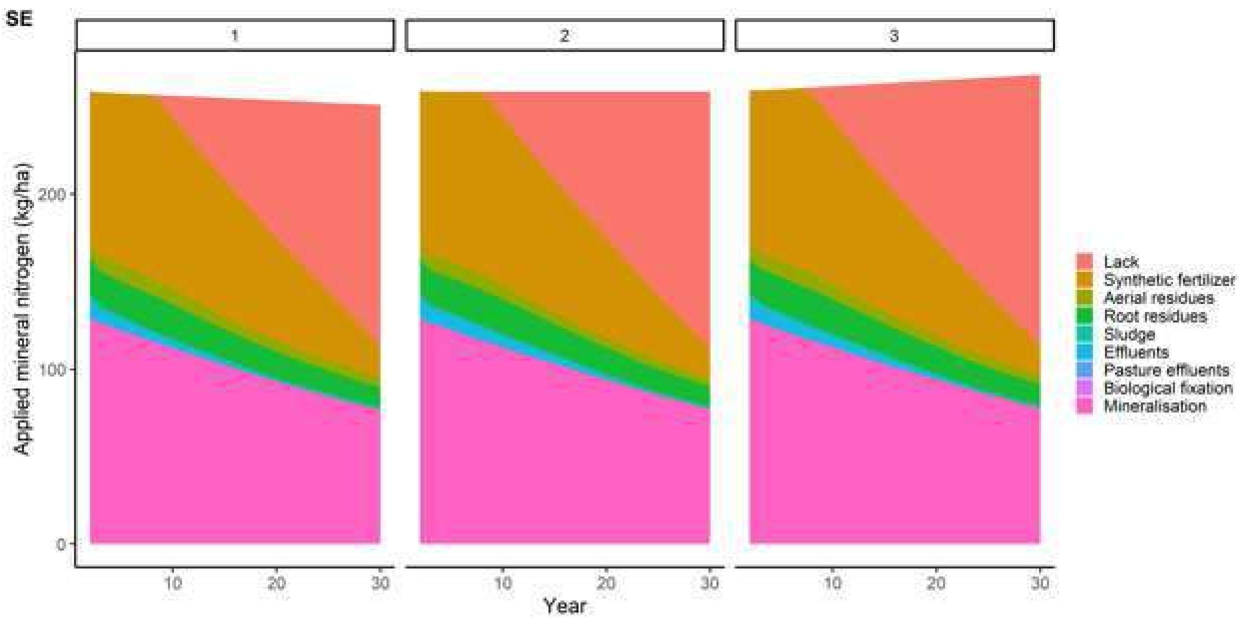


Figure 3.4.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Swedish case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.4.3 Land use optimization

Concerning the conflict between crop production and carbon storage, the regional land cover configuration seems very close to the optimized configuration, with a strong conflict between agricultural land (promoted by annual crops) and carbon storage (promoted by forests). Expansion of agriculture over forest can be done but in very little measure and with forms of agriculture more friendly for carbon sequestration.

Concerning the nitrogen fluxes simulations, it seems that the agricultural system is poorly robust to shortages in chemical fertilizer and external feed availability, however the system has internal resources for increasing the livestock sector (especially the monogastric sector). This is allowed, because the system has already a diversified agricultural system producing diversified feed types: an expansion of the agricultural land would sustain an increased livestock sector. It is however to be noted that the expansion of agricultural land would be at the expenses of the forest.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.5 Results of the ecosystem service modelling assessment: Belgian case study

3.5.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Belgian SURE-farm case study region, i.e., the Flanders region, gives the Pareto frontier depicted in Figure 3.5.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

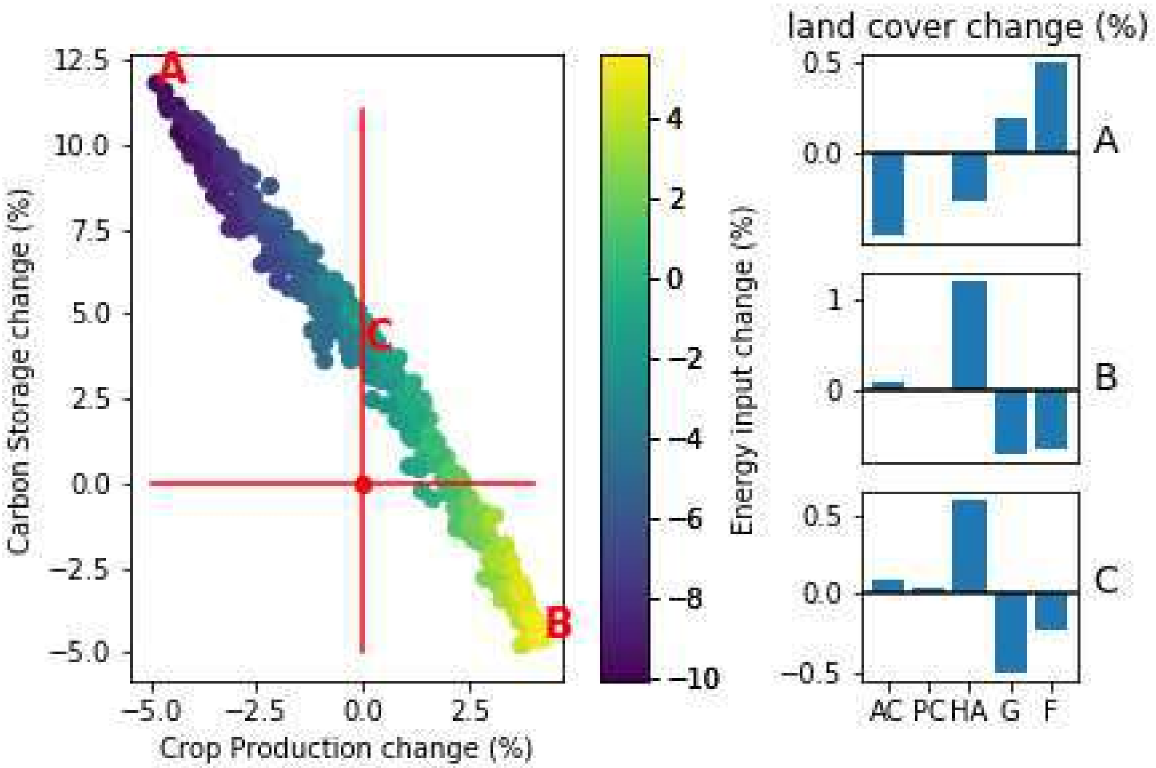


Figure 3.5.1 - Results of the land use optimization model for the Belgian case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The Belgian case study is centered on the Flemish intensive dairy farming system. The impact of this farming system on the land use of the region consists mainly in fodder cultivation. In this analysis, fodder cultivation falls mostly into the category of “Annual Crops” or can be part of “Heterogeneous Agricultural Land”. The region has a big share of agricultural land occupied by

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

heterogenous agricultural land, which, following the Corine Land Cover classification, is specifically identified in "Complex Cultivation Patterns". The impact on land use is also in the form of cultivated grassland, which falls into the category of "Grassland". It is to be noted that the region is characterized by a high feed-food competition as much land is dedicated to fodder production and not to human-edible crops.

The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.5.1) maximizes carbon storage and minimizes crop production and shows that an increment of 11.8% in carbon storage is possible but with a decrease of 5% in crop production. Point B (Figure 3.5.1) maximizes crop production and minimizes carbon storage and shows an increase of 4.2% in crop production with a decrease of 5.1% in carbon sequestration. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Belgian case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 18.5% of the total number of optimized points: this is the lowest detected in all the SURE-farm case studies. The difficulty of increasing both ecosystem services comes from the fact that the land use of the region is already diversified and very close to an optimized configuration for addressing the tradeoffs between the two ecosystem services considered.

Figure 3.5.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.5.1 (maximization of carbon storage), increases in carbon sequestration are obtained by means of an expansion of the conservation land (forest and grassland) over cultivated land. Being the agricultural system already diversified and balancing crop production and carbon storage, an ulterior increase in carbon storage would be made possible by an increase in conservation land. This would however provoke a loss in crop production. In Point B of Figure 3.5.1 (maximization of crop production), the model suggests an expansion of heterogeneous agricultural land, as well as a slight expansion of annual crops, over conservation land. With the parameters calibrated for the Belgian case study the heterogeneous agricultural land results particularly productive for both crop production and carbon storage. In Point C of Figure 3.5.1 (maximization of carbon sequestration without decreasing crop production), land use changes are in the same directions of point B but to a less extent.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Overall, the agricultural land use in Flanders is already occupied to a great extent by complex cultivation patterns that make the landscape diversified and very close to optimized conditions (for the tradeoff between carbon storage and crop production), meaning that it is difficult to still increase both ecosystem services at the same time. While the agricultural land promotes a synergy between the two ecosystem services, changes in balance between the agricultural land and the land for conservation (i.e., grassland and forest) can move the system along the tradeoff towards one ecosystem service and the loss of the other. It is however to be noted that, in relation to the Eur-Agri-SSP1 scenario, the feed-food competition (caused by the intensive dairy system as well as by the presence of other intensive systems – pig and beef cattle) in the region is very high. If at least one part of the fodder production was converted to human-edible crops, the system would be better adapted to this scenario.

3.5.2 Nitrogen fluxes model

The land cover of the agricultural context of the Belgian farming system is characterized by a big presence of fodder (69%) with a 17% of cereals and the remaining is for other crops, including vegetables. The livestock sector is particularly developed with a 2.22 livestock unit per hectare of agricultural land all intensive (i.e., no grazing). Changes in the agricultural system compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP3) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.5.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.5.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.5.3 shows that an important source of mineral nitrogen comes from animal effluents. The contribution of crop residues left on field is not as high as other similar case studies (e.g., the Netherlands), probably due to the cultivation of fodder which do not leave many residues on field. The system depends on some synthetic fertilizer, but the dependence is lower than other case studies. Being fodder the main cultivated crop, the production of crops for human consumption is low and its contribution to the overall food provision (mainly coming from animal production) is not very high.

The first scenario (Eur-Agri-SSP1, sustainability) consists in a progressive reduction of the agricultural land for giving more room to land for conservation, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. The imposed de-stocking of livestock has a negative impact on the crop

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

compartment (Figure 3.5.2), decreasing the source of mineral fertilizer and anticipating the time in which the system experience shortage of fertilizer (Figure 3.5.3). The decrease in livestock number has also a negative impact on the organic matter in the soil. However, comparing to other case studies, the system arrives to shortage in fertilizer later than other case studies.

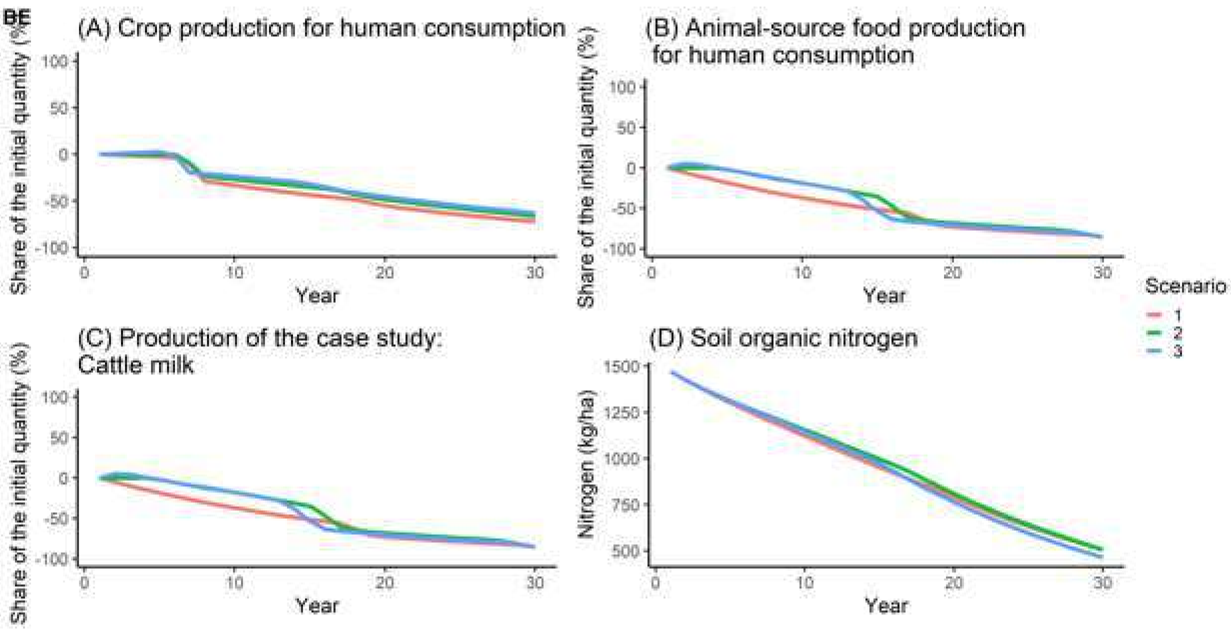


Figure 3.5.2. Simulation results of the nitrogen fluxes model for the Belgian case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study region (cattle milk) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the second scenario (Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In this scenario, the region does not have feed self-sufficiency to maintain the current number of livestock and to maintain the same level of animal production. Therefore, the livestock production (Figure 3.5.2B) and in particular the dairy sector (Figure 3.5.2C) decreases because of feed limitation, but at a slower pace than in the first scenario. This makes it possible to have a delay in the shortage of fertilizer and indicates a better robustness. The organic matter in the soils keeps at higher levels along the whole simulation.

In the third scenario (compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. Despite the livestock number is allowed to increase in this scenario, the limited feed self sufficiency allows only a very small increase in it

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

for the Belgian case study and, therefore, the outputs of this scenario is not very different from the previous (Eur-Agri-SSP2) in terms of functions provided.

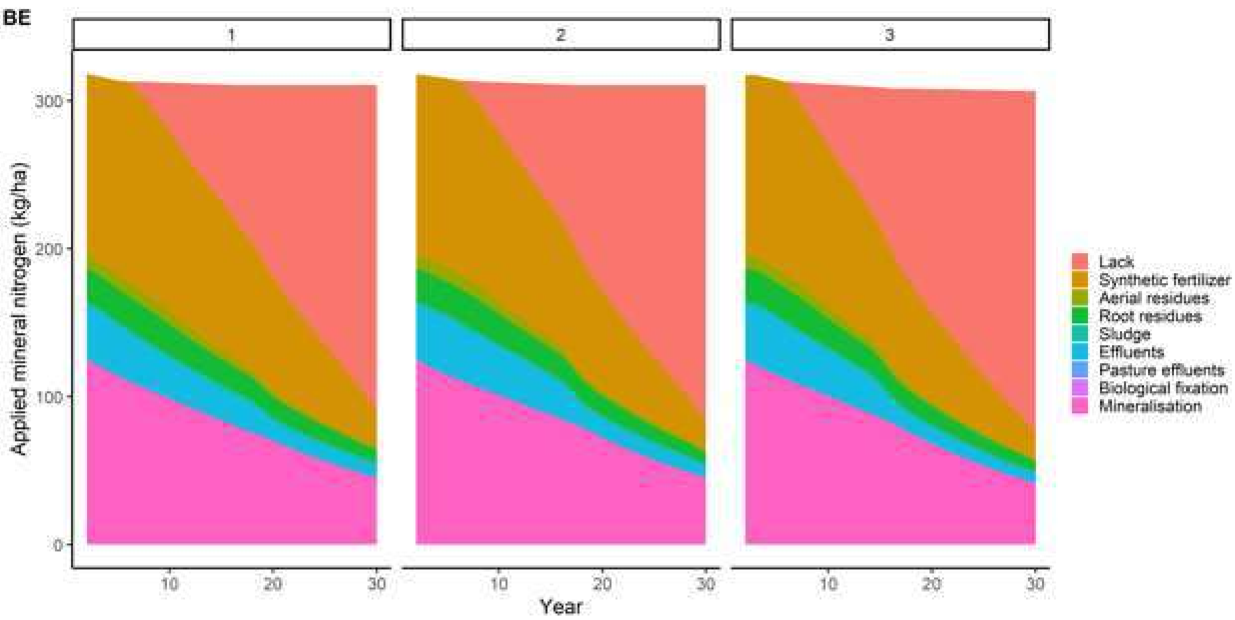


Figure 3.5.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Belgian case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.5.3 General considerations

The region of the Belgian case study has a very diversified agriculture, already addressing the tradeoff between carbon storage and crop production. Substantial increase in carbon production can be obtained by increasing land dedicated to conservation (this indeed would be beneficial also for other ecosystem services, e.g., biodiversity, timber production, and nitrogen deposition). The intensive livestock production causes much of the land to be cultivated with fodder, increasing the feed-food competition.

Concerning the scenario Eur-Agri-SSP1, the system can be adaptable if feed-food competition is reduced, meaning that most of the forage cultivation is converted into human-edible crops. Animal production should be reduced, as this scenario envisages a reduction in the production of animal-source food. However, the presence of livestock in high density at the beginning of the simulation is important to build system reserves in terms of availability of manure and increased organic matter in the soil. These reserves in fertilizer make it possible for the system to be robust and have much time before experiencing shortage in fertilizer. During this time, it would be possible to explore adaptation or transformation strategies.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Concerning the scenarios Eur-Agri-SSP2, and Eur-Agri-SSP5, the system shows that increases in the livestock sector (or even the maintenance of the current level) are not possible as the region is dependent on import of external feed for some items (mostly protein crops and meals). In this sense, the system could be more adaptable if feed-food competition is avoided, for example by converting some fodder cultivation in crops (e.g., oil and protein crops) whose co-products can be valorized for animal production.

3.6 Results of the ecosystem service modelling assessment: German case study

3.6.1 Land use optimization

The land uses considered for the analysis are seasonal crops, permanent crops, heterogeneous agriculture, grassland and forest. The optimization of the land uses for addressing the tradeoff

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

between crop production and carbon sequestration in the region of the German SURE-farm case study region gives the Pareto frontier depicted in Figure 3.6.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

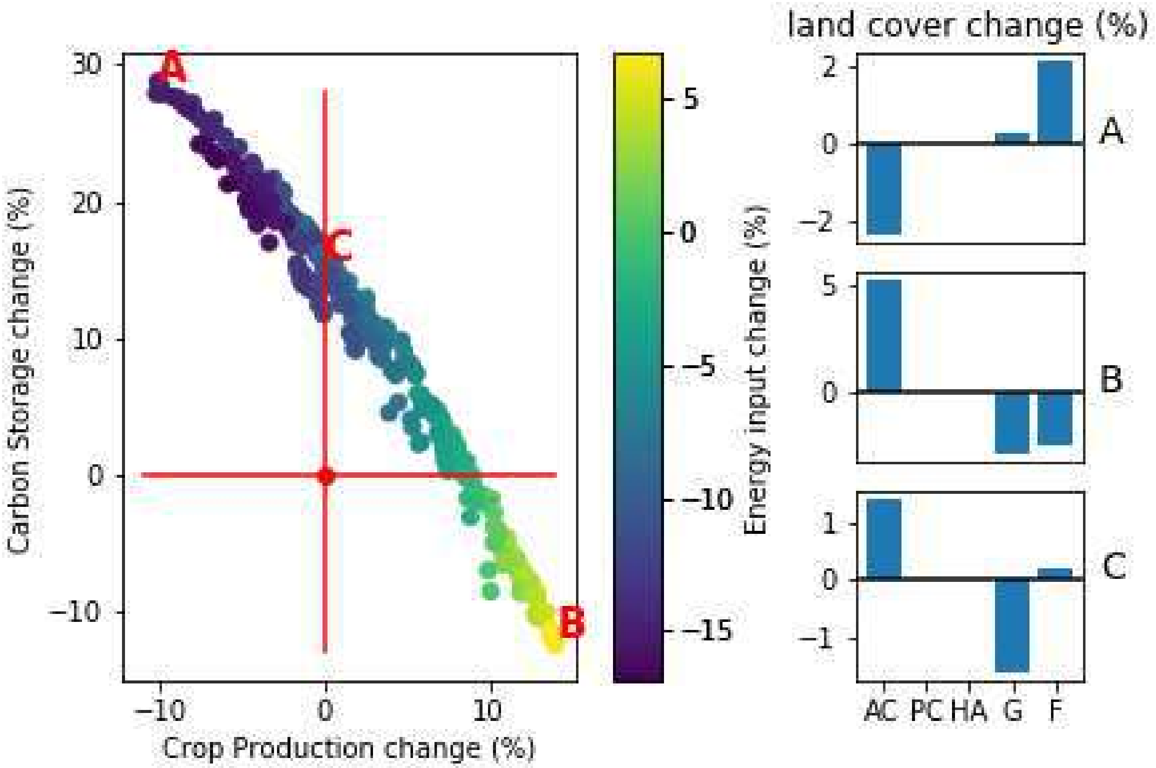


Figure 3.6.1 - Results of the land use optimization model for the German case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The German case study is a mixed crop-livestock system, in which the crop part is centered around the cultivation of cereal, oil crops, potatoes and sugar beet, and the livestock part is centered on the production of meat and milk. The impact on the land use of this system is in the form of annual crop (falling in the category "Annual Crops" for this analysis). In the overall region, the main land uses, according to the Corine Land Cover map, are annual crops, grasslands, and forests, without forms of heterogeneous agriculture or permanent crops. The

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

conflict for land is therefore between land for crop production and land for conservation, with a neat separation between the provision of crops and carbon storage.

The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.6.1) maximizes carbon storage and minimizes crop production and shows that an increment of 28.8% in carbon storage is possible but with a decrease of 11% in crop production. Point B (Figure 3.6.1) maximizes crop production and minimizes carbon storage and shows an increase of 14% in crop production with a decrease of 10% in carbon sequestration. The shape of the Pareto frontier shows that large increases can be obtained in the two ecosystem services, but this also comes at the cost of a relatively large decrease in the other ecosystem service. This shows that the conflict between the two ecosystem services is very strong and the German farming system is in strong competition for land with land for conservation. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the German case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 41.4% of the total number of optimized points which is considered as average with respect to the other case studies. This means that, despite the conflict is quite sharp (increase of one service, along the Pareto frontier, arrives to a high loss in the other service) it is still possible to have an increase of both services at the same time with respect to the current land use configuration of the region.

Figure 3.6.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.6.1 (maximization of carbon storage), the increase in carbon storage is obtained by means of an increase in forest as well as a slight increase in the grassland, occurring at the expense of annual crops. The land for agriculture is de-intensified. In Point B of Figure 3.6.1 (maximization of crop production), the land use changes correspond to the dual situation as in point A: annual crops are expanded over grassland and forest. The configurations in the two extreme points show that the land used by the German case study is in direct competition with land for conservation and its expansion over other regions of the land use provoke a decrease in carbon storage in the region. In Point C of Figure 3.6.1 (maximization of carbon sequestration without decreasing crop production), both annual crops and forests (to a less extent) are expanded over grassland. In this situation grassland is decreased. Actually, in point C and in the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

other points promoting an increase in both ecosystem services, grassland is considered as a “buffer” that can be replaced by annual crops and forests in different fractions. In the context of the scenario Eur-Agri-SSP1, where crop production and carbon storage are optimized, grassland is considered not productive for crops and not as efficient as forest for carbon storage. Therefore grassland provides room for expansion of forest and cropland and therefore possibility to increase crop production and carbon storage in the region.

Overall, the region containing the German case study is characterized by a clear separation between agricultural production and nature. The presence of grassland constitutes some room for adaptability to the Eur-Agri-SSP1 scenario in which it is possible to manage the conflict between crop production and carbon storage. It is however to be noted that grassland in the Altmark region cannot be converted to other forms of land cover (especially arable land) because of geomorphological conditions. This is not accounted for in the model and should be kept into consideration for interpreting the results, and Point B in Figure 3.6.1 is only theoretical. In addition, grassland is strongly linked to the dairy sector and its reduction would then cause a transformation of the production of the region.

3.6.2 Nitrogen fluxes model

The land cover of the agricultural context of the German farming system is characterized by cereals (67%), fodder (20%), and oil and protein crops (12%), with the rest 2% occupied by other crops. The livestock density is not very high (0.42 livestock units per hectare of agricultural land and 52% ruminants). Livestock is mostly raised in intensive system, with almost no cattle on graze, being most cattle fed on grass silage. Changes in the agricultural system compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.6.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.6.3, in which the “lack” term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.6.3 shows the main sources of mineral fertilization are plant residues and mineralization of organic nitrogen. A contribution from the livestock sector is present and is higher in the third scenario, where the increase in the livestock number is envisaged.

The first scenario (Eur-Agri-SSP1, sustainability) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

of ruminants and monogastrics are progressively decreased. In the second scenario (Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In the third scenario (Eur-Agri-SSP5, fossil-fuel development), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available.

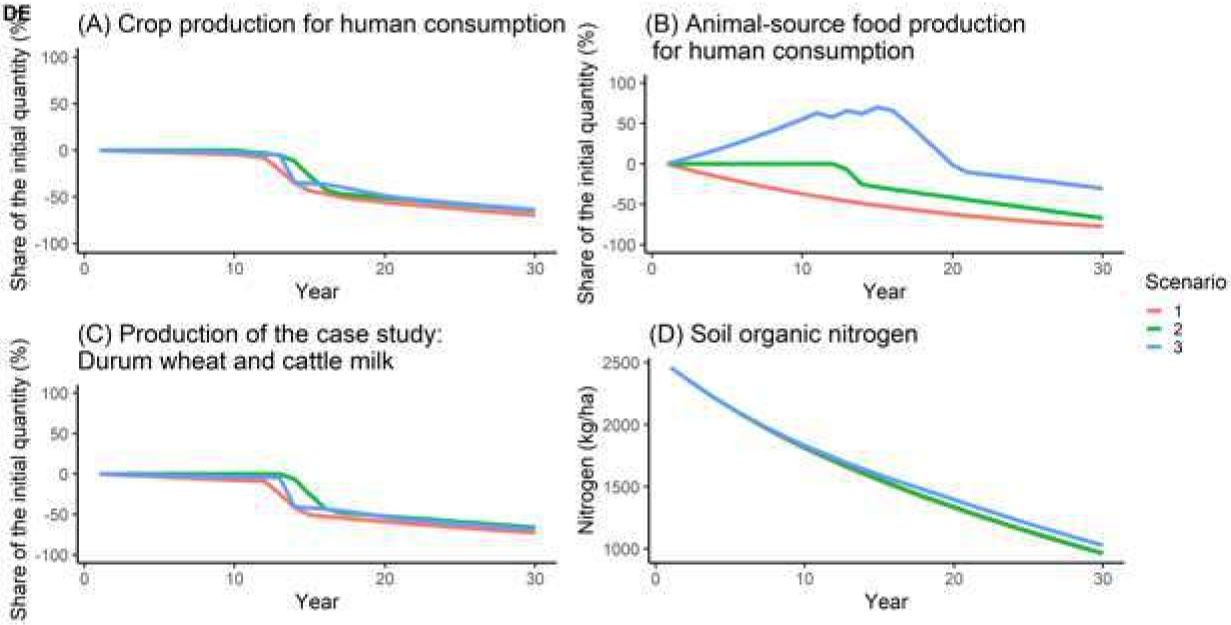


Figure 3.6.2. Simulation results of the nitrogen fluxes model for the German case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (durum wheat and cattle milk) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

The main differences between the three scenarios are visible in the production of animal-source food (Figure 3.6.2B). In the first scenario the animal production declines because of an imposed destocking of the livestock. Concerning the second and third scenario, the system has some internal resources for feed self-sufficiency (it is indeed a crop-livestock system) and it even increases in the third scenario. In the second scenario production if the system is maintained until year 13 and then it starts decreasing. In the third scenario, the livestock sector can increase in the first years (Figure 3.6.2B) and it declines as both internal production (due to decrease in chemical nitrogen availability) and external feed availability put the system in lack of resources. The feedbacks on the crop production are not very strong: indeed there is a greater contribution in nitrogen from animal effluents in the third scenario (Figure 3.6.3), but this does not make a big difference in the provision of crops for human consumption (Figure 3.6.2A)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

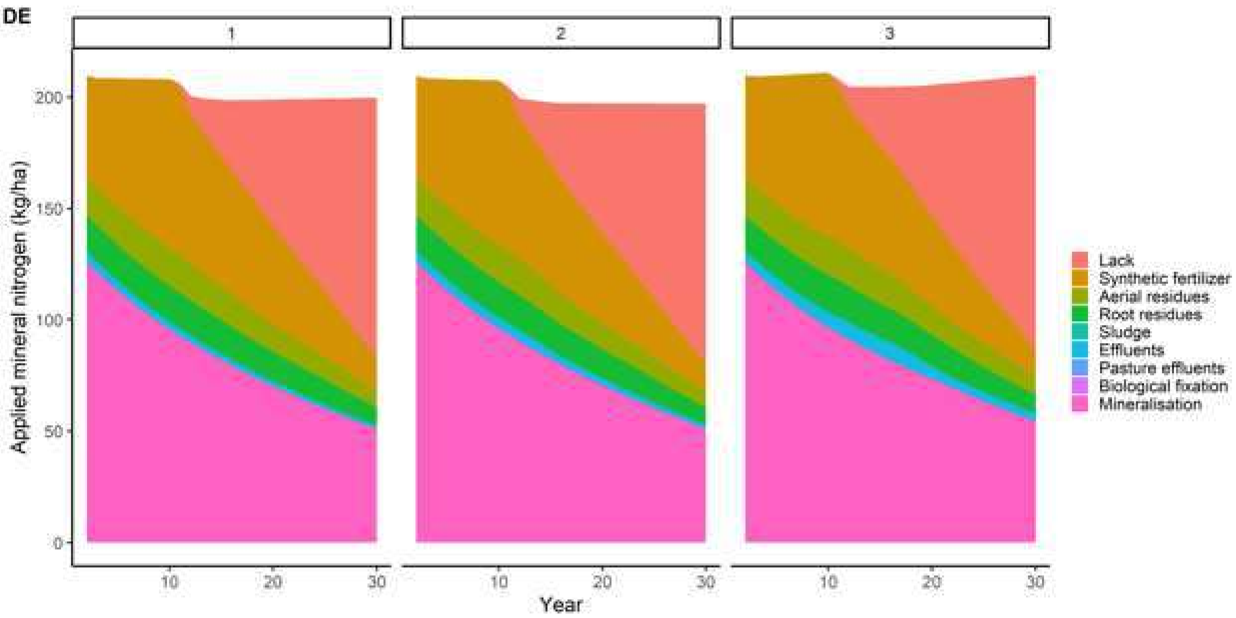


Figure 3.6.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the German case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.6.3 General considerations

The German case study is characterized by a relatively high degree of competition with land for conservation. The land use optimization model suggests expanding forest and cropland over grassland in order to increase the provision of both crop production and carbon sequestration at the same time. However, this solution can result in other consequences that are not accounted for in the model and have to be put in a more detailed context in relation to the case study. In addition, in the region, expanding arable land over grassland is not possible for reasons related to soil quality, geomorphology and hydrology.

Although the system is mixed, the livestock sector density is quite low in relation to the land. Therefore the feedback (in terms of provision of manure for fertilization) is quite weak in comparison to the demand for fertilizer of the crop sector and the system relies on chemical fertilizer.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.7 Results of the ecosystem service modelling assessment: Bulgarian case study

3.7.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Bulgarian SURE-farm case study region gives the Pareto frontier depicted in Figure 3.7.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

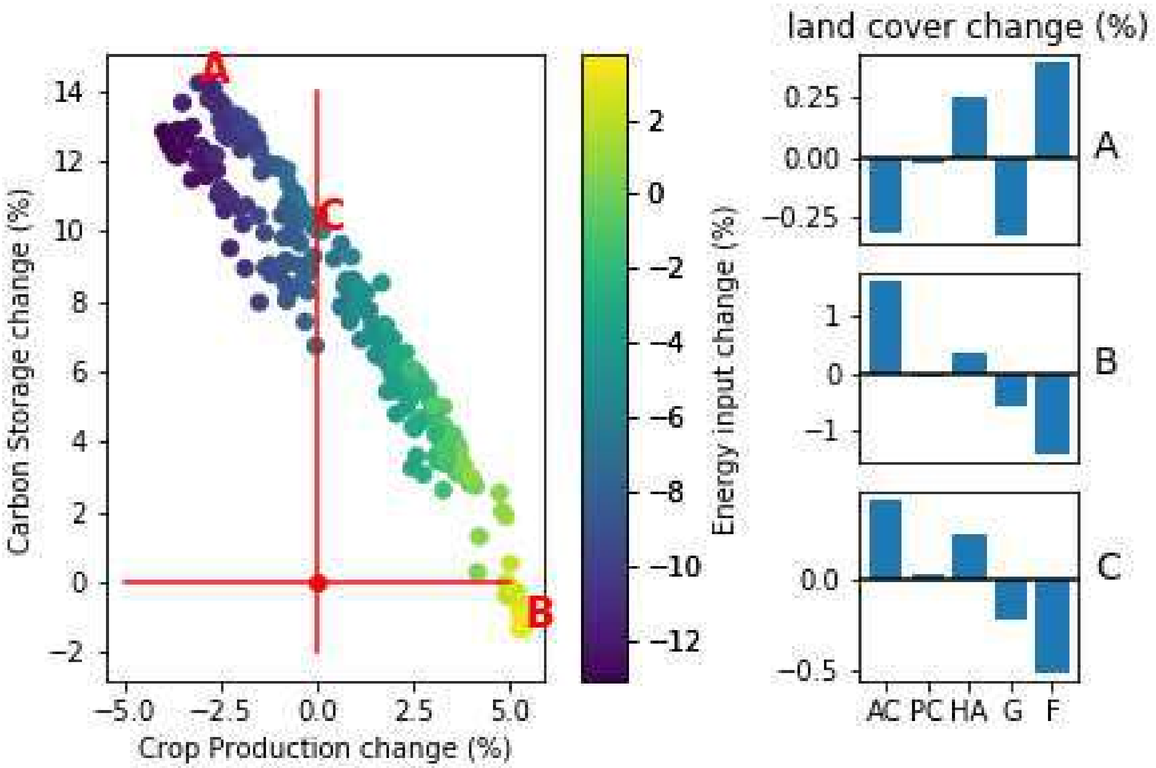


Figure 3.7.1 - Results of the land use optimization model for the Bulgarian case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A and B on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel indicated with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage. The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state.

The Bulgarian case study is focused on the production of grain, maize, and sunflower, which, in this analysis is considered as “annual crops”. In the region, other present land uses are grasslands, some permanent crops, and heterogeneous agriculture. The Pareto frontier (Figure 3.7.1) shows that the region has some margin of improvement for carbon sequestration and few

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

margin of improvement for crop production, as the region is already well performing in that objective. The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.7.1) maximizes carbon storage and minimizes crop production and shows that an increment of 14.2% in carbon storage is possible but with a decrease of 3% in crop production. Point B (Figure 3.7.1) maximizes crop production and minimizes carbon storage and shows an increase of 5.4% in crop production with a decrease of 2% in carbon storage. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Bulgarian case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 48% of the total number of optimized points: this is considered as average in comparison to other case studies.

Figure 3.7.1 also shows bar diagrams with the land use changes occurring in the points A, B and C marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to seasonal crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.7.1 (maximization of carbon storage), the model shows an increase in forest and heterogeneous agriculture over annual crops. For reaching the highest increase in carbon storage, forest should be increased and other forms of agriculture should replace the main agricultural type of the Bulgarian case study. However the changes in land use are not so big (only 0.25% of land is converted) In Point B of Figure 3.7.1 (maximization of crop production), the model shows a slight increase in seasonal crops and heterogeneous agriculture over forest. Permanent crops are slightly decreased. The expansion of seasonal crops over permanent crops is suggested as such land use, because of model calibration, considers annual crops more productive than permanent crops, however, the economic value of the crop (which can play an important role) is not accounted for in the model. In Point C of Figure 3.7.1 (maximization of carbon sequestration without decreasing crop production) the trend in land use change is the same as in point B but to a less extent. The points in the Pareto frontier that make it possible to have an increase in both ecosystem services are characterized by an increase in annual crops but also in other forms of agriculture, mostly heterogeneous agriculture, which is more efficient for carbon storage. Instead, for having a larger increase in carbon storage, annual crops should be decreased in favor of conservation land, but this would imply a loss in crop production. Overall, results suggest that land cultivated with grain of the Bulgarian case study constraints the adaptation of the region to the scenario Eur-Agri-SSP1. The region would

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

be more adaptable to this scenario in case other forms of agriculture, e.g., heterogeneous agriculture, would be expanded in the region.

3.7.2 Nitrogen fluxes model

The land cover of the agricultural system of the Bulgarian case study is mainly formed by cereals (59%) and oil and protein crops (36%), with only few land dedicated to grassland, fodder, and other crops. The livestock density is quite low compared to the agricultural surface (0.27 livestock units per hectare of agricultural land, with 42% ruminants). 27% of ruminants is on graze. The livestock sector is very small, this makes it easier to achieve feed self-sufficiency, but, on the contrary, the livestock sector does not give a strong positive feedback on the crop system, which is highly dependent on external fertilizer.

Changes compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.7.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.7.3, in which the “lack” term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.7.3 shows that the main sources of mineral fertilization are soil mineralization of organic nitrogen, crop residues and chemical fertilizer. The agricultural system experiences shortage in fertilizer at around year 12.

The first scenario (compatible with Eur-Agri-SSP1) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. In the second scenario (Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In the third scenario (Eur-Agri-SSP3, regional rivalry), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

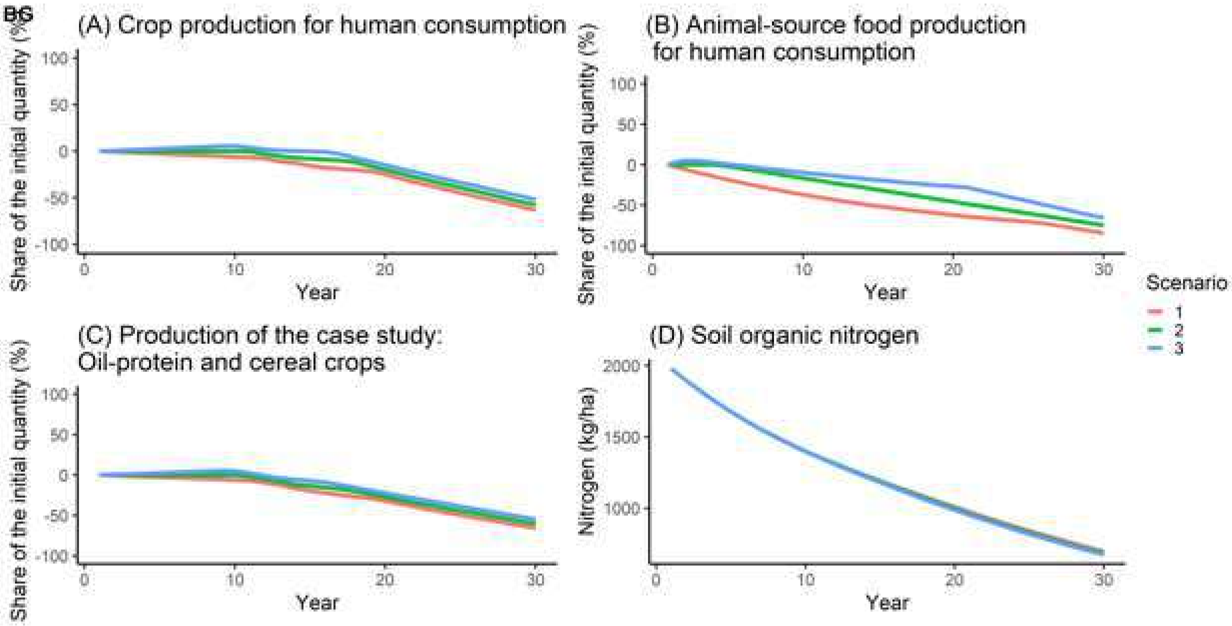


Figure 3.7.2. Simulation results of the nitrogen fluxes model for the Bulgarian case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (oil and protein crops and cerals) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In all the three scenarios crop production to humans decreases without showing much difference between the three trajectories (Figure 3.7.2A and Figure 3.7.2C). The animal production, on the contrary, has substantial differences (Figure 3.7.3B). In the first scenario it decreases for imposed destocking, in the second scenario it is constant until year 16, when it begins experiencing feed shortage. In the third scenario the animal population is increased as the region has internal resources for feed self-sufficiency. The increase is stopped at around year 5 and then it decreases becoming negative at around year 16.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

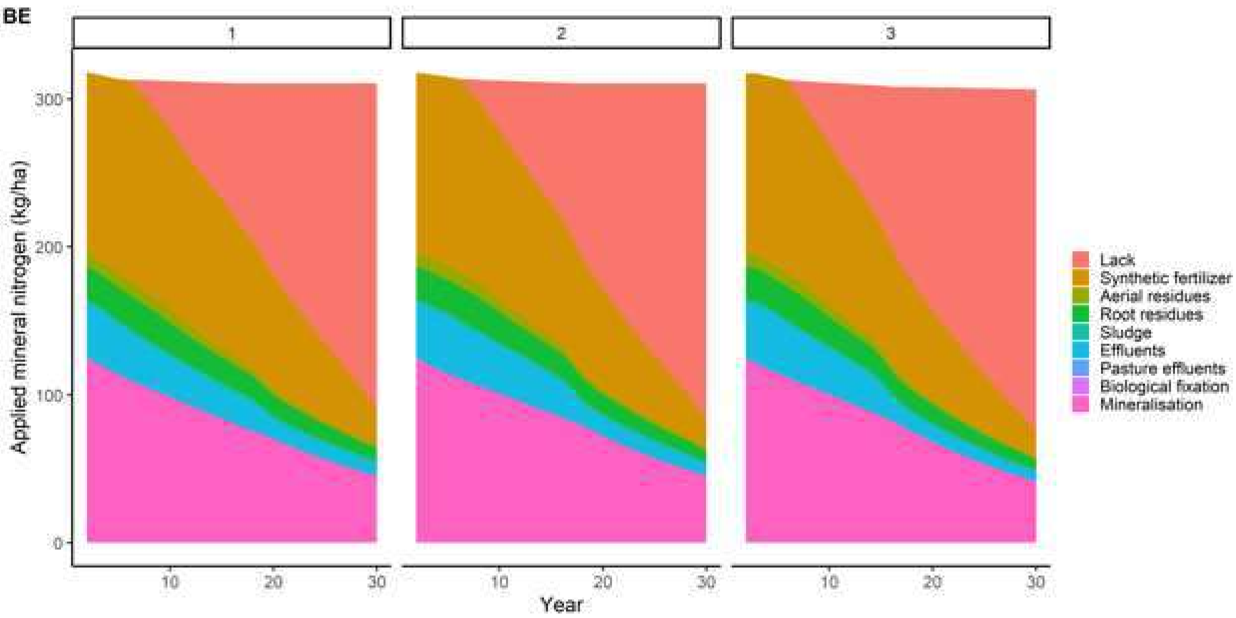


Figure 3.7.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Bulgarian case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.7.3 General considerations

The land use optimization model shows that the grain crop system characterizing the Bulgarian case study is in competition with land for conservation, but also with other forms of agriculture providing more carbon sequestration. The grain farming system is not a good provider of carbon sequestration: it can improve carbon storage with some practices, or it can give some more space to other forms of heterogeneous agriculture.

The Bulgarian farming system case study is fundamental in sustaining the livestock sector in the region, however, there is no feedback from the livestock sector to the crop system, which is highly dependent on chemical nitrogen fertilization. The livestock system is under-developed and has some margin to grow. In the scenario Eur-Agri-SSP5, the livestock sector has the potential for improvement, however, more coupling between livestock and crops could strengthen robustness and adaptability of the system. It is to be noted however that the increased use of animal effluents for fertilization is at moment not an option envisaged by the farmers. In fact expanding the livestock sector is a difficult strategy to adopt because of lack of labor; rather, what is observed is that farmers – aware of the reduction of fertility of the soils –

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

try to change and transform their technology and practices, e.g., no-till, strip till, new crops to dress crop rotation, biostimulation (e.g., Penergetic).

3.8 Results of the ecosystem service modelling assessment: Dutch case study

3.8.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Dutch SURE-farm case study region gives the Pareto frontier depicted in Figure 3.8.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

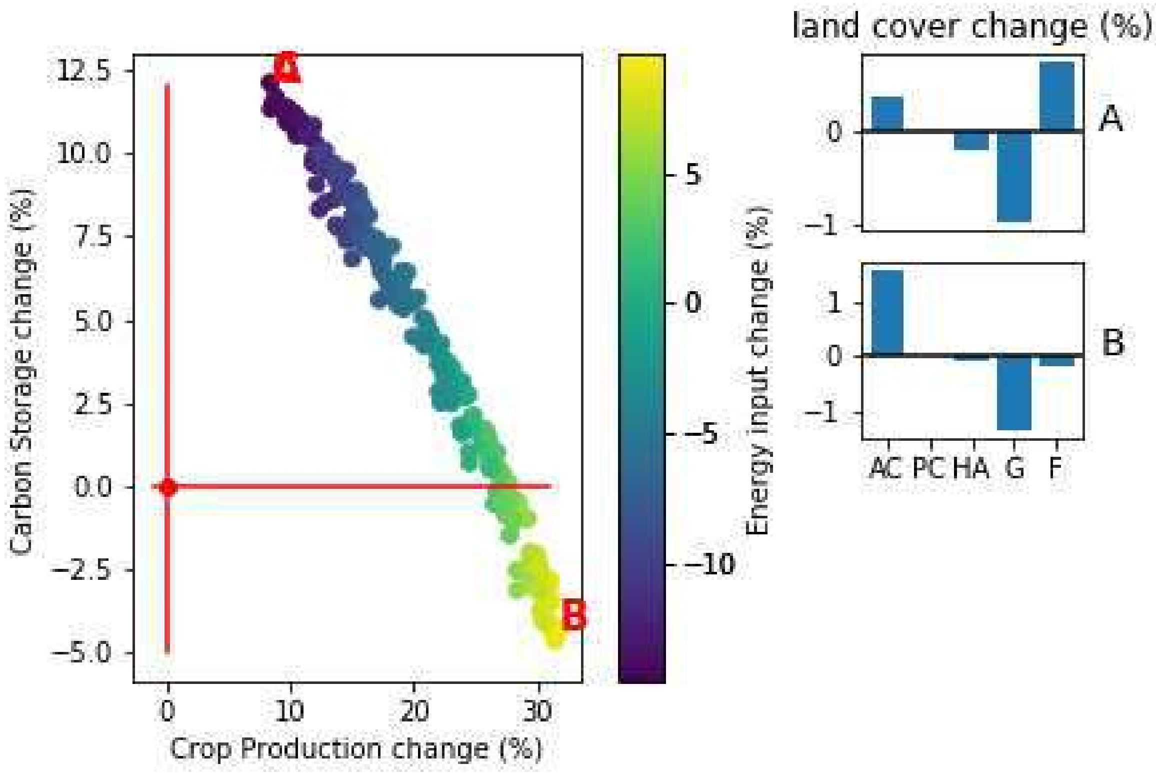


Figure 3.8.1 - Results of the land use optimization model for the Dutch case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, and B on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The analysis of the Corine Land Cover categories present in the NUTS3 region containing the Dutch case study show a high predominance of annual crops with some presence of heterogeneous agricultural land and a little forest. The Dutch case study is centered on the production of starch potatoes which, according to the categories used in this analysis, can fall into "Annual crops". The region has also a fraction of "Heterogeneous agricultural land", indicating associations between permanent and annual crops or "Complex cultivation patterns" (following the Corine Land Cover nomenclature).

The extreme points of the Pareto frontier (Points A and B in Figure 3.8.1) show the maximum extent at which crop production and carbon storage can be maximized, as well as the effect of their maximization on the other ecosystem service. Point A maximizes carbon storage and minimizes crop production and shows that an increment of 12.1% in carbon storage is possible and still crop production can be increased. Point B maximizes crop production and minimizes carbon storage and shows that an increase of 31.8% in crop production is possible, but this would determine a loss in carbon storage of around 5%. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Dutch case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 73.7% of the total number of optimized points, this is considered as high number in comparison to other case studies. This shows that the system has very high potential to increase both carbon sequestration and crop production at the same time. A closer look to the land use changes in the different points of the Pareto frontier helps to understand how this is possible.

Figure 3.8.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to seasonal crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.8.1 (maximization of carbon storage), the model increases forest and annual crops over grassland. Forest is preferred over grassland because it is more efficient in carbon storage and grassland does not provide crops. Therefore, in the context of this scenario, the increase in carbon storage (while still trying to maximize crop production) is obtained by expanding forest and (to a larger extent) annual crops, over grassland. In Point B of Figure 3.8.1 (maximization of crop production), a portion of grassland is reduced for being replaced by annual crops. In the context of Eur-Agri-SSP1, where animal-source products will decrease for being substituted by vegetal-source products, grasslands lose their functions and are replaced by other land cover.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

This does not apply to those grasslands that are present due to geo-morphological or hydrologic conditions where other land covers are not possible (however, this type of constraint is not included in the model).

3.8.2 Nitrogen fluxes model

The land cover of the agricultural context of the Dutch farming system is formed by cereals (22%), fodder (10%), grasslands (34%) and other crops (33%), where other crops include starch potatoes mainly. The density of livestock in the region is relatively high (2.51 LU/ha), with a 35% of ruminants (and 65% of monogastrics) and a 66% of ruminants on graze. The presence of grassland is relatively high and this constitutes a big difference with the Belgian case study that has similar livestock density but relies mostly on fodder cultivation. Starch potatoes constitute the main focus of the Dutch case study, however, in this analysis they are considered in the agricultural context in which they are embedded. The dairy sector, present in the region and sustained by grassland and fodder cultivation, interacts with the Dutch case study via competition for land cover and via interactions by means of manure and feed exchange.

Progressive decreases in chemical fertilizer availability and feed import availability are simulated in different scenarios. The scenarios consisted of changes in the agricultural system compatible with Eur-Agri-SSP scenarios simulated over a period of 30 years (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.8.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.8.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.8.3 shows that, in all the three scenarios, the sources of mineral fertilizers are mainly the mineralization of organic nitrogen, animal effluents, plant residues and some chemical fertilizer. Compared to other SURE-farm case studies, the system benefits from a high percentage of nitrogen from organic sources. The high availability of manure is due to the high density of livestock in the area, the high availability of residues is due to practices and presence of grasslands. As for the mineralization of soil organic nitrogen, the organic nitrogen pool is kept filled by the organic sources and is emptied slowly due to a low mineralization rate (2%). With the progressive declines in chemical fertilizer availability and changes in land covers, the nitrogen sources decrease progressively and the system arrives to a shortage in nitrogen at a certain point in the three scenarios. However, compared to other case studies, this shortage arrives relatively late: this is due to a combination of factors (high nitrogen input from organic sources, and low mineralization rate) that keep the system reserves high.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The first scenario (compatible to the Eur-Agri-SSP1 scenario) consists of a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. The simulation (Figure 3.8.2) shows that animal production is decreased and this is obtained by the voluntary destocking of the livestock population envisaged in the scenario. Concerning crop production for human consumption (Figure 3.8.3A), the initial decline is due to the decrease in the area dedicated to agriculture. The ulterior decrease in the crop production (at around year 20) occurs because the system arrives in lack of synthetic fertilizer. Because the shortage arrives quite late, the system is robust and has time to implement strategies for preventing the loss, those strategies should be linked to elements not included in the model, e.g., the introduction of technology increasing nitrogen use efficiency (which is still compatible with the narrative of Eur-Agri-SSP1)

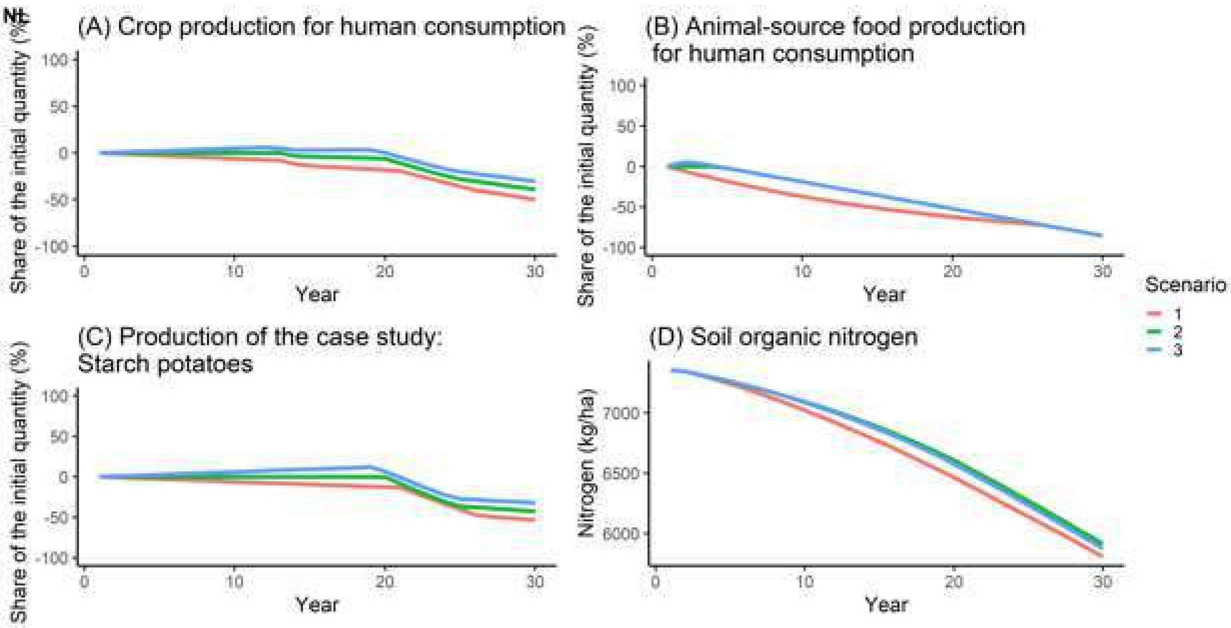


Figure 3.8.2. Simulation results of the nitrogen fluxes model for the Dutch case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (starch potatoes) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the second scenario (compatible with the Eur-Agri-SSP2 scenario), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In this the crop production for human consumption is not varying until year 17 (Figure 3.8.2A) and the production of starch potatoes follows the same trend (Figure 3.8.2C). The livestock population decreases being limited by feed shortage (Figure 3.8.2B). Indeed the region is self-sufficient in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

terms of grass, but is limited, according to the model's assumption, for cereals and meals and fodder. Soil organic matter (Figure 3.8.2D) is improved relatively to the first scenario.

In the third scenario (compatible with the Eur-Agri-SSP3 and Eur-Agri-SSP5 scenarios), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. In this scenario, the model tends to slightly increase livestock population and therefore the animal production is slightly increased at the very beginning of the simulation (Figure 3.8.2B), causing a higher quantity of animal effluents to be available for fertilisation. However, the system experiences shortage in fertilizer availability earlier than in the other scenarios (Figure 3.8.3) because the land dedicated to agriculture is increased and the demand for nitrogen is higher. The Dutch case study is dependent on feed imports for some dietary component, this prevents the system to perform well this scenario, where the livestock system could provide some organic fertilizer for crop cultivation.

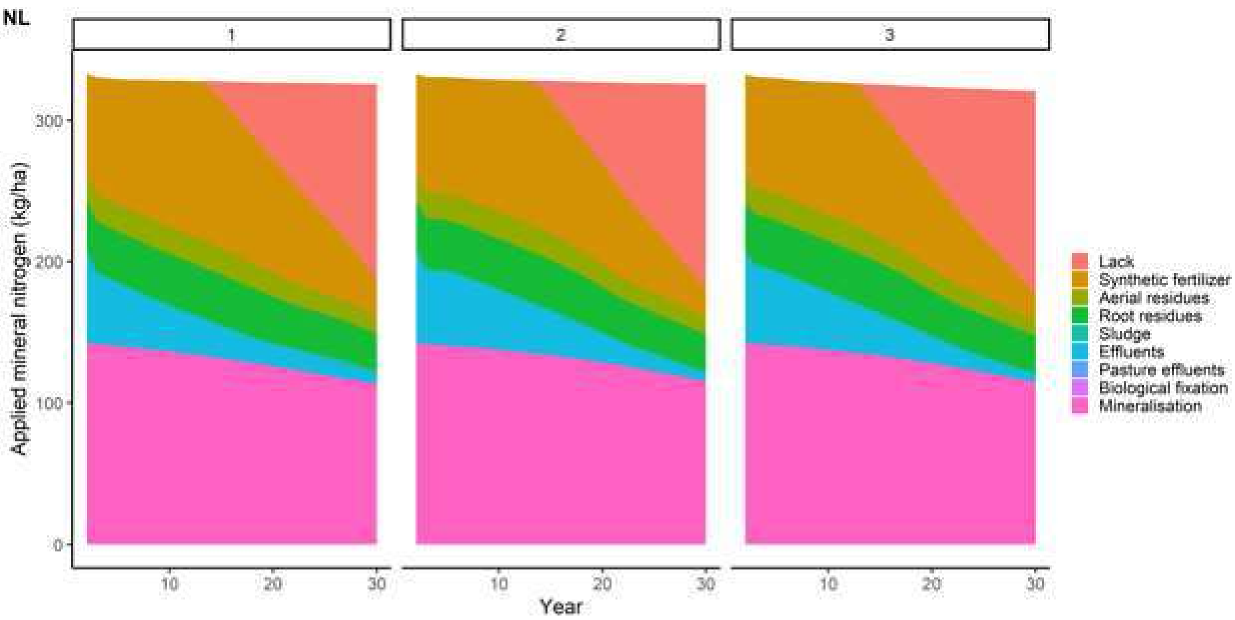


Figure 3.8.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Dutch case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.8.3 General considerations

The land use optimization model suggests a grassland decrease in order to increase both crop production (via expansion of cropland) and carbon storage (via expansion of forest). This has to be carefully taken into consideration for the Dutch region. First, grassland reduction is discouraged and prevented by policies and cannot occur also for geo-morphologic reasons. Second, the reduction of grassland would also harm the dairy sector, which constitute an important source of manure in the region. Therefore, the role of grassland, as well as the interactions between livestock and the starch potato production need to be carefully discussed for Eur-Agri-SSP1. In the land cover optimization model, carbon sequestration data is strictly related to land use (Maes et al., 2012), without regard to the input of organic carbon in the field coming from manure. If the low presence of forests (and the prevalence of agricultural land) in the Dutch region causes a low average carbon storage per hectare, however, the nitrogen fluxes model considers that the soil organic carbon is relatively high compared to other case studies.

In general, the region containing the Dutch case study is quite robust to the decrease in chemical fertilizer availability and not to the decrease in feed imports. The robustness to lack in chemical fertilizer availability implies that a shortage of fertilizer arrives quite late in time, giving time to the system to adapt and change practices. One strategy could be to increase the use of technology for increasing the yield and the nitrogen use efficiency, another strategy would be to expand the land dedicated to agriculture (however conflicts with other land uses should be considered as in Figure 3.8.1). The high livestock density in the region makes it possible for the farming system to rely on a relatively high level of organic nitrogen in the soil. At the regional scale, the system is highly performing in crop production but poorly on carbon storage.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.9 Results of the ecosystem services modelling assessment: UK case study

3.9.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the UK SURE-farm case study region gives the Pareto frontier depicted in Figure 3.9.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

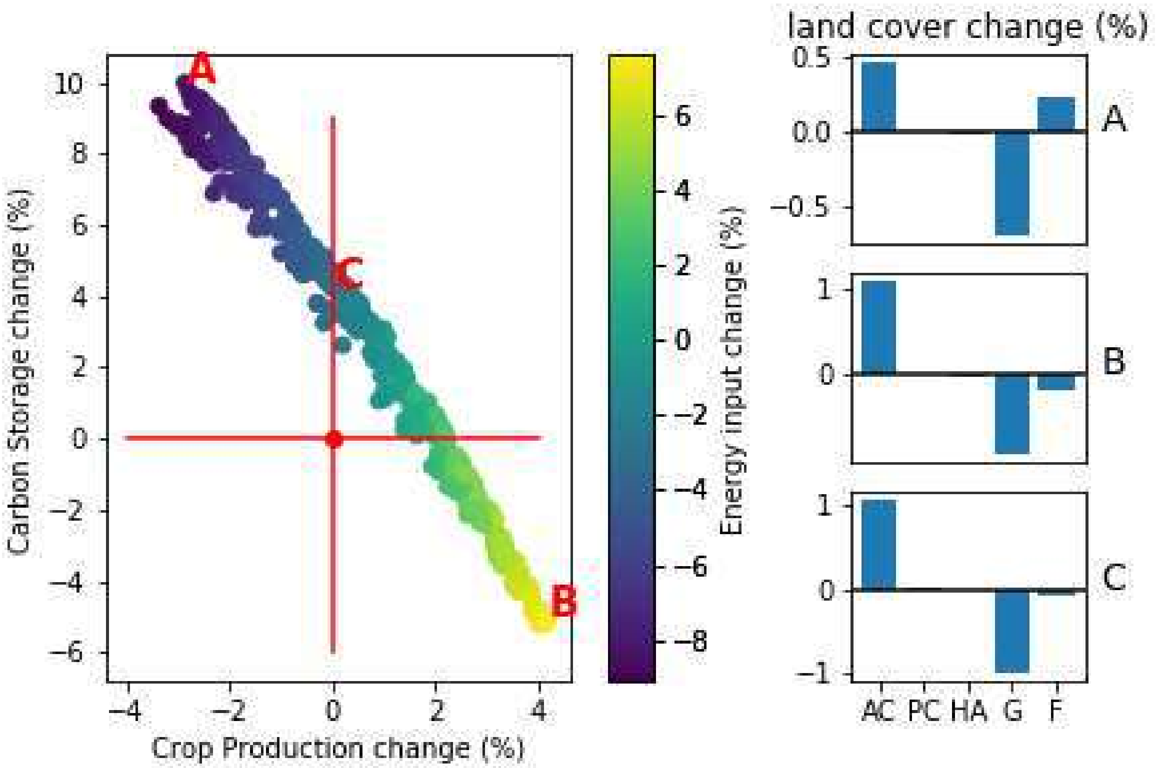


Figure 3.9.1 - Results of the land use optimization model for the UK case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The UK case study is centered on the production of arable crops, where cereals are the most frequently grown crops often in rotation with open-field horticultural crops such as potatoes, for both human and animal consumption, which, in the analysis are included in the “annual crops”. According to the analysis of D5.3 (Reidsma et al., 2019), this farming system is quite specialized

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

lowering the diversity of ecosystem services provided by the rest of the region, although some practices are put in place to increase the level of ecosystem services (e.g., organic matter in the soil) in the cropland. The main land uses involved in the region are annual crops, forest, and grassland, with very poor presence of heterogeneous agricultural lands (associations between annual and permanent crops) and permanent crops. Therefore, the region is characterized by a neat separation between land for agriculture and land for conservation. The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. The shape of the Pareto frontier shows that the room of improvement is modest (lower than other SURE-farm case studies) for both ecosystem services. Point A (Figure 3.9.1) maximizes carbon storage and minimizes crop production and shows that an increment of 10% in carbon storage is possible but with a decrease of 4% in crop production. Point B (Figure 3.9.1) maximizes crop production and minimizes carbon storage and shows an increase of 4.2% in crop production without a decrease of 5.1% in carbon sequestration. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the UK case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 28.3% of the total number of optimized points: this is considered as low in comparison to other case studies. The difficulty of increasing both ecosystem services at the same time comes from a strict land use conflict between land uses providing different ecosystem services. This does not occur in other SURE-farm case studies where other land uses promoting (e.g., heterogeneous agriculture) promoting both ecosystem services are present.

Figure 3.9.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto frontier. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to annual crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.9.1 (maximization of carbon storage), the model shows a slight increase in forest (0.5% of the total land is converted to forest from other land uses) and in annual crops, with a de-intensification. Grassland is decreased for increasing forest and annual crops. Grasslands are decreased because, in a scenario of maximization of crop production and carbon sequestration, they do not provide crops and are less efficient than forests for carbon storage. The de-intensification and increase of cropland surface consists in a “land sharing strategy”, i.e., promoting a more extensive and less intensive form of agriculture. In Point B of Figure 3.9.1 (maximization of crop production), the model shows a slight increase and intensification of

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

annual crops at the expense of forest and grassland. In Point C of Figure 3.9.1 (maximization of carbon sequestration without decreasing crop production), agricultural land is increased (more than in Point A) but de-intensified and forest and grassland are slightly decreased. The model suggests that the land use configuration in its present conditions is already very close to the optimized configuration and the room for improvement is very little. The region is characterized by a clear separation between land for production and land for conservation, making it difficult to balance the provision of the two ecosystem services at the same time. Possible strategies for softening the conflict come from the application of practices aimed at increasing carbon storage in the agricultural land.

3.9.2 Nitrogen fluxes model

The land cover of the agricultural context of the UK farming system is characterized by a big presence of cereals (69%) and, in minor proportions, other land uses (10% of fodder, 15% of oil and protein crops and 7% of other crops). The density of livestock is moderate (1.11 livestock units per hectare of agricultural land with 42% of ruminants). Ruminants are kept in housing and not on graze. The overall agricultural system shows largely feed autonomy in terms for cereal, but also for other feed items (e.g., protein crops and meal). Therefore, according to the model's assumption, the UK case study contributes to the feed self-sufficiency for the livestock sector in the region. However, the region has a high need in external nitrogen fertilizer which is not fully met by internal sources of organic nitrogen (manure or plant residues).

Changes in the agricultural system compatible with Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP3/5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.9.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.9.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.9.3 shows that the inputs from animal effluents and plant residues are quite small in relation to the nitrogen demand and the system relies on a high input of chemical fertilizer. In the three scenarios, the system experiences shortage of fertilizer before year 10 in all the scenarios. In addition, the high mineralization rate (8%) empties quickly the soil organic matter.

The first scenario (Eur-Agri-SSP1, sustainability) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. In the second scenario (Eur-Agri-

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In the third scenario (Eur-Agri-SSP5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. The variation in crop production for human consumption and of cereals follows the same decreasing trend without showing big differences between the three scenarios (Figure 3.9.2A and Figure 3.9.2C). However, there is a change in the behavior of the production of animal production.

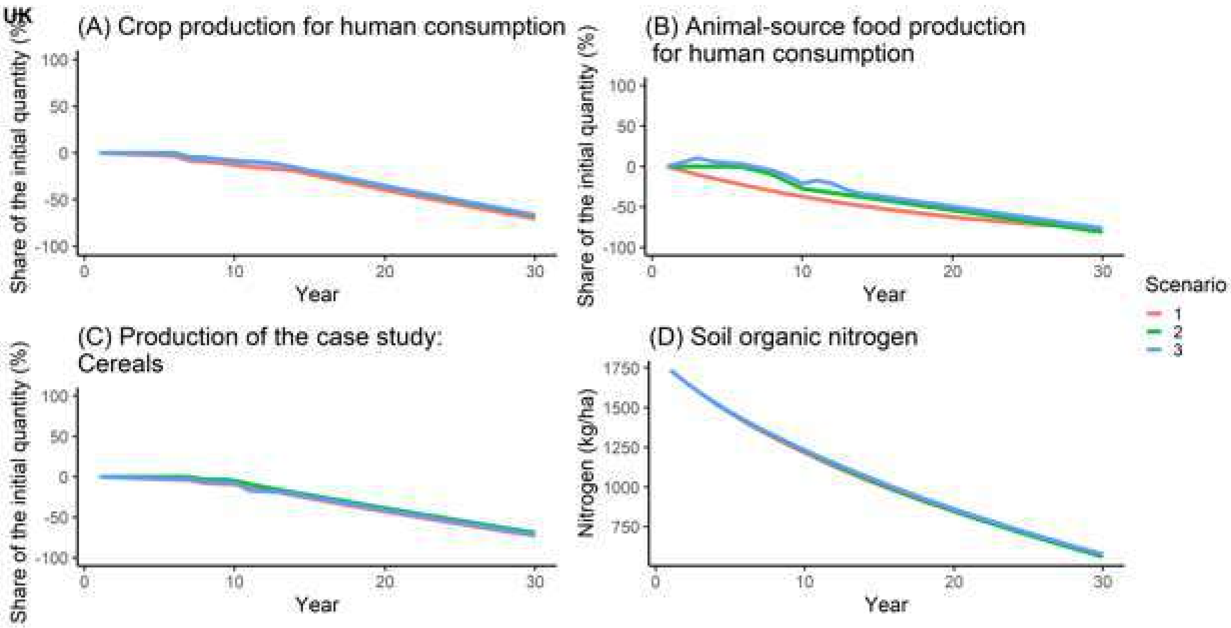


Figure 3.9.2. Simulation results of the nitrogen fluxes model for the UK case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (cereals) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

Contrary to the first scenario where the livestock sector is voluntarily reduced, in the second and third scenarios, the livestock sector is allowed to stay constant or to increase, respectively. Because the agricultural system has reserves for feed self-sufficiency, the livestock sector does not experience shortages in the first years and it even increases in the third scenario. However, in the following year, where shortage in chemical fertilizer and extern feed increases, the livestock sector is reduced due to feed shortage.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

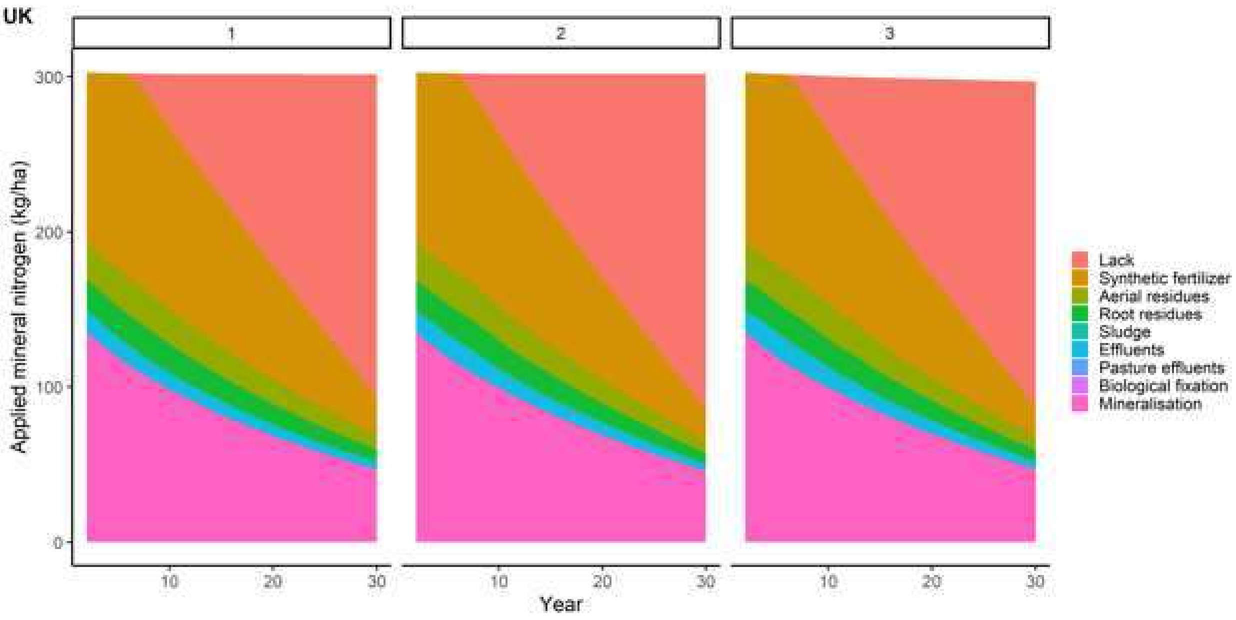


Figure 3.9.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the UK case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.9.3 General considerations

The UK case study, characterized by intensive cereal cultivations, is in competition for land with other land uses in the region more dedicated to conservation. This separation between functions at the regional level makes it difficult to address the conflict between carbon storage and crop production, especially due to the lack of forests. Regarding the Eur-Agri-SSP1 scenario, the system has a low adaptability, unless practices are promoted to increase carbon storage in the cropland. In addition, none of the points examined on the Pareto frontier promote a reduction in the land dedicated to annual crops (see land use changes in Points A, B, and C in Figure 3.9.1), which is something envisaged in the scenario. Overall, the model suggests that the land use configuration in its present conditions is already very close to the optimized configuration and the room for improvement is very little.

The nitrogen fluxes simulation model shows that the system has high dependency on chemical fertilizer. The robustness in the Eur-Agri-SSP1 scenario is quite low because the system relies on

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

chemical fertilizer and on the agricultural land. Concerning the scenarios Eur-Agri-SSP2 and Eur-Agri-SSP5 the system can, for the first years, rely on the livestock sector, for which the region has a good level of feed self-sufficiency. The cereal system characterizing the UK case study farming system is therefore an important element contributing to regional feed self-sufficiency as well as to the provision of vegetal source food for human consumption.

3.10 Results of the ecosystem service modelling assessment: Italian case study

3.10.1 Land use optimization

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Italian SURE-farm case study gives the Pareto frontier depicted in Figure 3.10.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state (i.e., the ecosystem service provision corresponding to the current land cover configuration of the region) is represented as a red point at the origin of the axes.

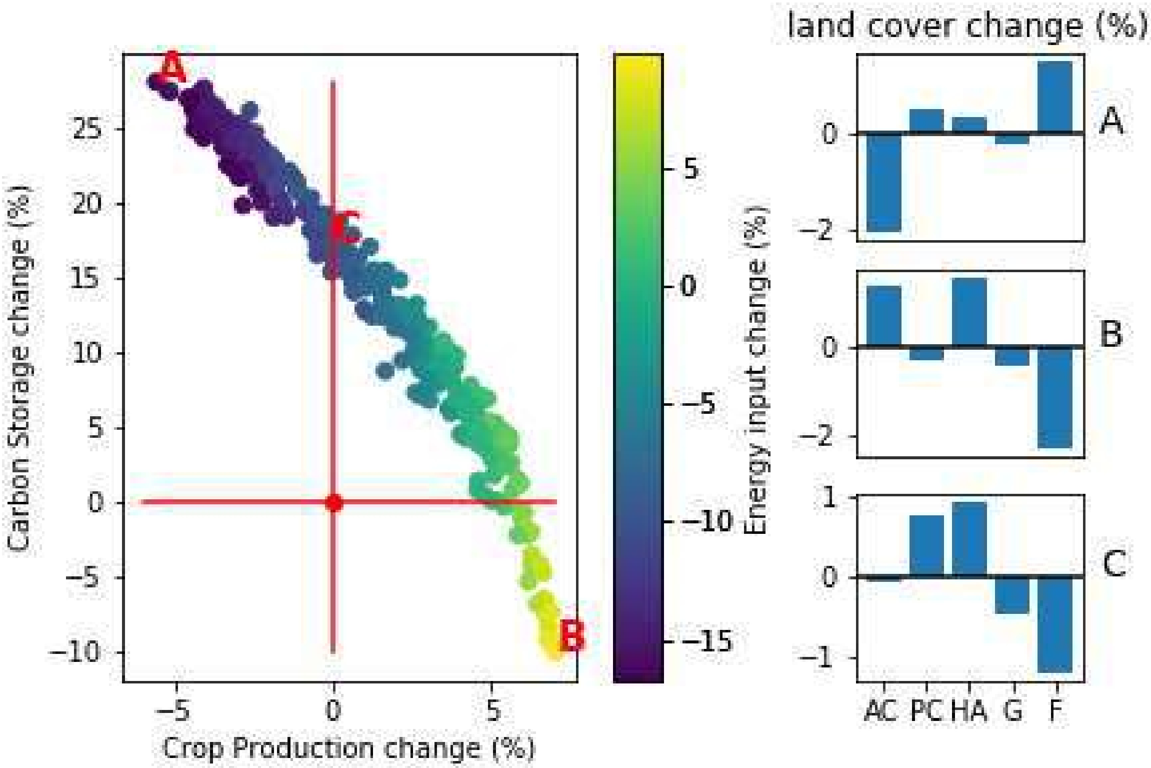


Figure 3.10.1 - Results of the land use optimization model for the Italian case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

.

The Italian case study is centered on the production of hazelnuts, which, in this analysis, are included in the "permanent crops". This particular land cover has at the same time a good potential for crop production and for carbon storage. The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. The shape of the Pareto frontier shows that the margin of relative increment possible for carbon sequestration is greater than the margin of relative increment for crop production. Point A (Figure 3.10.1) maximizes carbon storage and minimizes crop production and shows that an increment of 28% in carbon storage is possible but with a decrease of 6% in crop production. Point B (Figure 3.10.1) maximizes crop production and minimizes carbon storage and shows an increase of 17.4% in crop production without a decrease of 10% in carbon sequestration. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives (crop production and carbon storage) are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Italian case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 50.3% of the total number of optimized points. This is considered as average in comparison to other case studies.

Figure 3.10.1 also shows bar diagrams with the land use changes that should be made to reach points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to seasonal crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.10.1 (maximization of carbon storage), the model shows a simultaneous increase in forest and permanent crops, with the forest being increased largely. Forests are the most performing on carbon storage, however, permanent crops, such as hazelnut, are also important in this sense as they provide both carbon storage and food production. The increase in permanent crops and forest comes at the expense of seasonal crops, being the least efficient in carbon storage. Such an increase in carbon storage comes at a modest decrease in crop

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

production. In Point B of Figure 3.10.1 (maximization of crop production), the model shows a slight increase in seasonal crops and heterogeneous agriculture over the forest. Permanent crops are slightly decreased. The expansion of seasonal crops over permanent crops is suggested as such land use, because of model calibration, considers seasonal crops more productive than permanent crops, however, the economic value of the crop (which can play an important role) is not accounted for in the model. In Point C of Figure 3.10.1 (maximization of carbon sequestration without decreasing crop production), agricultural land is de-intensified and an expansion of permanent crops and heterogeneous agriculture is suggested over grassland and forest. The model suggests that the tradeoff between crop production and carbon storage can be softened with a balance between the forest, permanent crops and heterogeneous agriculture, whereas seasonal crops would put the system towards an increase in crop production enhancing the conflict with carbon storage. In relation to the scenario Eur-Agri-SSP1, which envisages a synergistic increase between crop production and environmental services, permanent crops become a means of adaptability.

3.10.2 Nitrogen fluxes model

The land cover of the Italian farming system region shows a high fraction of permanent crops and fruit and vegetables (forming the 30% of the total surface and with the majority of this fraction occupied by hazelnut cultivations). Other land fractions are occupied by cereals (25%), fodders (25%, including alfalfa), and grassland (19%), with a very low percentage of oil and protein crops. The livestock density is quite low (0.70 LU/ha with 56% ruminants) with 31% of ruminants on graze. According to the data, the agronomical configuration of the system causes a relatively high dependency on both chemical fertilizer and external feed. Concerning the dependency on chemical fertilizer, the region has a relatively small livestock sector, that does not provide a big amount of manure. In addition to that, the system does not rely on a big amount of residues from crops. Despite the relatively high quantity of crops promoting nitrogen fixation (e.g., alfalfa, peas, chick peas) and the relatively low need for fertilizers by permanent crops, the system is still in need of external sources of fertilizer. Concerning the dependency on external feed, the main limiting factor is due to the low presence of oil and protein crops for animal consumption.

Changes compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP3) were simulated over a period of 30 years with a progressive decrease in the availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.10.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

nitrogen for plants are depicted in Figure 3.10.3, in which the “lack” term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.10.2A and Figure 3.10.2B shows that in all the scenarios simulated the system experiences a decrease in all the functions provided. Repartition of mineral fertilizer sources shows that the system is in shortage of fertilizer within year 7 and 8 for all the scenarios (Figures 2A, 2B, and 2D), which is quite early in relation to other case studies. However, if we refer to hazelnut (Figure 3.10.2C), the production is quite robust

The first scenario (Eur-Agri-SSP1, sustainability) consists of a progressive reduction of the agricultural land, an increase in the share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. In the second scenario (Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In both these scenarios, the decline in crop production (Figure 3.10.2A) is due to a reduction of agricultural land (first scenario) and a reduction of fertilizer (first and second scenario).

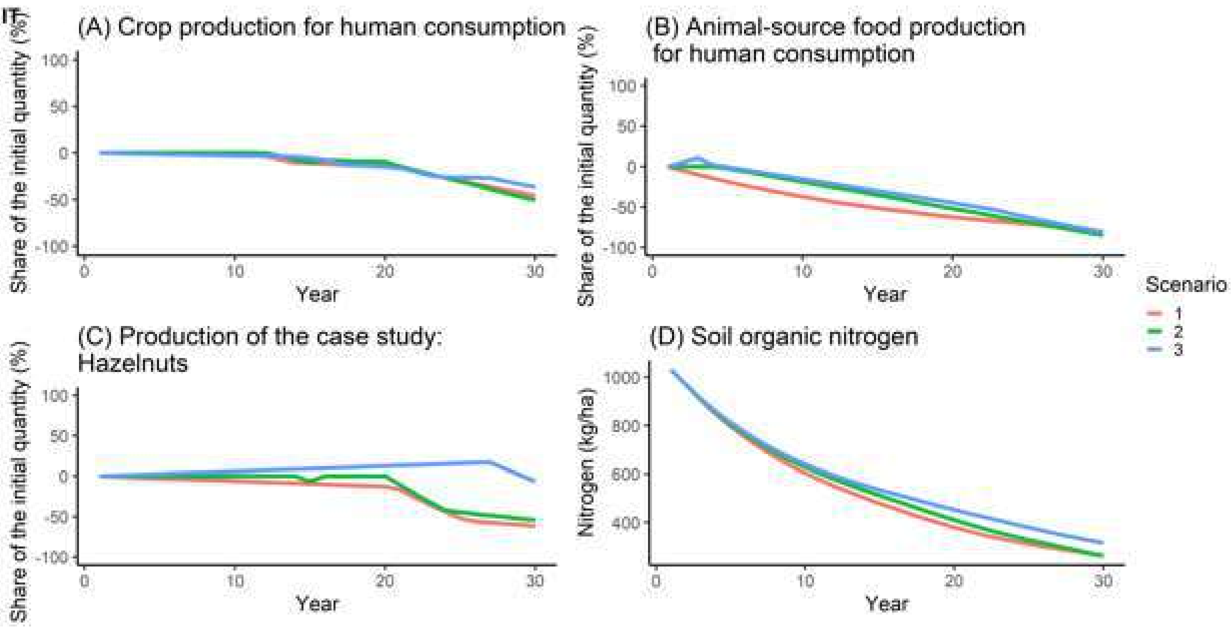


Figure 3.10.2. Simulation results of the nitrogen fluxes model for the Italian case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (hazelnuts) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

In the third scenario (Eur-Agri-SSP5, fossil-fuel development), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. Under these conditions the livestock sector decreases with less severity along the simulations (Figure 3.10.2B), however, the lack of internal feed resources prevents a stronger development of it. The slight increase of the livestock compartment provides more fertilizer from animal effluents, but it is not in a quantity to make the difference (as it happens, for example, for the Romanian case study). In this scenario, the production of hazelnut increases for almost all the simulation (Figure 3.10.2C) because the hazelnut cultivation is not highly demanding in nitrogen.

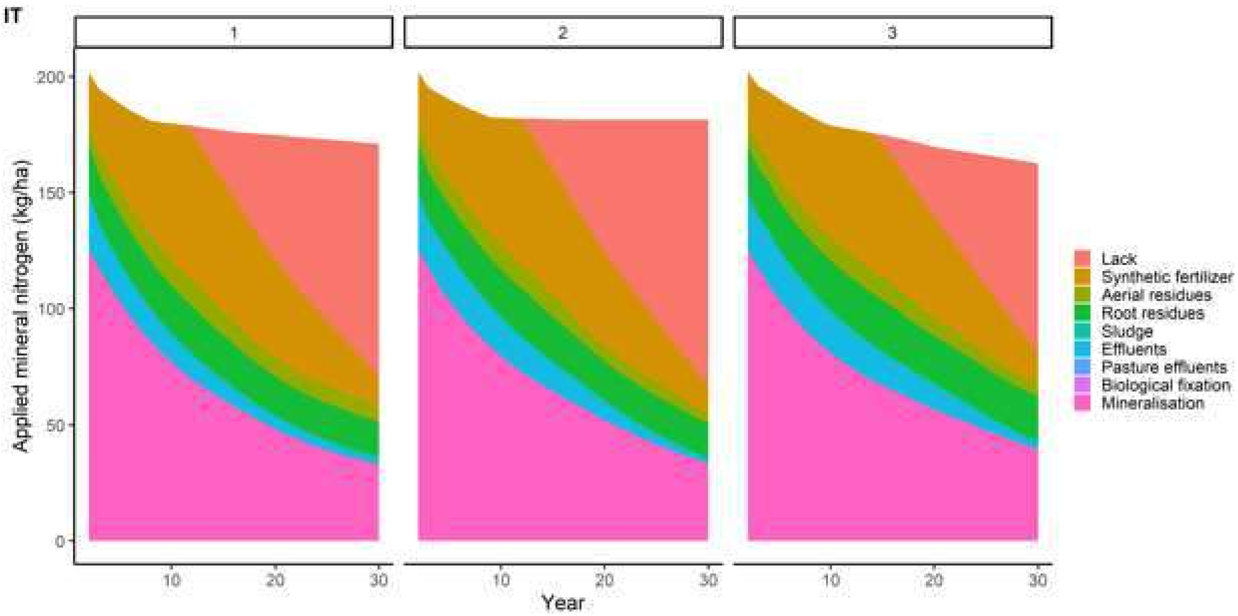


Figure 3.10.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Italian case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.10.3 General considerations

The land use optimization model (Figure 3.10.1), shows that the region has some possibility to increase at the same time environmental services and crop production. This can be achieved by regulating the balance between permanent crops, heterogeneous agriculture and forest. These three land covers result in competition with seasonal crops that increase only crop production but not carbon sequestration. The Pareto frontier shows that the gain in carbon storage that can be achieved is higher than the gain that can be achieved in crop production. The conflicts and

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

synergies between these land uses can be the object of discussion between stakeholders. Overall, we can say that the system has, from the point of view of land cover, some adaptability to the Eur-Agri-SSP1 scenario, because of the synergy that hazelnut cultivation can promote between production and carbon storage.

The nitrogen-flux simulation model shows that the system is not robust to a decrease in availability in external fertilizer and external feed. The system has a low livestock sector and at the same time low feed self-sufficiency. Therefore, in all the three scenarios considered, it is important to consider strategies to increase internal reserves of the system. However, the hazelnut cultivation does not require a high nitrogen input, therefore its cultivation is relatively highly robust.

3.11 Results of the ecosystem service modelling assessment: Polish case study

3.11.1 Land use optimization

The land uses considered for the analysis are seasonal crops, permanent crops, heterogeneous agriculture, grassland and forest. The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Polish SURE-farm case study region gives the Pareto frontier depicted in Figure 3.11.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

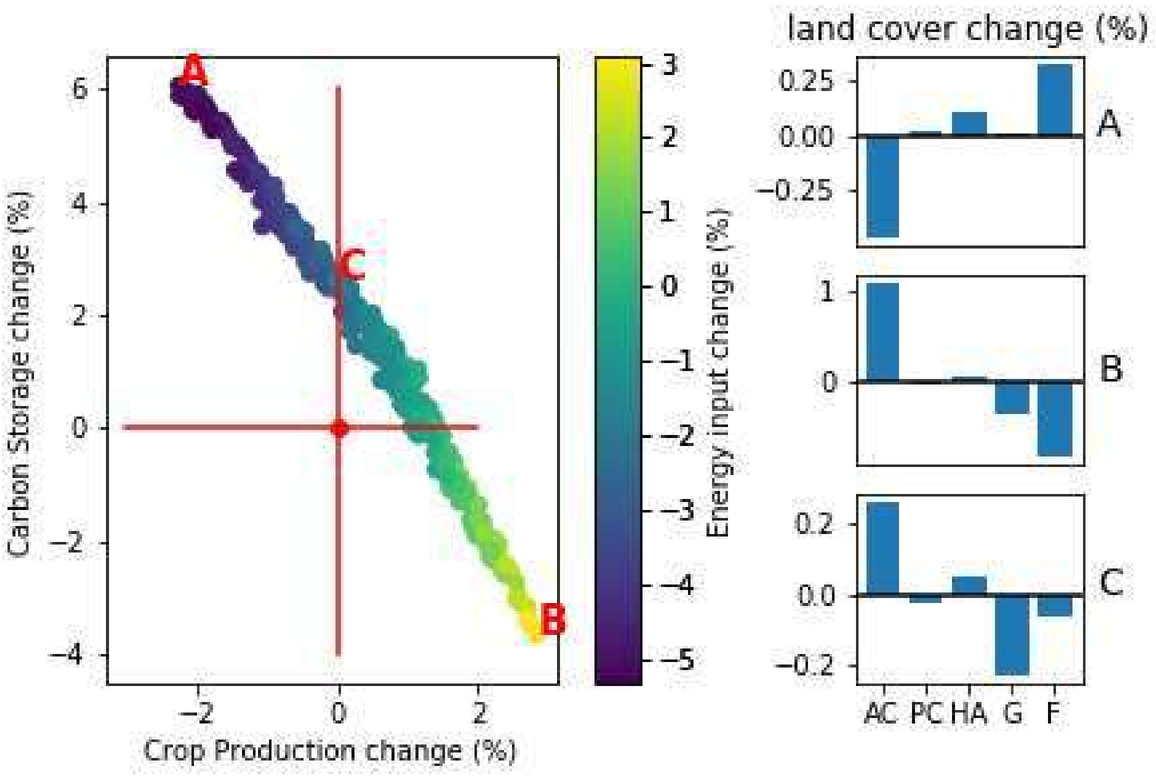


Figure 3.11.1 - Results of the land use optimization model for the Polish case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The Polish case study is focused on horticultural products, characterized by a mixture of permanent and seasonal crops. Within the land uses considered in this analysis, the Polish case study land use can be classified in “permanent crops” and “heterogeneous agriculture” (which is interpreted as a mixture of seasonal and permanent crops). The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Comparing to other case studies, the region can reach only small improvements in both the ecosystem services considered. Point A (Figure 3.11.1) maximizes carbon storage and minimizes crop production and shows that an increment of 6% in carbon storage is possible but with a decrease of 2.1% in crop production. Point B (Figure 3.11.1) maximizes crop production and minimizes carbon storage and shows an increase of 2.8% in crop production with a decrease of 3.9% in carbon sequestration. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts under the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Polish case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 27% of the total number of optimized points: this is considered as low in comparison to other case studies. This very low percentage of points that can increase both ecosystem services, as well as the closeness of the actual situation to the Pareto frontier, indicates that the system is already very close to a good balance between the two ecosystem services considered. This can be probably due to the already very diversified landscape and the predominance of heterogeneous forms of agriculture.

Figure 3.11.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to seasonal crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.11.1 (maximization of carbon storage), the model shows a decrease in seasonal crops (almost 0.5% of seasonal crops are converted into other land uses). Also heterogeneous agriculture and permanent crops are expanded as they can still provide crop production and increase carbon storage at the same time. In Point B of Figure 3.11.1 (maximization of crop production), is obtained with an expansion of seasonal crops and heterogeneous agriculture, with a decrease in forest, permanent crops and grassland. In Point C of Figure 3.11.1 (maximization of carbon sequestration without decreasing crop production), seasonal crops are slightly increased as well as heterogeneous agriculture. However, changes in land use are extremely limited (below 0.2% of the total land is converted in use). Heterogeneous agricultural land has a role in increasing carbon sequestration while maintaining the same level of crop production.

The model suggests that the system in its current state is already very close to the Paretian configurations, with a small room for ulterior improvements in both ecosystem services at the same time. This means that the landscape is already diversified enough and with some forms of agriculture already maximizing both ecosystem services at the same time. In addition to that, the form of agriculture characterizing the Polish case study, has a role at the regional level promote a synergy between carbon sequestration and crop production

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.11.2 Nitrogen fluxes model

The land cover of the agricultural context containing the Polish farming system case study shows a high percentage of cereals (56%) and of fodder (32%) and a small percentage of grassland (2%), oil and protein crops (5%) and other crops (5%). Other crops contain vegetables and permanent crops that are the main characteristics of the Polish farming system case study. The livestock density is quite low (0.68 LU/ha with 55% ruminants) with a 12% of ruminants on graze. According to the data, despite the big share of land cultivated with cereals, the region still has some diversification in the rest of land, providing different source of feed for the livestock sector. The relatively small livestock sector has therefore some feed self-sufficiency.

Changes compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.11.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.11.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.11.2 shows that in all the scenarios simulated the system decreases all the functions provided. Repartition of mineral fertilizer sources (Figure 3.11.3) show that the system is in shortage of fertilizer at around year 11 for all the scenarios.

The first scenario (compatible with Eur-Agri-SSP1) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. In the second scenario (compatible with Eur-Agri-SSP2, business as usual), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In both these scenarios, the decline in crop production is due to a reduction of agricultural land (first scenario) and a reduction of fertilizer (first and second scenario) (Figure 3.11.2A), trends are similar for the production of fruits and vegetables (Figure 3.11.2C)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

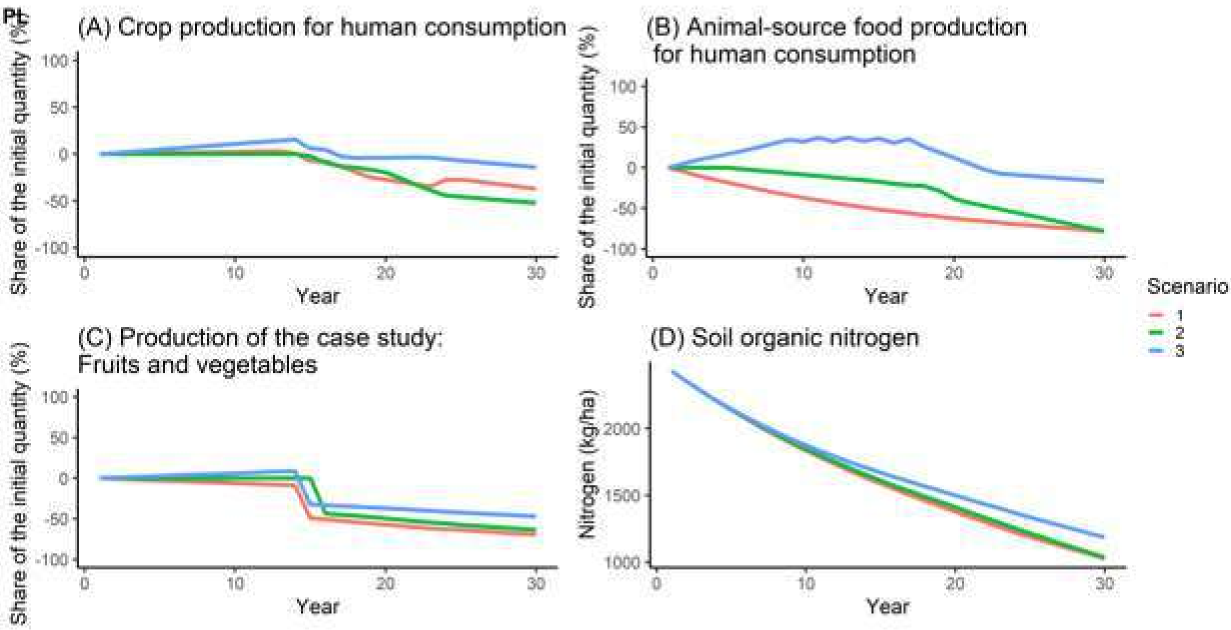


Figure 3.11.2. Simulation results of the nitrogen fluxes model for the Polish case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), production of the case study (fruits and vegetables) (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the third scenario (compatible with Eur-Agri-SSP3/5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. Under this scenario, crop production is increased at the beginning of the simulation (Figure 3.11.2A) because of increase in the agricultural land; animal production is increased in the first years of the simulation (Figure 3.11.2B), because the region provides internal resources for feed self-sufficiency and there is room to increase for the livestock sector. However, such increase is only for the first years (e.g., not prolonged as in the Romanian case study). The increase in the livestock sector causes an increase in the mineral nitrogen for crop fertilization (Figure 3.11.3) and increases the organic matter in the soil.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

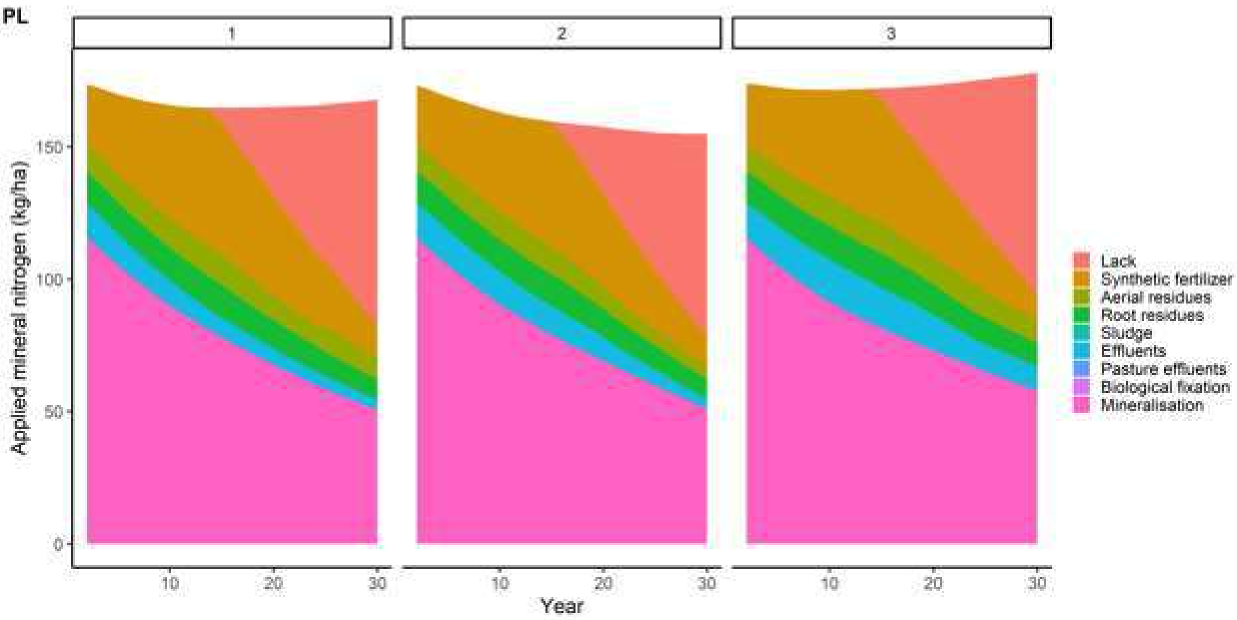


Figure 3.11.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Polish case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.11.3 General considerations

The land use optimization scenario show that the system as at near-optimal condition for addressing the tradeoffs between carbon sequestration and crop production. The system has a restricted margin for improvement because it is already in a good configuration, with a diversified landscape promoting synergies between carbon sequestration and crop production at the same time. In addition, the Polish case study is centered on horticulture, permanent crops and mixes of thereof, and it has a role in the region for promoting the synergy between the two ecosystem services. From the point of view of nitrogen fluxes, the system shows some dependency on external chemical fertilizer. This makes it very difficult for the system to adapt to the Eur-Agri-SSP1 scenarios if synthetic fertilizer availability is decreased in the long term. However, the system has potential to increase the livestock sector because of internal diversified resources promoting feed-self sufficiency.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.12 Results of the ecosystem service modelling assessment: Romanian case study

3.12.1 Land use optimization model

The optimization of the land uses for addressing the tradeoff between crop production and carbon sequestration in the region of the Romanian SURE-farm case study region gives the Pareto frontier depicted in Figure 3.12.1. The points on the Pareto frontier represent variations in crop production and carbon storage as percentages of the initial state. The initial state is represented as a red point at the origin of the axes.

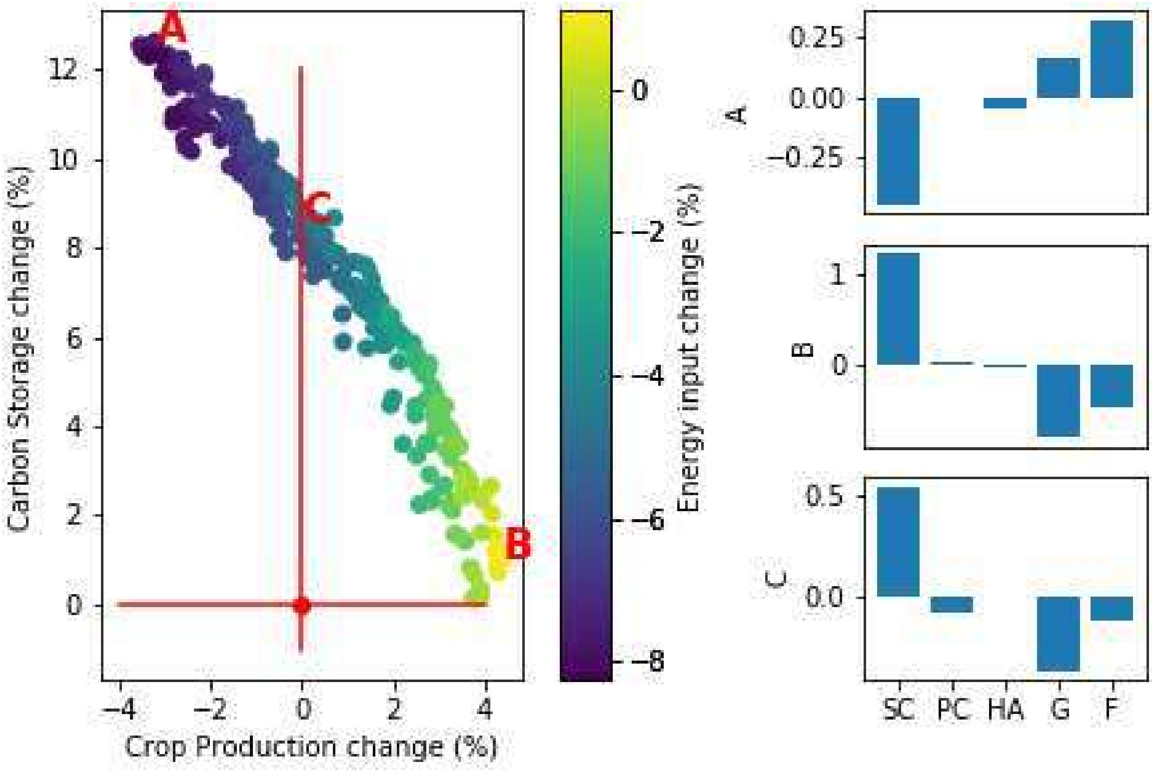


Figure 3.12.1 - Results of the land use optimization model for the Romanian case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified as a red point in the origin of the axes). The color scale represents the percentage variation in energy input. Panels A, B and C on the right column of the figure represent the changes in land cover, as percentages of the total land, for annual crops (AC), permanent crops (PC), heterogeneous agriculture (HA), grassland (G) and forest (F). The panel labeled with A represents the land cover variations in the point on the Pareto frontier minimizing crop production and maximizing carbon storage (Point A on the Pareto frontier). The panel indicated with B represents the land cover variations on the on the Pareto frontier maximizing crop production and minimizing carbon storage (Point B on the Pareto frontier). The panel indicated with C represents the land cover variations in the point maximizing carbon sequestration while keeping the same level of crop production as in the initial state (Point C on the Pareto frontier).

The extreme points of the Pareto frontier show the maximum extent at which single objectives can be maximized as well as the effect on the other objective. Point A (Figure 3.12.1) maximizes

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

carbon storage and minimizes crop production and shows that an increment of 12.6% in carbon storage is possible but with a decrease of 3.8% in crop production. Point B (Figure 3.12.1) maximizes crop production and minimizes carbon storage and shows that an increase of 4.4% without decreasing carbon sequestration is possible. The increase in crop production that is obtained is very modest compared to the other case studies. We defined as a metric relevant to resilience the percentage of points in the Pareto frontier for which both objectives are increased with respect to the initial situation. Such a metric is considered as a proxy of the adaptability of the region to the land use conflicts in the Eur-Agri-SSP1 scenario, for which a simultaneous increase in crop production and other environmental functions are expected. For the Romanian case study region, the points in the Pareto frontier that increase both objectives at the same time represent the 57.8% of the total number of optimized points, this is considered as average in comparison to other case studies.

Figure 3.12.1 also shows bar diagrams with the land use changes occurring in the points A and B marked on the Pareto front. Land use changes are represented as percentages of the total land (e.g., the percentage of the total land that was converted to seasonal crops or the percentage of the total land that was converted to seasonal crops from other land cover types). In Point A of Figure 3.12.1 (maximization of carbon storage), the model increases forest and grassland over seasonal crops. In fact forest and grassland are the land covers performing better on carbon sequestration. The increase in grassland is also in line with a possibility of extending the cattle sector, even if animal production is not considered in this scenario. In Point B of Figure 3.12.1 (maximization of crop production), grassland and forest are reduced for expanding land dedicated to seasonal crops and, at a small extent, to permanent crops. Only 1% of land is converted to seasonal crop from other land uses and this makes it possible only a small increase in crop production, meaning that for the system it is quite difficult to increase crop by extending the surface dedicated to crops. Point B indicates an increase in the energy input, indicating that, increase in yield can be obtained through a bit of intensification. In Point C of Figure 3.12.1 (maximization of carbon sequestration without decreasing crop production), grassland and forests are reduced for expanding seasonal crops but a less extent with respect to point B. We note that heterogeneous agriculture is not enhanced as in other case studies (for example the Dutch case study), this is probably due to the small extension of this type of agriculture in the Romanian case study region and to a lower performance of it in relation to the two ecosystem services considered.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

3.12.2 Nitrogen fluxes model

The land cover of the Romanian farming system is formed by cereals (40%) and grassland (25%), with also a presence of fodder (16%), oil and protein crops (10%) and other crops (6%). Such a land cover repartition makes the Romanian farming system one of the most diversified of the SURE-farm. The livestock density is quite low (0.60 LU/ha with 51% ruminants) with a high percentage of ruminants on graze (90%). Overall the system is mostly focused on crop cultivation with a low presence of livestock. On the one hand, this facilitates the system to be self-sufficient (less feed needed and more possibility to produce it internally), on the other hand, the system has a low quantity of manure and the organic fertilization comes only from plant residues and fertilization. In addition to this, because of the high percentage of ruminants grazing, a low fraction of manure reaches crop fields.

Changes in the agricultural system compatible with three Eur-Agri-SSP scenarios (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP5) were simulated over a period of 30 years with progressive decrease in availability of nitrogen and feed import (Table 2.1.3). The trajectories obtained for the relative variation of vegetal production for human consumption, animal production for human consumption, total food production, and organic matter are depicted in Figure 3.12.2. Variations are to be considered as percentages with respect to the initial state. The different sources of mineral nitrogen for plants are depicted in Figure 3.12.3, in which the "lack" term indicates that the total mineral nitrogen available is not sufficient to fulfill the demand by the plants. Figure 3.12.3 shows that, in all the three scenarios, the sources of mineral fertilizers are mainly the mineralization of organic nitrogen, plant residues and some chemical fertilizer, some biological fixation. Contribution of manure is poor (except in Scenario Eur-Agri-SSP5)

The first scenario (compatible with Eur-Agri-SSP1) consists in a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops. Grasslands are kept constant and livestock populations of ruminants and monogastrics are progressively decreased. The region of the Romanian case study has a quite high fraction cultivated with oil ad protein crops, and their increase softens the decrease in harvest provoked by the reduction of land dedicated to cereals and other crops. The system experiences at year 11 a shortage in synthetic fertilizer (Figure 3.12.3) and the poor presence of livestock does not refill the organic matter in the soil, which is emptied relatively quickly because of the high mineralization rate.

In the second scenario (compatible with Eur-Agri-SSP2), land cover fractions, total agricultural land and livestock population parameters are kept as in the current state. In this situation, the decrease in animal production is slower (Figure 3.12.2B) than in other case studies as the system has internal resources to sustain the livestock population. However, the livestock population is

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

small, therefore its impact on organic matter in the soil is very limited (Figure 3.12.2D) because of a poor quantity of manure produced and most of it deposited on graze and not reaching the fields. For this reason, the increase in the livestock population is not sufficient to have a virtuous impact on the crop compartment, reducing the dependency on chemical fertilizer.

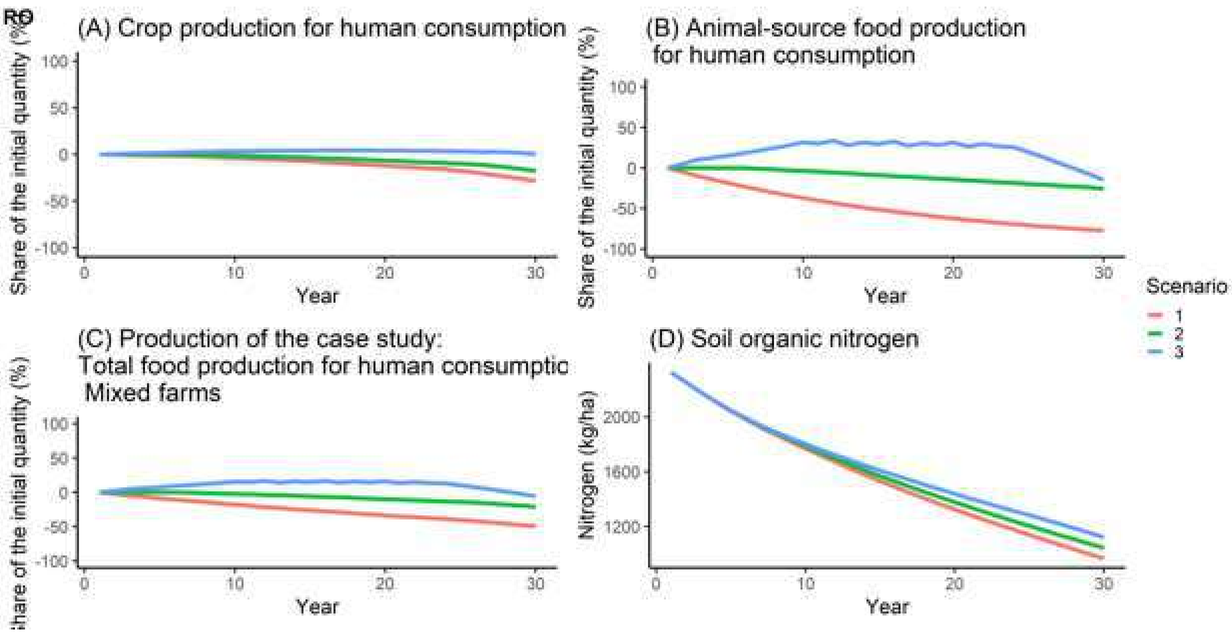


Figure 3.12.2. Simulation results of the nitrogen fluxes model for the Romanian case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), total food production (Panel C). Panel D represents the trajectory of the organic nitrogen in the soil. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

In the third scenario (compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5), agricultural production is boosted, therefore the agricultural land is increased and the livestock population is allowed to increase as long as feed resources are available. Under these conditions, the Romanian case study has room for increasing the population of ruminants and monogastric, having in itself a reserve of feed resources internally produced. The animal production in this scenario is even increased along the simulated time horizon (Figure 3.12.2B), following an increasing trend until year 12 and a decrease until the end of the simulation, still maintaining a production higher than the initial state. The repartition of the sources of mineral fertilizers (Figure 3.12.3) shows that the system begins being in shortage of fertilizer later than in the other scenarios and the amount of nitrogen coming from animal effluents is increased along the simulation. The increase in animal production has a positive impact on the total food produced (Figure 3.12.2C) and has a positive effect on the crop production. Among the three scenarios analyzed, this seems the most promising from the point of view of the Romanian case study.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

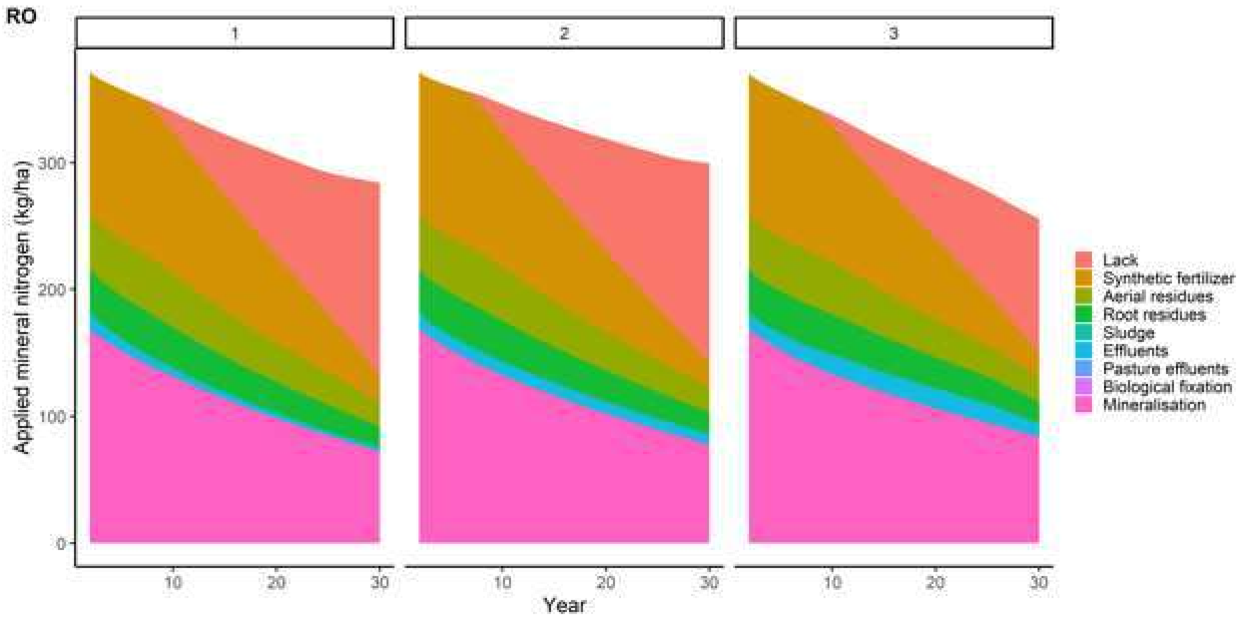


Figure 3.12.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the Romanian case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, animal effluents deposited on pasture, biological fixation, mineralization. The lack term indicates that the total mineral nitrogen available is not sufficient to fulfill plant nitrogen demand. Scenario 1 is compatible with Eur-Agri-SSP1, Scenario 2 is compatible with Eur-Agri-SSP2, scenario 3 is compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5.

3.12.3 General considerations

For the Romanian case study region, it seems that an increase in the livestock population is a possible strategy for increasing resilience in case of shortage in chemical fertilizer and feed import. On the contrary, the scenario Eur-Agri-SSP1, aiming at increasing crop production maintaining a high level of carbon storage, is not the optimal way to go. The land use optimization scenario shows that increasing crop production without decreasing carbon storage lead only to a poor increase in crop production and would reduce grassland, which are important for livestock production. Nitrogen flux model simulations show that the scenario 3 is the one for which the system has the greatest potential for improvement by means of an increase in livestock population that should be sustained by an increase in grassland. This is more compatible with point A in Figure 3.12.1 that envisages an increase in grassland and a consequent increase in carbon storage.

The Romanian case study is one of the most diversified among the SURE-farm case studies. Such a diversification makes it possible to have both food for human consumption and feed for animals at the same time. In addition, the crops for animal consumption are diversified so that all the dietary items are provided. Livestock population (especially the ruminant population) seems under-developed in the region and has margin for growth. This represents a form of adaptability of the system and it would represent an additional form of diversification. The

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

increase in the livestock population, by means of additional manure production, would improve the organic matter in the soil and would decrease over time the need for chemical fertilizer.

3.13 Ecosystem service modelling: synthesis and caveats

We systematically applied two ecosystem services models to all the SURE-Farm case studies. The first model is a land use optimization model for studying the trade-offs between crop production and carbon storage in the region containing the case studies. The second model is a model for simulating the dynamic nitrogen fluxes among compartments of agricultural systems with which it was possible to simulate the production of crops, animal-source food, and soil organic carbon. The aim of this synthesis is to discuss the results obtained with the two models in relation to the research questions addressed and in relation to the resilience attributes of the case studies. Specifically, for the land use optimization model, the research question is related to how possible is to increase crop production and carbon storage in the case study region; for the nitrogen fluxes model, the research question relates to the robustness of the farming system to decrease in availability in chemical fertilizer and feed for import. A resilience attribute is an attribute of the system than enhances the likelihood of the system of being resilient, we discuss some attributes (related to the assumptions of the model) and we link them to the resilience attributed listed in Cabell and Oelofse (2012).

3.13.1 Land use optimization model: discussion

The purpose of the land use optimization model is to assess the tradeoff between a private function (crop production) and a public function (carbon storage) in the region containing the SURE-Farm case studies. While the tradeoff is addressed at the regional level (NUTS3 regions containing the case studies), it was possible, by identifying the land cover category to which the case study belongs, to discuss the role of the case study farming system in softening or enhancing the tradeoff in their region. Insights from the results of this modelling exercise can tell how the SURE-Farm case studies are adaptable (based on their land cover configuration) to the Eur-Agri-SSP1 scenario. Such scenario is about increasing the production of vegetal-source food and the enhancement of public functions, while the animal-source production is discouraged.

Land cover in the SURE-Farm farming systems regions

For discussing the results of the land use optimization model it is important to consider the land cover distribution in the region (see Figure 3.13.1) and the land cover pertinent to the case study farming systems (see Table 3.13.1).

The land cover repartition shows diversity across the SURE-Farm case study systems (Figure 3.13.1). The Belgian case study region is the one with highest fraction of heterogeneous

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

agricultural land (specifically, the pertinent Corine Land Cover category is "Complex Agricultural Patterns"), the UK case study is the one with highest fraction of annual crops, the Italian case study region is the one with most extended fraction of permanent crops, and the Swedish case study region is the one with the highest fraction of forest. Grassland is present to a certain extent in all case studies, however the French case study region is the one with the highest fraction of grassland, followed by the Spanish region. Some case study regions are more diversified (e.g., the Italian, the Polish, and the Romanian), while others (e.g., the UK and Swedish) are mostly covered by annual crops and land for conservation (grassland and forest).

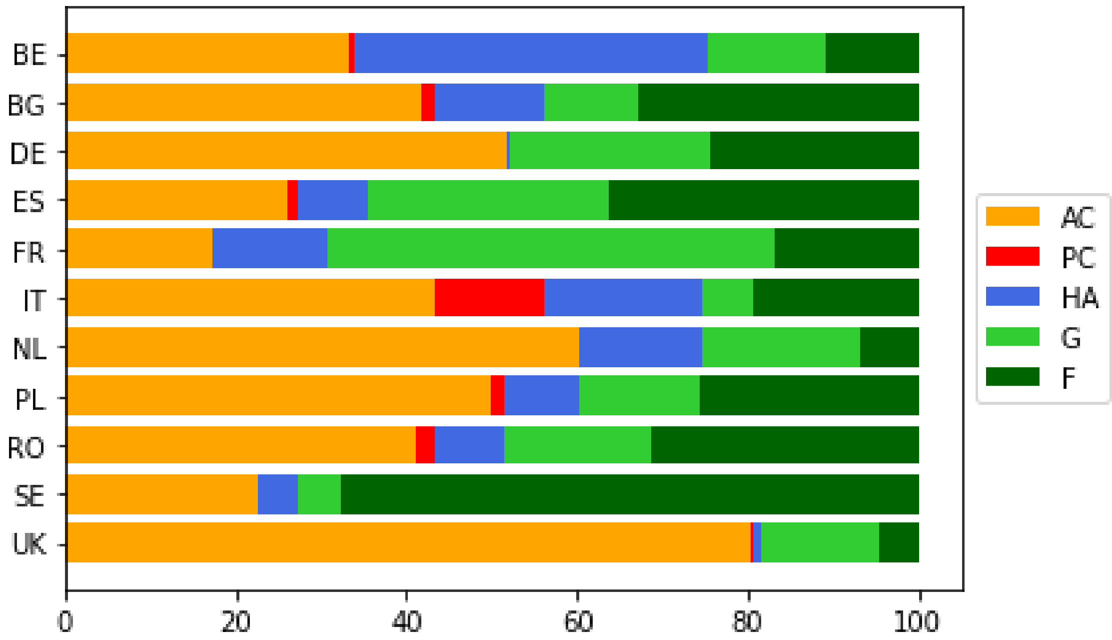


Figure 3.13.1 – Repartition of the land covers (in %) in the NUTS3 regions containing the SURE-Farm case studies in terms of Annual Crops (AC), Permanent Crops (PC), Heterogeneous Agricultural land (HA), Grasslands (G) and Forests (F). Fractions are re-elaborated from the Corine Land Cover 2012 map.

The Belgian case study focused on dairy production and its impact on land cover is mostly through forage cultivation, which can be categorized in "annual crops" or in "heterogeneous agricultural land" (this is highly probable, given the high presence of this land cover in the region). The Bulgarian case study falls into "annual crops", as well as the UK case study, the crop part of the German case study and the feed cultivation for the Swedish case study. The two SURE-Farm case study systems based on extensive animal production (the Spanish and the French ones) are based mostly on "grassland" but, to a certain extent, also on "annual crops" for

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

forage cultivation (for feed supplements). The Italian case study is based on “permanent crops”. The Polish case study is based on “permanent crops” and “heterogeneous agricultural land”. Finally, the production of the Dutch and on the Romanian case studies fall into the categories of “annual crops” and “heterogeneous agricultural land”.

Table 3.13.1 – Land cover categories pertinent to the different SURE-Farm case studies. Concerning the farming system based on animal production, the impact of land cover is given by the origin of the feed.

Case study	Farming system typology	Annual Crops	Permanent Crops	Heterogeneous Agricultural land	Grassland
BE	Dairy cattle	X		X	
BG	Arable	X			
DE	Mixed system	X		X	X
ES	Ovine	X			X
FR	Beef cattle	X			X
IT	Hazelnuts		X		
NL	Starch potatoes	X		X	
PL	Fruits and vegetables		X	X	
RO	Mixed system	X		X	
SE	Eggs and broiler	X			
UK	Arable	X			

Results of the land use optimizations

The Pareto frontiers represent, for the respective case studies, sets of possible alternative systems optimized according to crop production and carbon storage (with a minimization of energy input). Moving from one point to another of the Pareto frontier will improve one of the objectives but will worsen the other(s). Therefore, the method applied cannot make a conclusion on which is the best point on the frontier (i.e., the best alternative system for the case study, in terms of land cover combination), because this choice is a political choice and can be based on stakeholders’ preferences. Rather, the method can inform about the sharpness of the conflict between the two functions and about the distance of the current situation to the optimized situations.

With the same constraints posed on the optimization algorithm, some case studies performed better than others, meaning that some case studies can be more adaptable than others to the Eur-Agri-SSP1 scenario. However, results need to be carefully considered in relation to the characteristics of the case studies not included in the model. The room for adaptation to the Eur-Agri-SSP1 scenario can be measured in terms of (i) maximum relative improvement obtainable in crop production, (ii) maximum relative improvement obtainable in carbon storage, (iii) percentage of points in the Pareto frontier that can increase both ecosystem services at the same time (see these metrics presented in Table 3.13.2).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 3.13.2 – Overview of the indicators of the Pareto frontiers calculated for all the case studies

Case study	Maximum percentage increase in crop production [%]	Maximum percentage increase in carbon storage [%]	Percentage of solutions increasing both objectives at the same time [%]
BE	4.3	11.8	18.6
BG	5.4	14.2	47.9
DE	14.0	28.8	41.4
ES	4.2	5.5	53.6
FR	9.7	24.7	92.9
IT	7.1	28.0	50.3
NL	31.8	12.1	73.7
PL	2.8	6.0	27.6
RO	4.4	12.6	57.9
SE	2.9	1.7	57.4
UK	4.2	10.0	28.3

Closeness of the land use configuration to the optimized configuration

The closer the actual state is to the optimized configuration, the lower is the room for improvement of the system in both the ecosystem services considered, and the lower is the possibility to increase both ecosystem services at the same time. This might happen for two reasons: (i) the land use configuration is already optimal and diversified enough that both ecosystem services are well valorized in the region; (ii) the land use conflict is so sharp that changes in land cover might put the region to the loss of one of the two services.

The Belgian, Polish, and UK case studies have very low room (number of points increasing both ecosystem services in the Pareto frontier are less than 30%) for improvement in both ecosystem services (Table 3.13.2). For the Belgian and Polish region the reason is that the land use is already diversified enough with high presence of heterogeneous agricultural land, with crops produced for both human and animal consumption. Instead, for the UK region, the reason is that the tradeoff is very sharp between land for agriculture and land for conservation (grassland and forest). In the region of the Swedish case study, the possibility to increase both ecosystem services at the same time is average high (compared to the other case studies); however, the percentage increase in each of the two ecosystem services is extremely limited, because of the strong conflict between annual crops and forest. The Romanian case study is already quite diversified, but has room for improvement in both ecosystem services. The Italian case study makes it possible to have a relatively high possibility of an increase in both ecosystem services, and the permanent crops are able to promote both ecosystem services at the same time.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Concerning the Bulgarian case study, high room for improvement in both ecosystem services is possible, but this would be due to the expansion in heterogeneous agricultural land, which is not the land cover corresponding to the Bulgarian farming system case study. Concerning the German, Spanish, French, and Dutch case study, the room for improvement is given by the presence of grasslands, as grassland, in this scenario, can be replaced by cropland and forest to increase the two ecosystem services considered. This happens to a lesser extent for the German and Spanish regions, but to a higher extent for the French and Dutch regions. For the French region, a big part of grassland can be converted to cropland and forest for enhancing in particular carbon sequestration, and for the Dutch region, grassland can be converted for enhancing mostly crop production. For the French and Spanish case study it is important to consider that the main production of the respective case studies is based on animal-source food, therefore a reduction of grassland would correspond quite to a transformation of the system.

Role of grassland in the Eur-Agri-SSP1 scenario

The results of the land use optimization model for the SURE-Farm case study regions raise some attention to the role of grassland. Clearly, the optimization algorithm pushes the system to replace grassland with other land uses for enhancing the provision of crops and for enhancing carbon storage (see detailed results for Germany, Spain, France, and The Netherlands in particular). In fact, grassland does not provide a net contribution to crop production (therefore it is replaced by crops) and it is less efficient than forest for carbon storage (therefore it is replaced by forest).

An important consideration to make is that, in some case study regions, grassland cannot be substituted with any other land cover, because, for geomorphological and hydrological conditions, grassland is the only land use possible. However, this is not always true especially for France and Spain, where conversion from grassland to cropland (or to more intensive forms of cultivated grassland) is observed, as well as conversion from grassland to forest due to land abandonment and practices of agroforestry. In addition, often grassland is maintained by the presence of grazing livestock.

We believe and suggest that the role of grasslands should be considered in the formulation of the Eur-Agri-SSP1 scenario. Grasslands have a contribution to food production by means of livestock, however they become of secondary importance in a scenario in which animal-source food production decreases. The formulation of the Eur-Agri-SSP1 scenario leaves indeed space for some livestock production (only in some regions, where feed self-sufficiency is possible and sustainable), therefore we argue that livestock production coupled with grassland is a condition

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

for selecting the European regions to be dedicated to sustainable meat production (as also argued by De Boer and Van Ittersum, 2018). Also, it should be taken into account that grassland provides also other ecosystem services than the ones considered.

Considering resilience attributes

The land use optimization approach is highly specialized and targeted; therefore only a couple of resilience attributes can be adapted and reinterpreted. The first attribute considered is "diversity". In the context of land use optimization for ecosystem services, synergies are promoted by those land uses able to promote more ecosystem services at the same time. Therefore, in the SURE-Farm project, the case studies that promote at the same time carbon storage and crop production are the most adapted to soften the conflict between those two ecosystem services. This is the case of the Belgian, Italian, Polish, and Romanian case studies, which have an impact on land use able to promote both ecosystem services. This does not imply that conflicts are absent: for example, the hazelnut cultivations in Italy are in conflict with annual crops, which produce higher yields (even though with less economic value). However, those case studies have a role in softening the ecosystem services conflicts in their regions. On the contrary, the other case studies are strongly promoting crop production over carbon storage. In this case, both ecosystem services can be enhanced if there is a "neutral" land use to be converted (grassland in this modelling exercise), otherwise, there the expansion of crop production cannot occur without a loss in carbon storage at the regional level. Possible solutions for this are the increase in yield through intensification, reduced yield gap, and increased efficiency (land sparing approach) (Reidsma et al., 2015; Silva et al., 2017); or by making agriculture more friendly for carbon storage (land sharing approach), as some practices being promoted in the UK case study (see D5.3, Reidsma et al., 2019).

The second resilience attribute is "system reserves". In the context of this modelling approach, a system reserve is a land cover that can be used as a "buffer" and be used for increasing other land uses, more efficient from the points of view of the ecosystem services to optimize. In this modelling exercise that does not consider livestock production, grassland is a "buffer"; however the caution with which this affirmation should be taken is discussed in the previous subsection.

3.13.2 Nitrogen fluxes model: discussion

The purpose of the nitrogen fluxes model is to simulate the dynamical nitrogen fluxes in the SURE-Farm case studies and, specifically, the provision of animal-source food, crop-source food, and organic nitrogen in the soil. Though the modelling exercise was done considering all the agricultural systems in which selected farming systems are embedded (this was done in order to consider the necessary interactions with other neighboring farming systems), the results are

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

given only in terms of the specific functions provided by the farming systems. In commenting the results we consider intrinsic characteristics of the farming systems, as well as their relationships with the surrounding agricultural systems.

We used this model in order to test the robustness to a challenge common to all the case studies. The challenge considered was a gradual decrease in the availability of synthetic fertilizer and in feed to import, and was simulated in the context of three scenarios (see details in Section 3.1), the first mainly characterized by a decrease in agricultural land and in livestock number (compatible with Eur-Agri-SSP1), the second corresponding to constant values of agricultural land and livestock numbers (compatible with Eur-Agri-SSP2), and the third characterized by an increase in agricultural land and in livestock number (compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5). By simulating a decrease in external fluxes for the system, logically the provision of food decreased for all the farming systems. However, some case studies decreased less abruptly than others and/or started decreasing later than others (see the variability of farming system performances in Figure 3.13.2). According to the way trajectories decreased, we could say that some farming systems are more robust than others to the challenge and in the contexts (Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP3/5) considered.

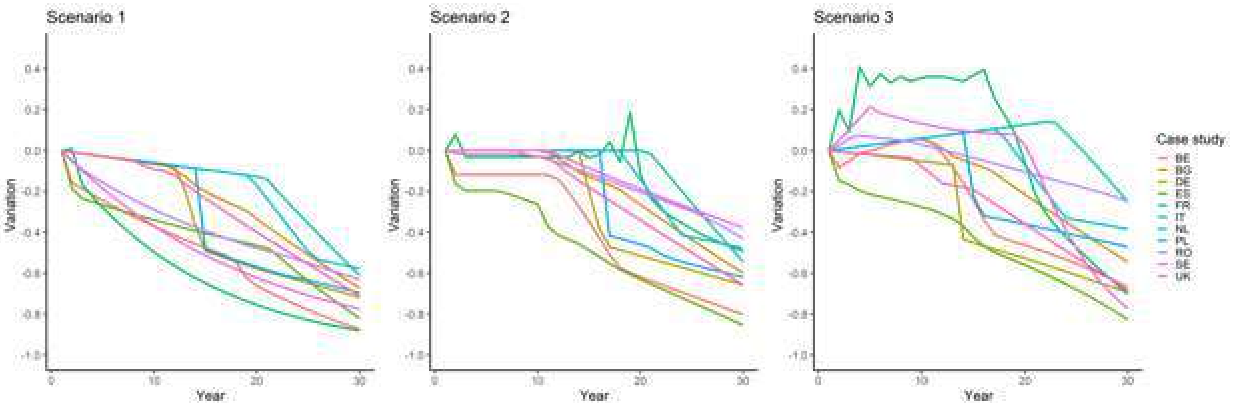


Figure 3.13.2 – Trajectories of food production for SURE-Farm case studies. Values are expressed as fraction of the same function provided in the initial state. Food production is referred to the specific case study production, i.e., cattle milk for Belgium (BE); oil and protein crops and wheat for Bulgaria (BG); durum wheat and cattle milk for Germany (DE); ovine meat for Spain (ES); beef for France (FR); hazelnuts for Italy (IT); starch potatoes for the Netherlands (NL); fruits and vegetables for Poland (PL); total agricultural production for Romania (RO); eggs and broiler production for Sweden (SE); and cereals for UK (UK).

For measuring the robustness, we consider at different times of the simulation the food provided as a fraction of the food provided at the initial state. The food provided was the specific production of the farming system, while the times considered are year 5, 10, 15, 20, 25,

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

and 30 (Table 3.13.3). In this way, we tracked the robustness over time, because one system can be robust in the short term but not robust in the longer term, especially with a long-term stressor like the one simulated. For the second and third scenarios, it was possible that for some case studies food production increased in the short-term. This was often due to an increase in livestock number and agricultural land. In this case we say that the farming system is robust, because the context provides some means for adapting to the situation, however we do not quantify the adaptability, we only discuss it.

Once the overview of the robustness of the systems are given, we discuss the differences in robustness in terms of the characteristics and of the resilience attributes of the resilience attributes.

Table 3.13.3 – Robustness indicators (% decrease in food production at different time steps) for the different farming systems at different time steps of the simulations under the three scenarios

	5	10	15	20	25	30
Scenario 1						
BE	-18.55	-36.98	-51.23	-72.85	-78.89	-85.56
BG	-2.67	-6.00	-19.58	-32.23	-49.50	-65.68
DE	-3.38	-7.39	-50.58	-59.08	-66.13	-72.77
ES	-18.55	-36.98	-51.23	-66.43	-76.12	-84.82
FR	-18.55	-36.98	-51.23	-62.26	-70.80	-77.41
IT	-2.67	-6.00	-9.33	-12.67	-52.04	-61.55
NL	-2.67	-6.00	-9.33	-12.67	-40.29	-53.42
PL	-2.67	-6.00	-49.00	-57.23	-63.67	-69.63
RO	-8.65	-17.98	-26.14	-33.54	-40.33	-49.32
SE	-18.55	-36.98	-51.23	-62.26	-70.80	-85.56
UK	-2.67	-9.33	-26.56	-42.92	-58.25	-72.87
Scenario 2						
BE	-2.22	-17.75	-34.76	-68.14	-74.43	-85.34
BG	0.00	0.00	-13.41	-27.27	-44.14	-60.21
DE	0.00	0.00	-25.25	-52.24	-59.25	-66.14
ES	-2.11	-19.05	-46.17	-64.81	-74.67	-86.79
FR	0.00	-12.17	-28.64	-52.17	-66.49	-79.78

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

IT	0.00	0.00	-6.35	-21.33	-44.48	-54.13
NL	0.00	0.00	0.00	-0.24	-36.51	-42.56
PL	0.00	0.00	0.00	-49.56	-57.34	-63.73
RO	0.00	-2.34	-5.77	-9.86	-14.09	-20.98
SE	-2.22	-18.89	-35.56	-52.22	-68.89	-85.56
UK	0.00	-4.48	-22.63	-38.69	-54.16	-69.19
Scenario 3						
BE	-2.22	-17.99	-53.16	-70.29	-76.48	-85.40
BG	2.67	5.12	-7.24	-22.19	-38.61	-54.62
DE	-1.45	-2.97	-41.85	-53.01	-61.36	-68.27
ES	-4.15	-23.23	-55.81	-76.99	-86.85	-94.81
FR	21.55	55.13	97.99	49.04	-19.99	-63.-5
IT	2.67	6.00	9.33	12.67	16.00	-6.49
NL	2.67	6.00	9.33	6.62	-27.33	-32.14
PL	2.67	6.00	-32.28	-37.01	-42.22	-47.06
RO	7.53	15.46	14.95	15.95	10.43	-6.02
SE	-2.22	-18.89	-35.56	-52.22	-68.89	-85.56
UK	-1.75	-7.28	-24.69	-41.05	-56.59	-71.48

Robustness of the farming systems in the three scenarios

The Eur-Agri-SSP1 scenario promotes a transition to a system with less agricultural land and progressive de-stocking of the livestock sector. In combination with limited availability of N inputs, this leads to a decrease in food production in all SURE-Farm farming systems. The systems with the highest advantage in this scenario are those with the highest nitrogen surplus at the beginning or with poor dependency on nitrogen. The system with the highest nitrogen surplus are those that mostly retard the moment in which the system experiences nitrogen losses (see the Dutch case study, in which starch potatoes rely on a high quantity of manure) and has therefore the highest time span to find solutions to adapt to the scenario (Figure 3.13.2). The systems totally focused on animal production are the least robust, because the Eur-Agri-SSP1 scenario undermines their identity in destocking the livestock sector. For these systems, their role in the Eur-Agri-SSP1 scenarios should be discussed: they could be either maintained with a sustainable livestock production or they can be transformed or converted to other production.

The Eur-Agri-SSP2 scenario favors the farming systems with a good equilibrium between the crop and the livestock compartment. In the short term, the most advantaged crop-based systems are those well coupled with a livestock sector (e.g., the Dutch case study) and the most advantaged livestock-based systems are those well coupled with a crop sector (e.g., beef production in France is well coupled with crops that provide feed supplement to the grassland-based diet) (Figure 3.13.2).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The Eur-Agri-SSP3 scenario favors the case studies that mostly have the opportunity to increase land and to increase the livestock sector because of internal feed self-sufficiency (this is the case for the Romanian, the Swedish, the UK, and the French case studies). The Polish and the Bulgarian case studies can increase their livestock sector in the same region but to a lower extent (Figure 3.13.2) and, for the Polish case study, not in the case study region, as it is highly fragmented and not adapted for livestock. However, increasing livestock with the challenge simulated can be beneficial in the short term but detrimental in the long term, because the impact on a bigger, over-dimensioned herd can be more severe than on smaller herds. The Italian case study has a big advantage in this scenario because it has poor dependency on nitrogen and can therefore increase production because of the increase of land without experiencing nitrogen shortage in the short term.

Short-term vs long-term robustness

Measuring robustness along a simulated trajectory allows making considerations about the impact of a disturbance in the long term and in the short term. The difference between these two types of robustness is important because if a system is robust in the short term but not in the long term, there is time to think about solutions for setting changes in order to adapt to the challenge and to the scenario. Systems with high reserves of nitrogen (e.g., the Dutch case study) or with reduced nitrogen need (e.g., the Italian case study) are more robust in the short term and have more time to think about alternative solutions for facing the scenarios (for example, based on the technology). Systems with a low robustness in the short term (for example the French, the Spanish, and the Swedish case study in the Eur-AgriSSP1 scenario) are strongly impacted by the challenge from the very first years.

In some cases it happens that the system is too robust in the first years, but very poorly robust in the long term. In the scenario Eur-Agri-SSP3, the French case study performs very well in the very first years by increasing the number of livestock. However, because of such increase in number, the impact of shortage in feed import is more severe in the long term, causing an abrupt drop of beef production in the last years of the simulated horizon.

Characteristics of the farming systems and resilience attributes

Different characteristics of the farming systems, from the agronomic point of view, can be considered and discussed in the context of the robustness indicators calculated and in the context of the resilience attributes (Cabell and Oelofse, 2012; Meuwissen et al., 2019) and resilience principles (Resilience Alliance, 2010). The system characteristics, with the resilience attributes in which they fit, are given in Table 3.13.4 for all the SURE-Farm case studies.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Exposed to disturbance. In the context of a progressive reduction in nitrogen fertilizer availability, the systems that have advantage are those that are normally functioning with reduced quantities of nitrogen inputs. This happens because of two main reasons: the crops cultivated are not highly demanding in nitrogen, or the system is already under-performing and fertilized with less nitrogen than its needs. The hazelnut cultivations in the Italian case study are low nitrogen demanding and they are therefore more robust to reduced nitrogen availability, even though the system lacks other resilience attributes (e.g, presence of organic nitrogen in the region, having a diverse production). The Romanian and Bulgarian systems are under-performing, and therefore less impacted by the reduced availability in nitrogen.

Response diversity. This attributes deals with the capacity of the system to provide diverse outputs. If a system is mixed it is better connected in its internal dynamics and has a differentiated response to the same challenge (crop and animal production). Usually, the lowered performance of one function can be compensated by the better performance of the other function. This is the case for the German and the Romanian case study, and the resilience attribute concerned is “Response diversity”. In contrast, if the system is highly specialized it might be poorly robust (the extreme cases are seen for the French, the Spanish, the Swedish, and the Belgian case study in the scenario Eur-Agri-SSP1 where livestock destocking is simulated). In case of non-mixed systems, the system has advantage if different crops are cultivated or different livestock species are reared. It is the case of the Polish case study that relies on a diverse production. An indicator constraining the response diversity is the feed-food competition. If a livestock system consumes biomass that could be used for human consumption, it reduces the capacity of the system to provide diversified responses to a challenge. Cultivations of fodder remove land for crops potentially dedicated to human consumption. The SURE-Farm farming system mostly concerned by the feed-food competition are the Belgian case study (fodder cultivation for the dairy production). The Spanish case study is concerned to the extent of the fodder cultivation for the ovine production.

Functional diversity. The presence of different crop species ensures different functions in the system In order to achieve feed self-sufficiency, not only is important to produce the right amount of protein in the region, but also to produce all the necessary and diverse food items for guaranteeing the right diet to the livestock. Having a diverse range of crops in the farming system or in the agricultural context, improves the robustness of the system to shortage of feed. In particular, the importance of feed self-sufficiency is recognized in the systems for which an increase in livestock is possible at the beginning of the Eur-Agri-SSP3/5 simulations (see the Romanian, French, UK, Bulgarian, Polish case studies). Another characteristic enhancing functional diversity is the presence of legume crops that can fix atmospheric nitrogen: this constitute an alternative functionality for reducing the dependency on external synthetic

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

fertilizer. Farming systems having a substantial fractions of legume crops are the Romanian and the Bulgarian case study.

Coupled with the natural capital and *ecologically self-regulated.* An extensive system based on grassland can be considered as coupled to the natural capital and likely to be ecologically self-regulated. Grazing systems can be considered as strongly self-regulated system, of course if the stocking rate respects the carrying capacity of the pasture and do not create unbalances like overgrazing and excess in greenhouse gas emissions. The French and the Spanish systems are those based on grasslands and have therefore the opportunity to exploit this coupling with the natural capital. A constraining indicator for this attribute is the low amount of residues left on field. The Belgian case study highly relies on the production of fodder, which leaves fewer plant residues on the field. This will in the long term deplete soil organic matter and will make the system more dependent on other sources of fertilizers (organic or synthetic).

Globally autonomous and locally interconnected and *appropriately connected with actors outside the farming system.* Results are discussed at the case study level, however, case studies are not islands and they interact with the surrounding farming systems. The interactions can be complementary or conflicting and these can constitute an enhancing or constraining characteristic, respectively, for the attributes "Globally autonomous and locally interconnected" and "appropriately connected with actors outside the farming system". Examples of complementarity with neighboring farming systems are the following: the beef production of the French case study receives feed supplements from crops cultivated nearby, increasing the feed self-sufficiency of the system; the starch potato production of the Dutch case study receives manure from the neighboring dairy sector. Examples of conflicts with neighboring farming systems are the following: irrigated crops and industrial crops for feeding intensive livestock farming limit the availability of feeding sheep farming; the same can be said for the Belgian farming system as the land cultivated with fodder is subtracted to the land cultivated for other intensive monogastric systems. We acknowledge that sometimes conflicts and complementarities are very hard to distinguish and a change in the balance can make an equilibrium turn from a complementarity to a conflict. For example, in the French case study, an increase in the fodder land can reduce grassland and cause a decrease in the cattle stock raised on grassland.

Excess of resources. The dependence on organic fertilizer can play different roles in different ways for increasing robustness. The system has a high organic nitrogen surplus at the beginning of the time horizon (this happens for the Dutch case study and, to a lesser extent, to the Belgian). In this case, the system at the beginning has a reduced dependency and a higher soil organic matter that is slowly mineralized over time. This makes it possible to arrive to a nitrogen shortage later and have more time to think about adaptation strategies. The presence of nitrogen surplus constitutes a system reserve and it is therefore classified in the resilience attribute "system reserves". It is however to be noted that the presence of a nitrogen surplus might constitute a problem regarding environmental issues, therefore this constitutes a tradeoff between system reserves and environment. In order to have available organic fertilizer, it is important that a livestock sector is connected to the farming system. This can happen if the farming system has a livestock sector incorporated (e.g., the French, the Romanian, and German case studies), or if the livestock sector belongs to another neighboring, but accessible farming system (in this case, the concerned case study is the UK). In the scenario Eur-Agri-SSP3, the capacity to depend more on organic fertilizer is given by the possibility to increase the livestock sector, as it happens for the Romanian, the UK, and to a lesser extent, for the Polish and Bulgarian case studies.

Table 3.13.4 – Agronomic characteristics (indicators) of the SURE-Farm case studies enhancing (+) or constraining (-) the resilience attributes (D5.2 (Paas et al., 2019), elaborated from Cabell and Oelofse, (2012)). Resilience attributes are linked to generic resilience principles (Resilience Alliance, 2010): diversity (DI), modularity (MO), openness (OP), tightness of feedbacks (TF), system reserves (SR). The resilience principle is indicated by each resilience attribute in brackets. The resilience attribute "Excess of resource" is not part of the list selected in D5.2 but its indicator (high organic nitrogen surplus at the beginning) could not fit into any of the other resilience attributes; the indicator could therefore fit into the generic resilience attribute SR. Some indicators refer to multiple resilience attributes: in this case more than one resilience attribute is given in the column heading.

Case Study	Exposed to disturbance (OP)	Response diversity (DI)	Functional diversity (DI)	Coupled with the natural capital (SR) *and* Ecologically self-regulated (TF)	Globally autonomous and locally interconnected (OP, TF) *and* Appropriately connected with actors outside the farming system (TF)	Excess of resources (SR)
BE		(-) Specialized system (-) high feed-food competition		(-) low amount of residues on field	(-) presence of conflicting farming systems in the region	(+) high organic nitrogen surplus at the beginning
BG		(-) Specialized system	(+) Presence of legume crops			
DE		(+) mixed system				
ES		(-) Specialized		(+) based on	(-) presence of conflicting	

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

		system (-) feed food competition		grassland	farming systems in the region	
FR		(-) Specialized system	(+) grassland and crops	(+) based on grassland	(+) presence of complementary farming systems in the region	
IT	(+) Low need in fertilizer	(-) Specialized system			(-) presence of conflicting farming systems in the region	
NL		(-) Specialized system			(+) presence of complementary farming systems in the region	(+) high organic nitrogen surplus at the beginning
PL		(+) Diversified crop production				
RO	(+) Under-performing system	(+) mixed system	(+) diversified crops (+) Presence of legume crops			
SE		(-) Specialized system (-) high feed-food competition			(+) presence of complementary farming systems in the region	
UK		(-) Specialized system			(+) presence of complementary farming systems in the region	

3.13.3 Conclusions

We applied two different models for assessing the provision of ecosystem services in the 11 SURE-Farm case studies under given future challenges and selected Eur-Agri-SSP scenarios. The models were focused on specific aspects of the farming systems, i.e., the land use and the nitrogen compartments and fluxes. Despite the limited field of investigation, it was still possible to make considerations about differences between farming systems, in the way they respond to challenges as a function of their land use or agronomic configuration.

The first limitation of the modelling approach is to be found in the field of investigations of the model themselves. The models are about a particular aspect of the biophysical component of the system, based on land use (optimization model) and nitrogen fluxes (simulation models). Therefore, the insights about resilience could be made only under these aspects. Results come with approximation. The models are conceived at the relatively large-scale, therefore some

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

phenomena are not modeled in detail: for such a reason, results do not have to be taken for their precise numerical value, but for the trends and patterns that they show.

With the land use optimization model it was possible to identify farming systems with greater possibilities to increase two ecosystem services at the same time. It was moreover possible to distinguish between the farming systems that soften the conflict between crop production and carbon sequestration in the region, from those that are in conflict with land for conservation. By simulating the nitrogen fluxes model under different scenarios (compatible with some Eur-Agri-SSP scenarios) it was possible to identify systems more suitable to different scenarios from the point of view of their agronomic configuration.

The main limits of this analysis are given by the fact that specific challenges were simulated. Some of these challenges were not mentioned by FoPIA stakeholders or simply not considered relevant. However, the aim was to apply a systematic analysis to all the case study in order to being able to compare the response of all the case study to the same challenge. For future perspective it is possible to design challenges more relevant to single case studies.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

4 SYSTEM DYNAMICS ASSESSMENT

Hugo Herrera, Lilli Shütz, Pytrik Reidsma, Wim Paas, Corentin Pinsard, Francesco Accatino, Birgit Kopainsky

System Dynamics (SD) is a modelling method focused on studying how outcomes of the systems are driven by system's own internal mechanisms (Richardson, 2011). SD focuses on understanding the circular relationships (feedback loops) driving the outcomes of the system (Richardson, 2011). Jay Forrester originally developed SD as a modelling method to explore and improve the performance of complex systems (Forrester, 1961). SD models the behaviour of complex systems through the causal relationships of its components, encompassing social goals, economic pressures and the physical constraints of the system (Meadows, 1976). Analysing the structure formed by these relationships and identifying its feedback mechanisms, it is possible to understand system behaviour and build computer simulation models to explore the effect of policies to improve it.

A poor understanding of the feedback loops and accumulations operating in the system often results on short-term policies that produce adverse unintended effects in the long-term (Forrester, 1961; Sterman, 1994). Authors like Diehl and Sterman (1995) and Sterman et al. (2007) have shown that human mind has troubles successfully predicting the behaviour of complex systems and trying to manage such complexity, policymakers can make decisions with unexpected and undesired results. As an alternative, SD uses computer simulations to help policymakers to understand complex systems. Through simulation models, policy makers and researchers can explore scenarios, evaluate strategies and communicate public policies (Antunes et al., 2006; Sterman et al., 2012; Sterman & Sweeney, 2002).

In the context of resilience assessment, Herrera and Kopainsky (2020) describe how SD can help policy makers to gain insights about a system's structure and the leverage points to design resilient systems. By building causal explanations and supporting them with computer simulations, SD allows policymakers to a) identify relevant feedback mechanisms driving system's responses when affected by disturbances; and b) explore policies that can potentiate or cancel theses mechanisms to improve the system's resilience.

The SD approach model systems by focusing on the variables that accumulate over time (stocks) and their accumulation rates (flows). This approach is particularly helpful for representing and investigating those variables commonly described in the resilience literature as 'slow variables'. Slow variables are variables that strongly influence the system but remain relatively constant over time (Chapin III et al., 2009). In SD models slow variables are represented as stocks (the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

rectangle in Figure 1). Stocks are ideal to represent slow variables because they only change through inflows (accumulation) and outflows (depletion).

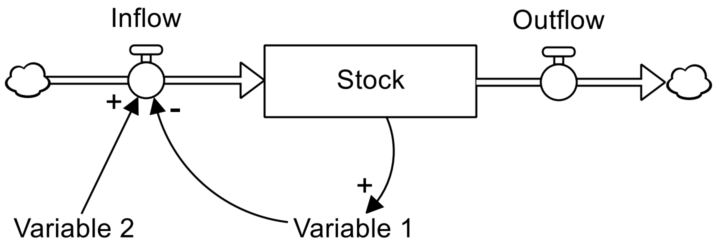


Figure 4.1: Nomenclature used in system dynamics models

The causal relationships between stocks, flows and other variables is indicated using one-way arrows indicating that the indicator from which the arrow originates is the cause of change in the indicator at which the arrow is pointed. The direction of this change is indicated using '+' or '-' letters next to the arrow heads. A '+' indicates that both variables change in the same direction (for example if one increases the other also increases) while a '-' indicated that the variable at the end of the arrow changes in the opposite direction than the one at the nod.

The term feedback loop is used to indicate circular causal relationships like the ones shown in Figure 4.1. Generally, there are two types of feedback loops (Morecroft, 2015; Ford, 2009), balancing and reinforcing loops. In a balancing loop a change in the condition of a given variable leads to a counteracting or balancing change when the effects are traced around the loop. By comparison a reinforcing loop amplifies or reinforces change. In a realistic multi-loop system, such as the transport example mentioned earlier, behaviour through time arises from the interplay of balancing and reinforcing loops.

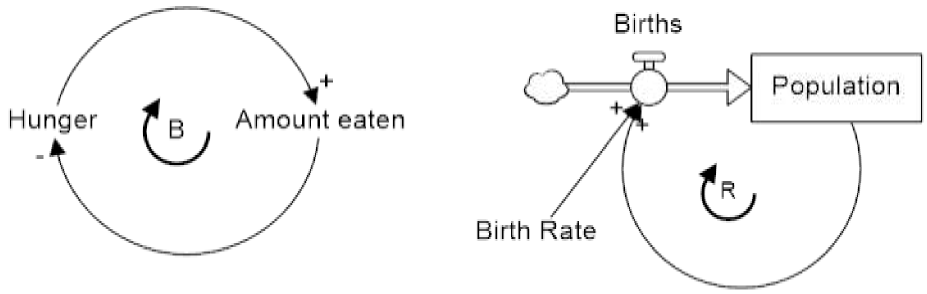


Figure 4.1: Examples feedback loop nomenclature

In real world systems stocks don't show dramatic changes instantaneously but as the result of phenomena that affected them over time. The delays between changes in one variable and changes in a stock indirectly affected by it give rise to complex non-linear behaviours. Just by

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

analysing the stocks and feedback mechanisms of a system it is possible to identify potential constraints and leverage points for the system. However, this qualitative analysis, falls short of accuracy when trying to determine which mechanisms are dominating the system, outlining pathways and comparing the impact of different strategies. Often, a quantitative analysis, using computer simulations, is needed to gain a more in depth understanding of the system behaviour.

In this chapter we summarise the insights gained from using the SD model to assess future resilience of European farming systems using both qualitative and quantitative analysis. The chapter proceeds as follow. First, we give a short overview of the methodology used to produce the analysis. Second, we describe the qualitative analysis conducted and a short summary of the qualitative insights gained from using a SD approach. Next, we present a quantitative analysis for two case studies in the SURE-Farm project. The chapter finalises with a summary of the insights gained and lessons learned.

4.1 Methodology

In the SURE-Farm Impact Assessment toolbox (see Herrera et al. 2018), SD is used to understand the feedback loop mechanisms driving systems responses to external disturbance. In particular SD is used to understand how system resources enable or constraint it response to disturbances affecting it (see Herrera-de-Leon and Kopainsky, 2019).

In SURE-Farm we use a SD model to understand European farming systems using both qualitative and quantitative analyses. For the qualitative analysis we developed a conceptual stock and flow diagram (SFD) representing, at an aggregated level, the main dynamics in European farming systems. The model is ‘conceptual’ because it is highly aggregated so that can be applied to many different contexts and issues (high generality) instead or being problem specific. As Constanza et al., (1993) noted, to achieve high generality, the conceptual models trades-off some level of precision and realism.

For the quantitative analysis, we developed mathematic simulation models for two of the SURE-Farm case studies: i) the the Veenkoloniën region in the Netherlands, and ii) the Bourbonnais region in France. The models used for this analysis were built as part of a desktop exercise based on case studies documented in the literature, historical data sets and empirical qualitative data collected as part of the SURE-Farm project (particularly during the FoPIA-SURE-Farm workshops).

Within the SD approach resilience is analysed through the behaviour of outcome functions over time (Herrera and Kopainsky, 2020) to disturbances or perturbations of relatively defined

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

duration (Bender et al., 1984). For analysis purposes, it is assumed that, after a sufficiently long time following a disturbance, the system will find an equilibrium (Arnoldi et al., 2018).

The concept of equilibrium has been conceptualised in two different ways in the resilience literature (Holling, 1973). The difference between these two views of equilibrium is summarized by Gunderson (2000, p.426) an rephrased next. One the one hand, it can be assumed that the system exists near a single or global equilibrium condition. In this case, resilience is the time required for a system to return to an equilibrium or steady-state. These return times are understood as an indication of the system stability or robustness (e.g. Ludwig, 1996; Holling, 1996; Henry and Ramirez-Marquez, 2012; Herrera, 2017; Arnoldi et al., 2017).

Alternatively, it can be assumed that the system operates within multiple equilibriums or stability domains (Walker et al., 2004). In this case, disturbances can flip a system into another regime of behaviour in a different stability domain (Holling, 1973; Gunderson, 2000). As Gunderson (2000, p.426) explains, when considering multiple potential equilibriums, "resilience is measured by the magnitude of disturbance that can be absorbed before the system redefines its structure by changing variables and process that control behaviour".

Levin (1998) elaborated that the magnitude of disturbance that can be absorbed by a system without shifting to a new stability domain is related to the systems' capacity to reorganise itself. The capacity can be grasped using SD models by looking at the feedback loops that drive the system behaviour. When facing a disturbance, a system can modify its behaviour without changing its structure by shifting the dominance of its feedback loops. Walker et al. (2004) argues that, in socio-ecological systems these shifts in the feedback loop dominance are mainly the result of human actions and interventions.

In a qualitative assessment assisted by a SFD, it is possible to identify the feedback loops that govern the system response to a disturbance. Feedback loops are invariably linked to stocks or slow variables that determine its strength. By identifying which feedback loops are fundamental for the system responses that enhance its resilience we can identify which resources (or slow variables) make such response more likely and/or more effective (Walker et al, 2012). While the relations between resources and resilience, are often no-linear, higher levels in these key resources (e.g. soil resources, biodiversity, etc.) are linked to higher adaptability and resilience (Chapin III et la., 2009).

Although it is not possible to get an accurate view on how resilient is the system using a qualitative analysis, it is possible to make a judgement on which responses are more likely by considering what resources are available in the system. For instance, responses that require highly skilled staff are unlikely to happen in systems where human capital (resource) is low. A

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

system with enough resources to implement many different responses is likely to be more resilient than a system that is limited to only one response. Correspondingly, the scenarios where the systems have been depleted of their key resources could be expected to be less resilient than does that have not.

Quantitative SD models allow to get a more operational view of resilience because the simulation results can be used to calculate measures of resilience, like those proposed by Gunderson (2000). Table 4.2 presents a short description of the operational definition for the resilience measures used in our analysis. More details are variable in Herrera (2017). As pointed out by many authors (Pimm and Lawton 1977, Gunderson, 2000; Arnoldi, 2017) recovery rapidity (see equation 1 in Table 4.2) can be used as an indication of robustness. Elasticity, on the other hand, can be used as an overall indication of the system resilience and the effectiveness adapting strategies (Walker et al., 2004).

Table 4.2: Operational measures of resilience using for assessing resilience in System Dynamics model. Adapted from Herrera (2017)

Measure	Description	Mathematical definition
Recover rapidity (R^{avg})	The average rate at which a system returns to equilibrium after a disturbance σ (Martin et al., 2011; Arnoldi et al., 2017; Herrera, 2017;). The bigger the R^{avg}, the faster the system recovers after the disturbance.	$R^{avg} = \int_0^t \frac{1}{\|x(t)\|} \frac{d\|x(t)\|}{dt}$ (1) *Where:* $x(t)$: is the distance to equilibrium N* for the function F(t) the Euclidean norm $\|x(t)\| = \sqrt{\sum_i x_i^t(t)}$ measures the phase-space distance to equilibrium. *t:* is time the function needs to go back to equilibrium N* See more details in Arnoldi et al. (2017) and how it is calculated for dynamic models in Herrera (2017)
Elasticity (σ_E)	The ability of the system to withstand a disturbance	$\sigma_E = M_E \times d_E$ (2)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	without changing to a different stability domain (Holling, 1996; Holling & Gunderson, 2002). The higher the elasticity the higher is the system resilience.	*Where:* M_E: is the maximum disturbance the system can withstand within the same stability domain with a duration equal to the minimum *dt* d_E: is the maximum duration the system can withstand within the same stability domain with a magnitude of *dm* See more details in Holling & Gunderson (2002) and how it is calculated for dynamic models in Herrera (2017)

The SD approach is limited when it comes to assess what happens beyond the elasticity threshold, because beyond this threshold the system transforms into a fundamental new system with alternative structures and feedback mechanisms driving its behaviour (Walker et al, 2004). Anticipate such new structures using a SD model would have been difficult. For instance, in the example, the transformation of cattle ranges in Zimbabwe in the 1980s into wildlife conservancies as results of the intense droughts affecting the system (Walker et al., 2004, p. 5) would have been difficult to anticipate in a SD model.

4.1.1 Future of farming systems

In order to explore how resilient European farming systems might be in the future, it is necessary to make some assumptions about how that future might look like. In our analysis, we use the medium- to long-term explorative scenarios developed by the SURE Farm project and described in its deliverable D1.2 (Mathijs et al., 2018). These scenarios describe outline possible futures for the external environment (including environmental, economic and social issues) that EU farming systems face.

These European agriculture scenarios are in line with the scenarios used in the framework of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), called Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014). The SSPs are defined based on two critical uncertainties, i.e., adaptation and mitigation challenges (Figure 4.2).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

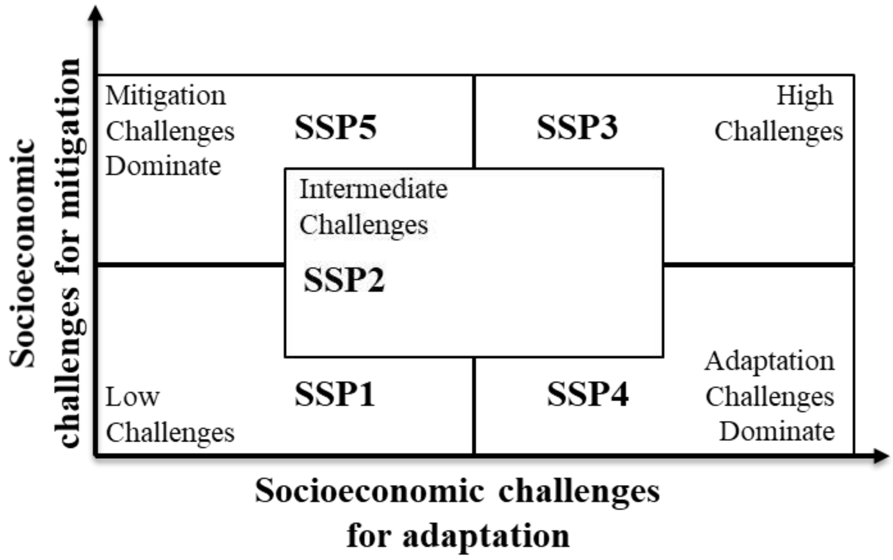


Figure 4.2: Shared Socioeconomic Pathways (O'Neill et al., 2014)

For the SURE Farm project, Mathijs et al. (2018) expanded the SSP narratives developed at global level into narratives that are meaningful for EU farming systems. The details about EU-Agri-SSPs and its their main variables (including land-use change regulation, land productivity growth, environmental impact of food consumption) are described in the deliverable D1.2. Here, we present as short summary of the scenario narratives,

In SSP1 (agriculture on sustainable paths), environmental externalities are internalized through effective policy leading to reduced meat consumption but also reduced trade. In SSP5 (agriculture on high-tech paths), diets are still high in meat and economic growth if driven by free trade and a resource intense economy. In SSP3 (agriculture on separated paths) economic rivalry severely constraints trade damping economic growth and innovation. SSP4 (agriculture on unequal paths) has elites enjoying high resource based consumption at the expense of the poor.

For our analysis we took key variables from each scenario and explore how they could affect the dynamics included in the conceptual model. The list of these variables and their expected behaviour in each of the EU-Agri-SSPs is summarised in Table 4.3.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 4.3: Overview of farming system description for the 5 Eur-Agri-SSP scenarios

	Population and urbanisation	*Economy*	*Policies and institutions*	*Technology*	*Environment and natural resources*
SSP1 Agriculture on sustainable paths	Strong network of small and medium sized towns and large cities	Diversity in agricultural supply chains supported by globally connected markets with internalized costs of trade	Multilevel cooperation, policy integration and societal participation	Pronounced technology development directed towards environmentall y friendly processes and cooperation	Increasing environmental awareness, resource use efficiency, and environmental health
SSP2 Agriculture on established paths	Urban agglomerations continue to grow	Few, powerful companies dominate agricultural supply chains and benefit from integrated markets	European agricultural policies follow multiple goals that are not always achieved	Agricultural technology development and diffusion focuses on resource use efficiency	High competition for resources and structural change affect environmental performance
SSP3 Agriculture on separated paths	Decelerated urbanization	National agricultural supply chains benefit from protectionism	National agricultural policy aiming at national food and energy security	Slow agricultural technology development and uptake because of reduced investments and scepticism	High pressure on natural resources through high national demand for agricultural commodities
SSP4 Agriculture on unequal paths	Territorial fragmentation	A business oriented elite dominates agricultural supply chains	A business oriented elite dominates European institutions and sets the policy agenda	Rapid technology development focusing on production and energy efficiency	Environmental awareness limited to the neighbourhood of the wealthy upper class
SSP5 Agriculture on high-tech paths	The vast majority of the European population lives in metropolitan areas.	High-tech companies of large size dominate globalized agricultural supply chains	European institutions foster international trade but delay environmental action	High affinity to output oriented technology	Lack of global environmental awareness

Source: D1.2 Scenarios for EU farming

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

4.2 Qualitative analysis

For presentation purposes, we aggregated the elements of the model in sub-sectors or modules. Each module has been developed at an aggregated level including variables and causal relationship to the minimum level of detail needed to explain the main dynamics in the system. For instance, we have not model in detail the chemical and biological relationships between the soil nutrients and crops yields. Similarly, the effect of local farming systems on the EU economy and EU food market has not been considered and economic factors (like Gross Domestic Product) are considered as exogenous factors (outside the boundaries of the model). The full SFD is presented in the Appendix D.

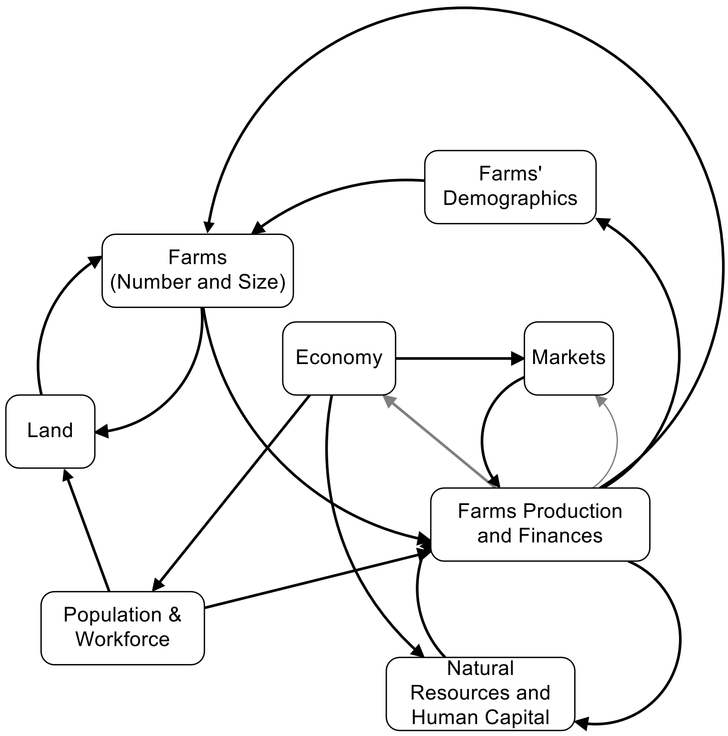


Figure 3.4: Overview of a conceptual model of European Farming systems

Splitting the system in sub-sector is helpful for presentation purposes but the boundaries of each component are not as rigid as the diagram in Figure 3 might suggest. In practice, there is some degree of overlapping between variables that could be allocated to more than one of them. Hence, we have decided to describe the model by describing the fundamental dynamics driving the system behaviour rather than sector by sector.

The number of farms: In this conceptual model we explain the amount of farmers, and hence the amount of farms, by looking at the economic attractiveness of farming (see B1 in Figure 4.4) and the attractiveness of farming to successors (see B2 in Figure 4.4). For simplicity, we have

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

only considered the economic attractiveness of farming as the main cause for entering (acquiring a new farm) or leaving (selling the farm) the system. The higher is the attractiveness of farming more farmers join. However, a higher number of farmers, , all other conditions remaining the same, reduces the economic attractiveness of farming.

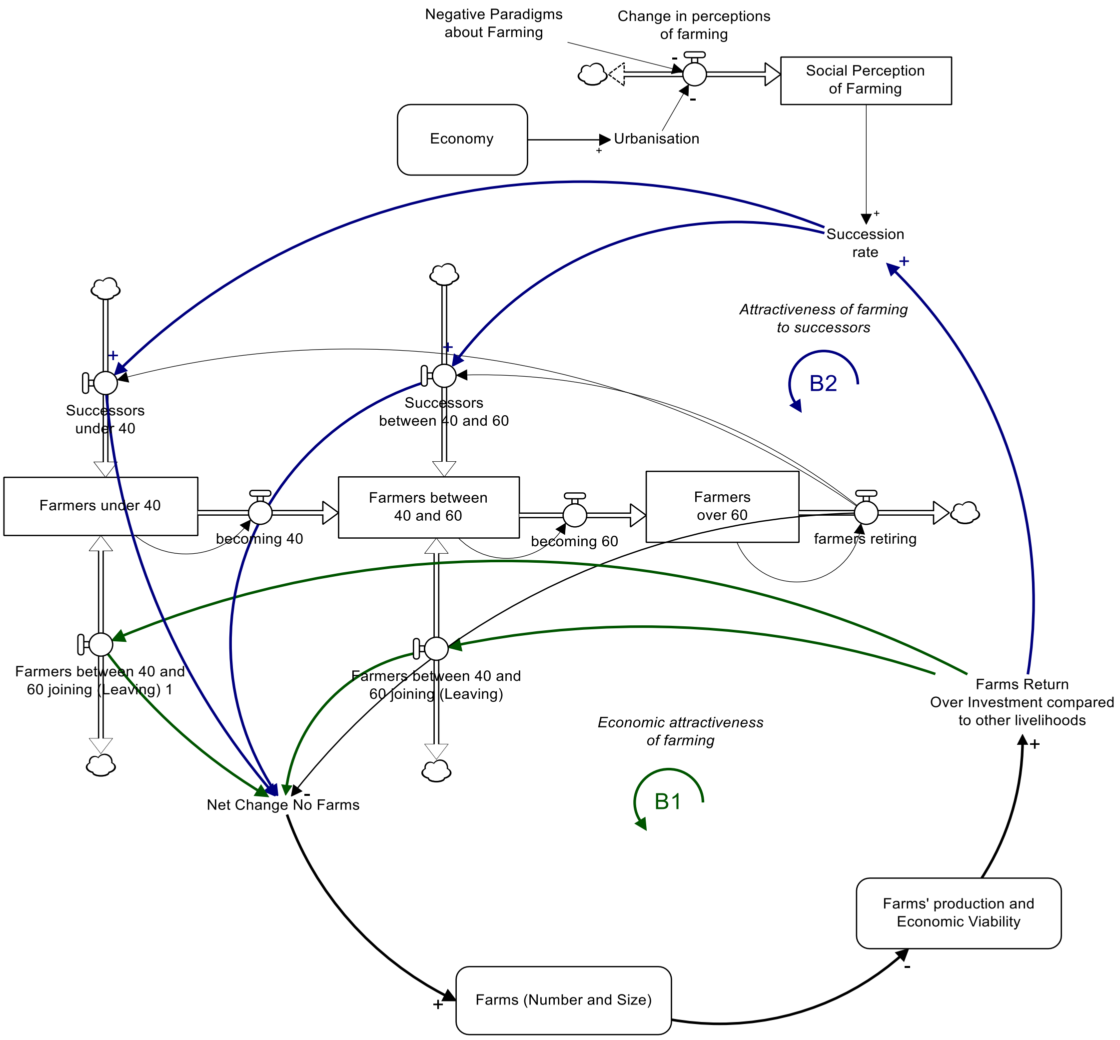


Figure 4.4: A causal loop exploring some dynamics influencing the number of local farms in a region

We use a similar logical for the attractiveness of farming to successors (see B2 in Figure 4.4). In this case, the likeliness of new generations taking over ('succession rate' in Figure 4.4) increases if the returns are high. However, there are also other factors affecting the 'succession rate' like paradigms about farming an rural life, gender stereotypes and increasing urbanisation of rural areas. We group those factors in a variable call 'social perception of farming'. In our model this variable is mainly driven by factor outside the boundaries of the model (exogenous factors).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The size of the farms: We use a similar level of abstraction to explore some of the dynamics affecting the size of farms [ha/farm]. In the model we focus on economies of scale (R1 in Figure 4.5) as drivers for larger farms. Namely, we focus on how the pressure for cutting costs encourages farmers to acquire more land, increase their production and maximize the return on their assets (e.g. equipment).

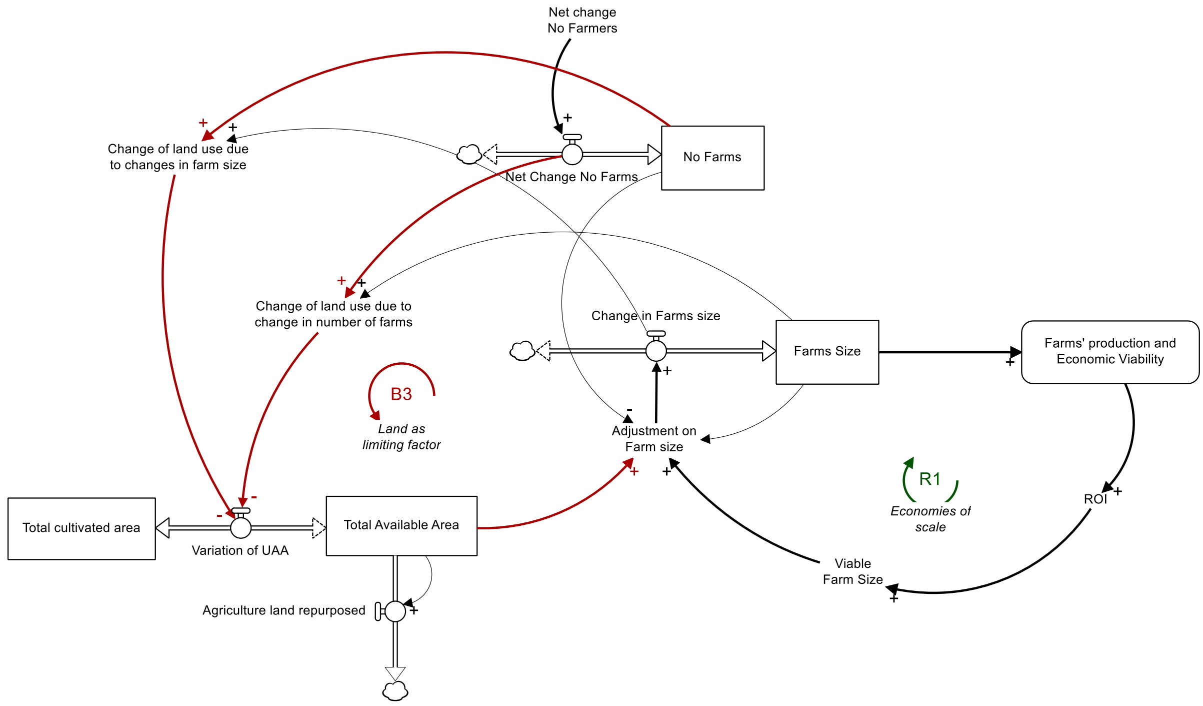


Figure 4.5: A causal loop exploring some dynamics influencing the size of farms in a region

However the increase on the farms' size is constrained by the amount of land available (B3 in Figure 4.5) and the number of farms that want it. For examples, if some farmers leave the system, there is more land available and less competition to get it. Those farmers that are still successful can acquire more land and increase the size of their farms. Urbanisation is an external factor that reduces the amount of land available as land is repurposed for other usages (e.g. housing, tourism, industry).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Mechanisation and intensification: One of the mechanisms farmers have to increase their net income is to increase their productivity. One way to increase productivity is through mechanisation and intensification. In the model mechanisation and intensification are conceptualised through the amount of capital invested in equipment and machinery, and this is only possible when farmers have enough cash (see R2 in Figure 4.6). As mechanisation increases productivity farmers have more spare cash to invest either in land (R1 in Figure 4.6) or in more equipment (R2 in in Figure 4.6). However, the benefits of mechanisation don't increase linearly forever and equipment also increases production costs (e.g. cost of maintaining equipment, depreciation, etc.) and reduces their 'return on investment' (ROI) as more capital is locked down in the farm assets (B5 in Figure 4.6).

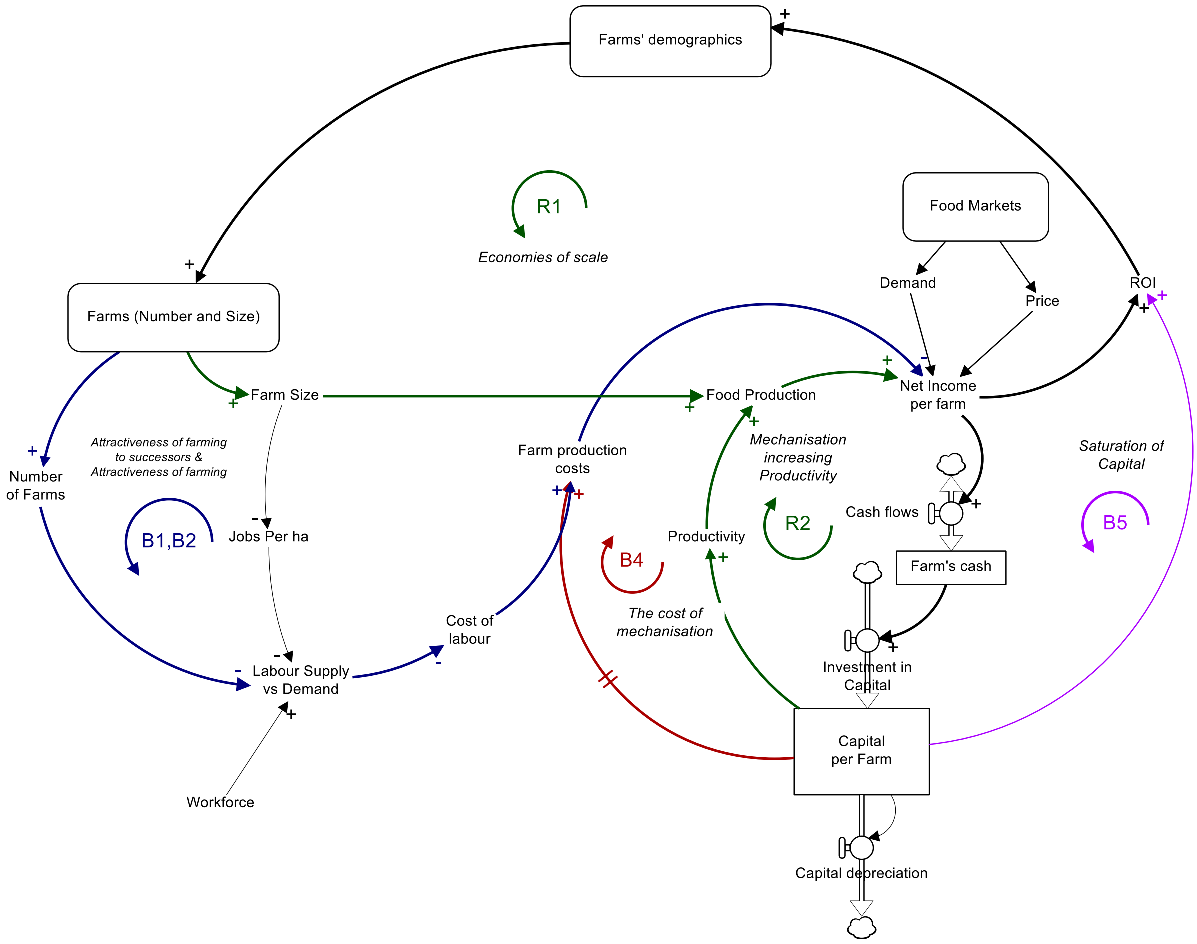


Figure 4.6: A causal loop exploring some dynamics linking farm productivity and mechanisation

Natural and human capital: Another alternative to increase productivity is through soft resources and human capital ('know-how'). Knowledge about better practices and more skilled labour results in skills based innovation, better management and more efficient usage of

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

resources (Pretty and Bharucha, 2014; Weltin and Zasada, 2018). Similar to the 'mechanisation dynamics' (R2 and B4 in in Figure 4.6). The increase of productivity in human capital generates more cash for developing even better practices (virtuous cycle R3 in Figure 4.7) but the marginal benefits of increasing know-how diminish as the cost of skilled labour increases (B8 in Figure 4.7).

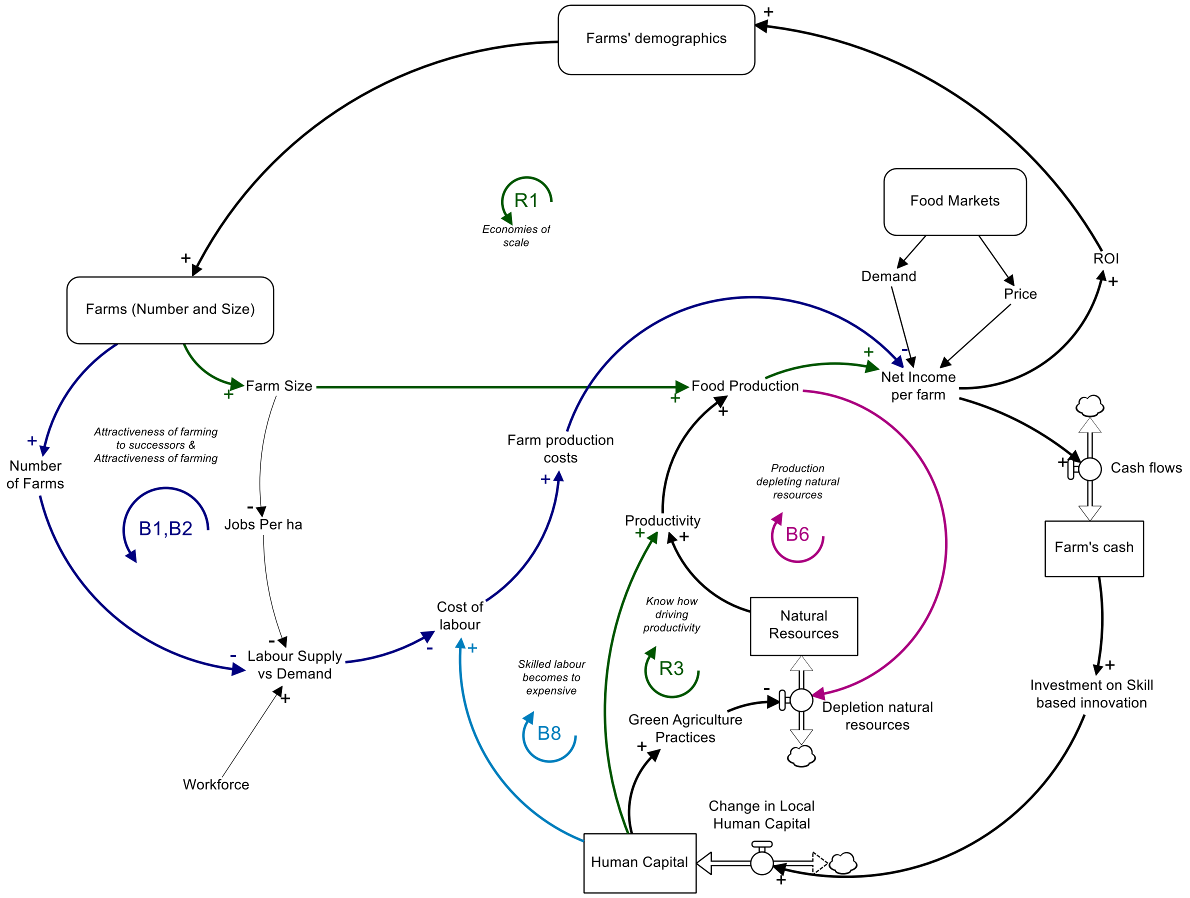


Figure 4.7: A causal loop exploring some dynamics linking farm productivity, sustainability and human capital

For simplicity we have only included natural resources as an aggregated stock, but in practice this stock represents water, minerals and organic matter in the soil and biodiversity. All of these resources provide ecosystem services to the farm that are directly related to its productivity. However, production itself depletes these resources (e.g. by taking nitrogen and phosphorus out of the soil) and there is simply so much production the system can sustain (Antonini and Argilés-Bosch, 2017; Pretty and Bharucha, 2014; Stoate et al., 2001). The constrain that natural resources put on production is represented in the model by the loop B6 in Figure 4.7.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

We argue that this is the main difference between a mechanisation and human capital driving productivity. Supported by the literature (e.g. Pretty and Bharucha, 2014; Weltin and Zasada, 2018), our model considers that mechanisation and farm intensification will increase the rate at which natural resources are depleted by increasing the farm's throughput. Skills based productivity has the same effect, but we in this case human capital can also support better resource management and green practices that reduce the rate at which natural resources are depleted.

The economy and the markets: Finally there are dynamic links between the economy, the local demand and the regional markets. There are two variables from the economy that have been included in the model gross domestic product and economic equality (see Figure 4.8). The two variables combined are affecting the average wages in rural areas and hence the cost of labour for farms and local purchasing power.

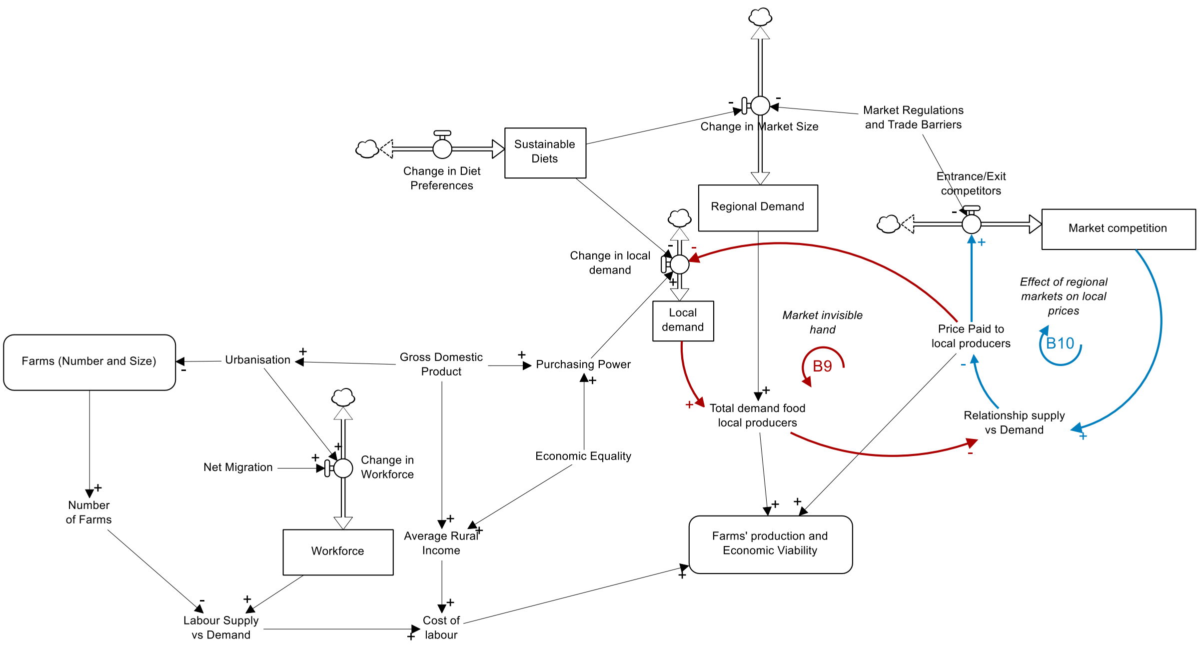


Figure 4.8: A causal loop exploring some dynamics between the economy and the food and workforce markets affecting the farming systems

If purchasing power increases, more individuals can afford more and better food. If the diet preferences remain unchanged, higher purchasing power increases the local demand. Higher demand translates eventually in higher prices which in turn reduces the amount of food affordable and hence the demand (see B9 in Figure 4.8). Higher prices also incentivise more competitors to enter in the market decreasing the prices due to competition (see B10 in Figure 4.8). These two mechanisms play together at different paces to define how much the farmers sell and how much they are paid for their products.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

4.2.1 Future of farming systems

Using the conceptual model described before, we assessed qualitatively what could be the behaviour over time of European farming systems in each of the scenarios describe. In particular we focus on the behaviour of four functions provided by farm systems:

1. Food production (the amount of food produced by the system)
2. Farm's economic viability (assessed through the farm's return on investment)
3. Jobs in farms (assessed through the amount of jobs generated by farms and the wages paid for those jobs)
4. Natural resources (assessed through the amount of nitrogen and organic matter in the soil)

The results of this qualitative analysis are briefly described next using relevant sections of the conceptual model described before. A summary of these findings is presented in Table 4.4. The results correspond to a high level analysis of the European farming systems in general. The focus of the discussion is on the structural dynamics of the system rather than specific parameters.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Causal loop diagram for Eur-Agri-SSP1

The SSP1 assumes that gross domestic products and equality will increase. A consequence of higher gross domestic product and higher economic equality, the average rural income increases and so do the costs of farming. This increase in production costs together with a reduction of the demand due to more sustainable diets puts pressure on farmers to look for economies of scale. However, tighter regulations regarding land usage damp the increase on farm's size (B4 in Figure 4.9). This is compensated by higher commodity as consumers are willing to pay for the ecosystem services provided by farmers and the costs of maintaining natural resources.

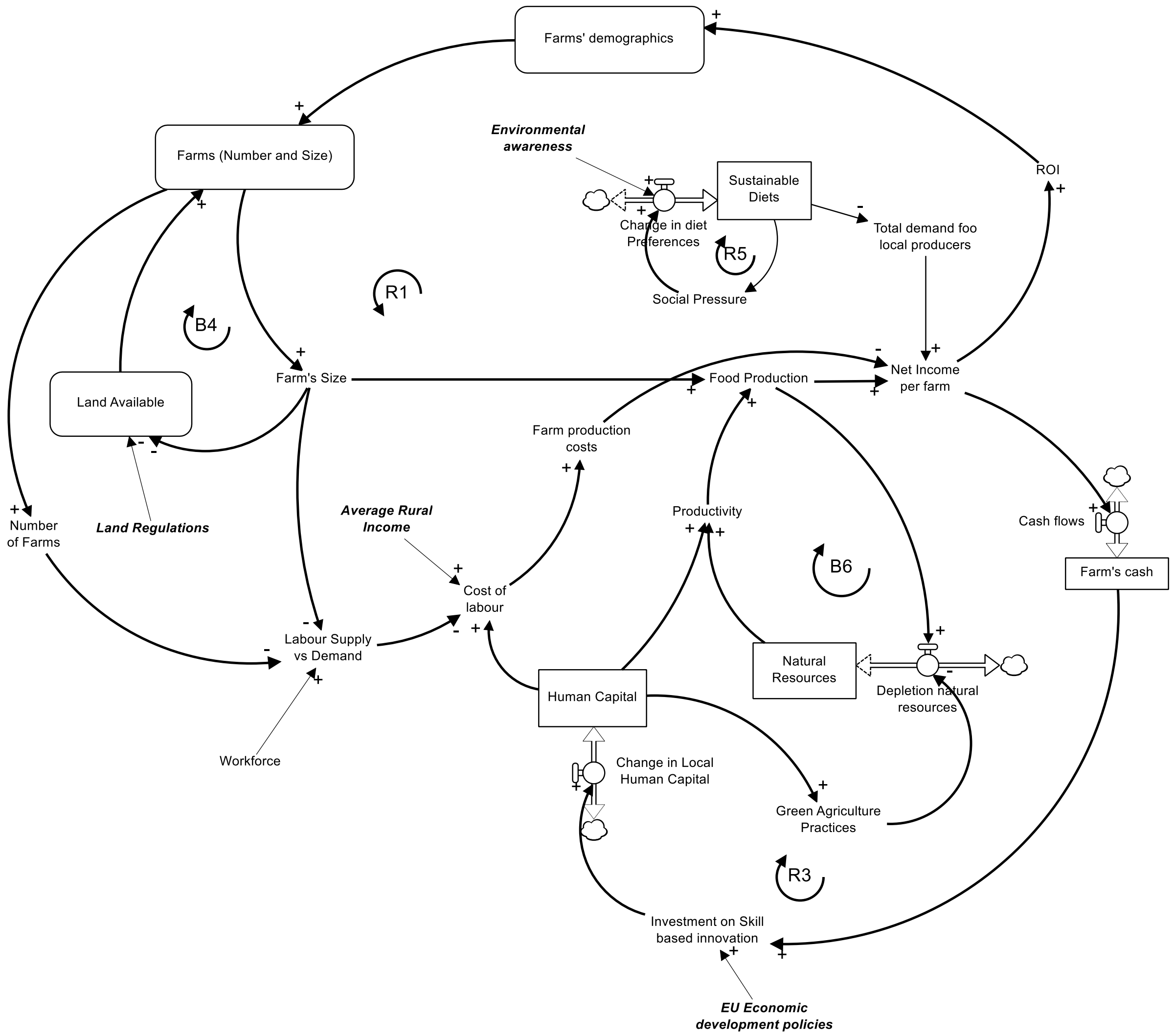


Figure 4.9: A causal loop diagram presenting some important dynamics considered to estimate potential behaviour of European systems for the SSP1-Sustainability

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

However, policies for economic development in the rural areas enabled by high gross domestic products, result in higher human capital. Higher human capital allow for innovation, better and more environmental agricultural practices increasing long term productivity (see R4 in Figure 4.9). Higher productivities driven by good natural resource management and skill based innovation result allow incomes to go back to previous levels increasing the number of farms.

The future of EU farming systems in this scenario SSP1 could be expected to have a large number of small highly productive farms producing mainly for local markets. The farms are likely to have moderate returns and its productivity could be expected to be driven by skills and good management of natural resources rather than mechanisation.

Causal loop diagram for Eur-Agri-SSP2

This scenario seems to be close to the business as usual scenario for many farming systems in Europe. The system is mainly driven by the pressure of external markets and the need to become more competitive. This drive for competitiveness moves the system towards larger and more mechanised farms (see R1 and R2 in Figure 4.10).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

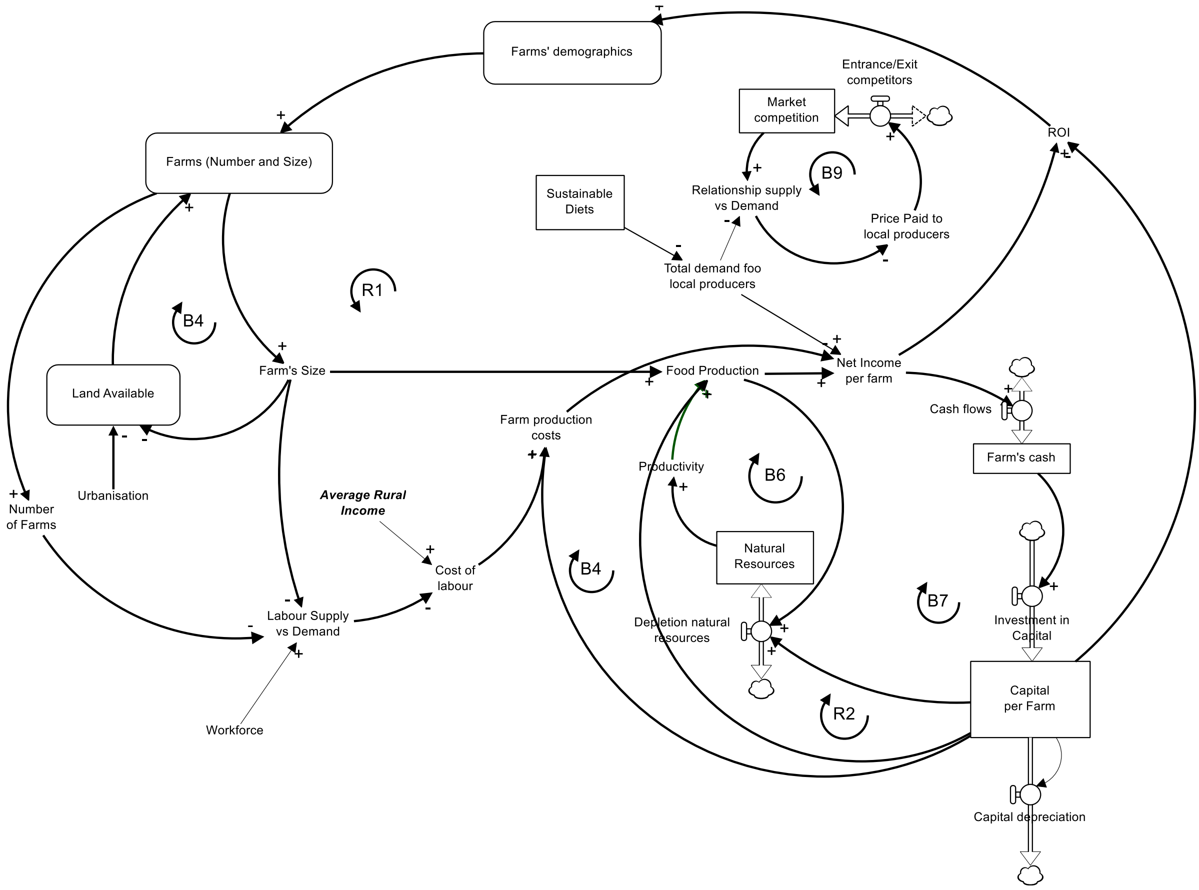


Figure 4.10: A causal loop diagram presenting some important dynamics considered to estimate potential behaviour of European systems for the SSP2-Middle of the road

However, the system is constrained by the land available for agriculture (see B4 in Figure 4.10) as households move away from rural life styles and successors transform old farms into other activities (e.g. tourism, housing, etc.). The gains of mechanisation also diminish as the need for capital and maintenance costs keep going up and the intensive usage of natural resources exhaust soils and water (see B6 and B7 in Figure 4.10).

The future of EU farming systems in this scenario SSP2 could be expected to be a combination of medium and large farms increasingly mechanised. In this scenario, farms are likely to be dependent of international markets and prices are volatile. Urbanisation might constrain farmers desired to scale farm's size up.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Causal loop diagram for Eur-Agri-SSP3

The behaviour of the farming systems in this scenario is driven by the consequences regional rivalry has in three components of our model. The first is the reduction of gross domestic product (GDP). A lower GDP is expected to result in lower average rural incomes. Lower average rural incomes will in turn reduce the production costs of farming and, if other conditions would remain the same, farming will become more attractive (see B1 and R1 in Figure 4.11). In an economically constrained environment with less opportunities, more successors might be compelled to take over the farms (see B2 in Figure 4.11). However, lower GDP also reduces the local's purchasing power. Lower purchasing power reduces local demand reducing the strength of the previous dynamics.

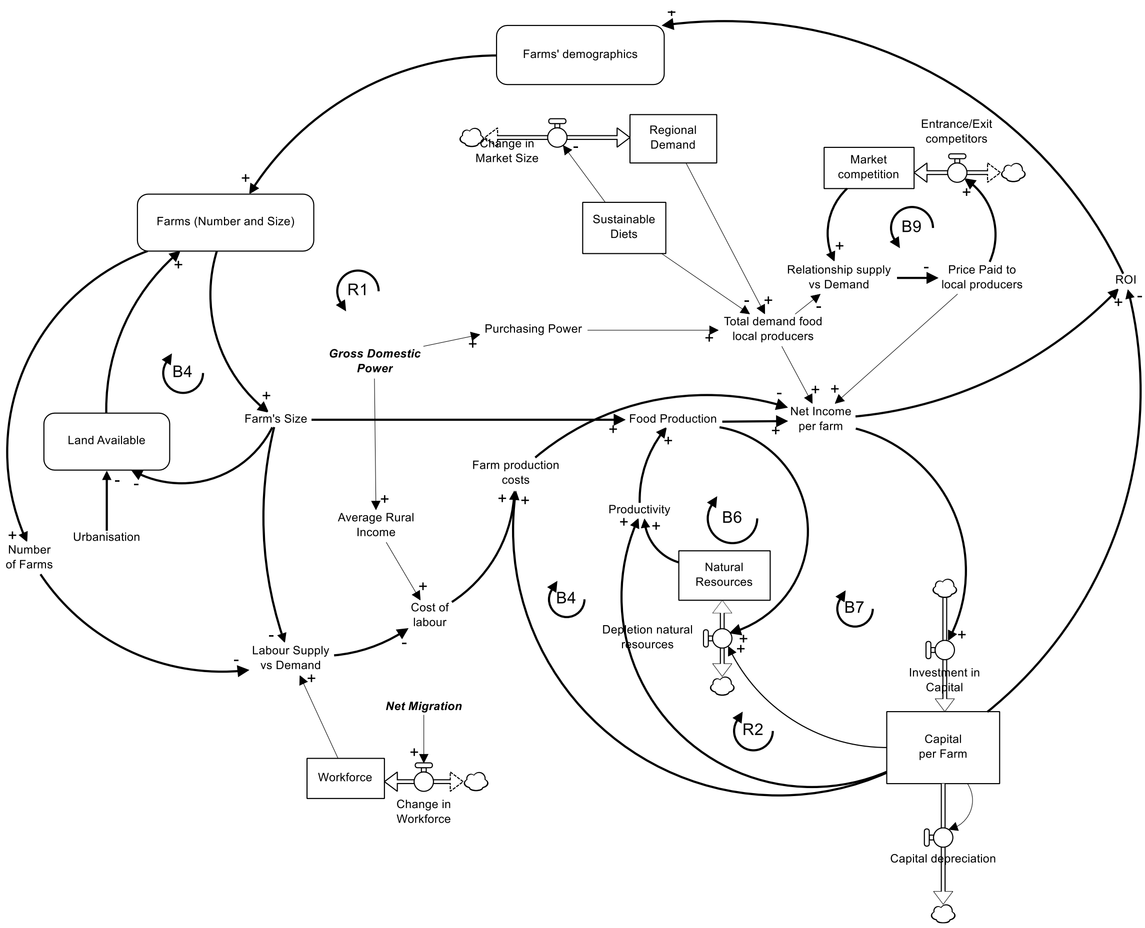


Figure 4.11: A causal loop diagram presenting some important dynamics considered to estimate potential behaviour of European systems for the SSP3-Regional rivalry

The component driving the system behaviour is the introduction of or the increase in trade barriers. This is likely to have uneven effects across different systems as both regional demand and the market competition decreases. To those systems producing food that traditionally have

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

had local demand, the introduction of trade barrier might bring stability and higher prices (see B9 in Figure 4.11). To those systems producing products mainly for regional markets the introduction of trade barriers will represent a severe challenge.

Newer and/or tighter trade barrier could be also expected to increase the cost of capital diminishing the benefits of mechanisation against its costs (the strength of R2 vs the strength of B4 in Figure 4.11). However, lower mechanisation might be expected to reduce environmental impact of farming systems.

The final component to consider, it is the effect of regional rivalry on immigration. The access to labour is likely to constraint the number of farms and overall weaken the effects of lower rural incomes in the production costs.

The future of EU farming systems in this scenario SSP3 could be expected to have a large amount of medium and large farms with medium to low productivities. Farms are likely to produce for medium income and high income groups in their local markets and sell food to higher margins as competition is low.

Causal loop diagram for Eur-Agri-SSP4

The behaviour of the farming systems in this scenario is mainly driven by the economy and the impact of gross domestic growth in both purchasing power and the average rural income as it is distributed uneven across the population. On the one hand high inequality might reduce the production costs by keeping farming wages low making farming more attractive (see R1 in Figure 4.12). Lower labour costs could be expected to reduce the driver for investing in capital and mechanisation, which will weaken the impacts of the loops R2, B4, B6 and B7 (see Figure 4.12) and result in more labour intensive farms with lower environmental impact.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

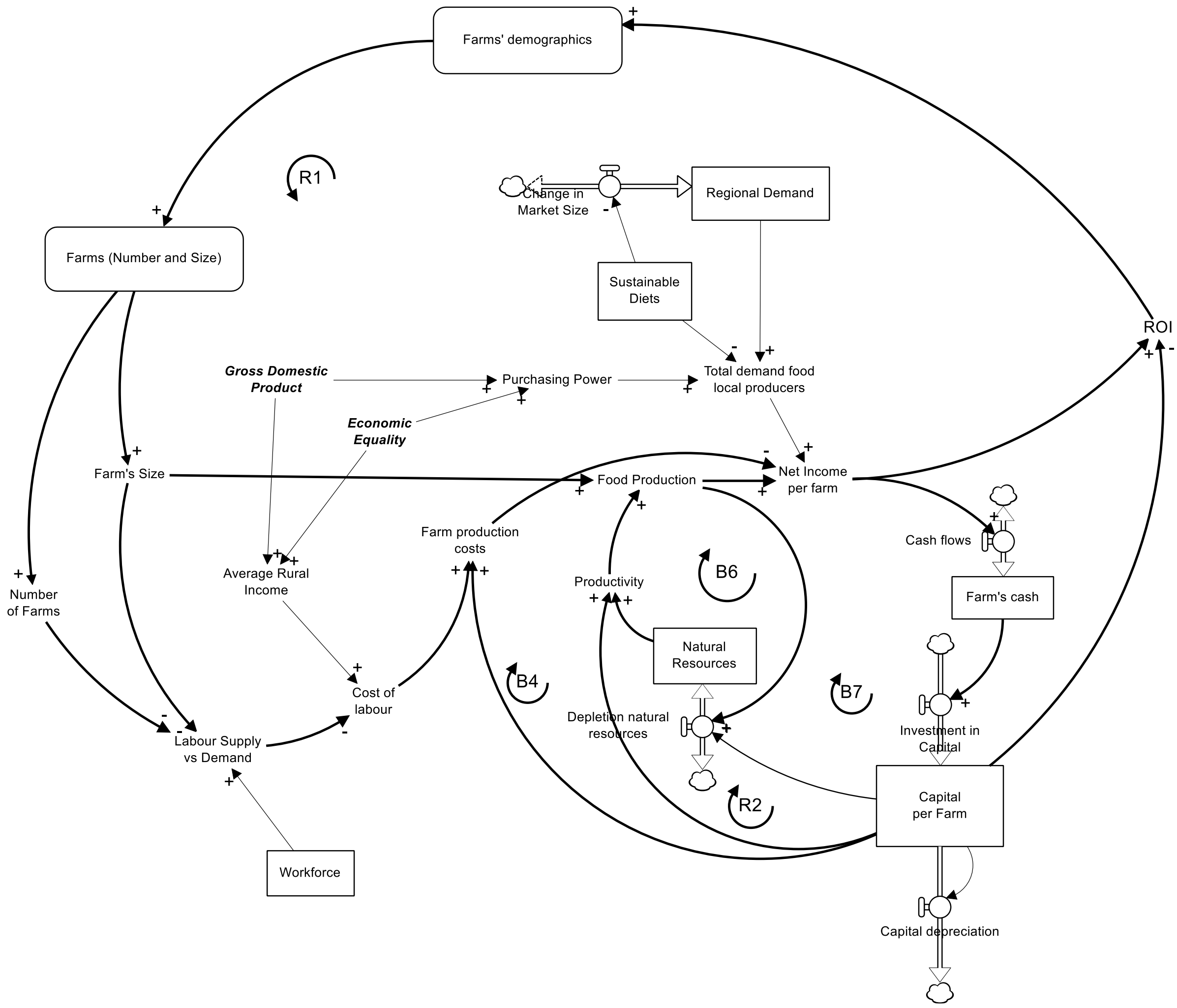


Figure 4.12: A causal loop diagram presenting some important dynamics considered to estimate potential behaviour of European systems for the SSP4-Inequality

On the other hand, inequality will reduce purchasing power and hence the demand. It will depend of the extent to which inequality affects all areas in the region in the same way, but it could be expected that most of the food production will be sold regionally rather than locally. A higher dependency on regional markets will mean lower and more volatile prices resulting from a highly competitive environment. However, since local labour could be expected to be cheap, EU farming systems might remain competitive.

The future of EU farming systems in scenario SSP4 could be expected to have many labour intense farms producing mainly for elites abroad. The dependency on the regional markets threaten the farms' economic viability, but the lack of opportunities keep farmers in the system. Availability and cost of labour is likely to make mechanisation less attractive but it could be an avenue open for the larger farms.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Causal loop diagram for Eur-Agri-SSP5

The SSP5 scenario assumes that gross domestic product will increase without major changes in income distribution versus the current position. A consequence of higher gross domestic product the average rural income increases and so do the costs of farming. Without or with lower regulations for land usage and natural resource management, the pressure for efficiencies is likely to result in both an increase on the farm's size and an increase of mechanisation (see R1 and R2 in Figure 4.13).

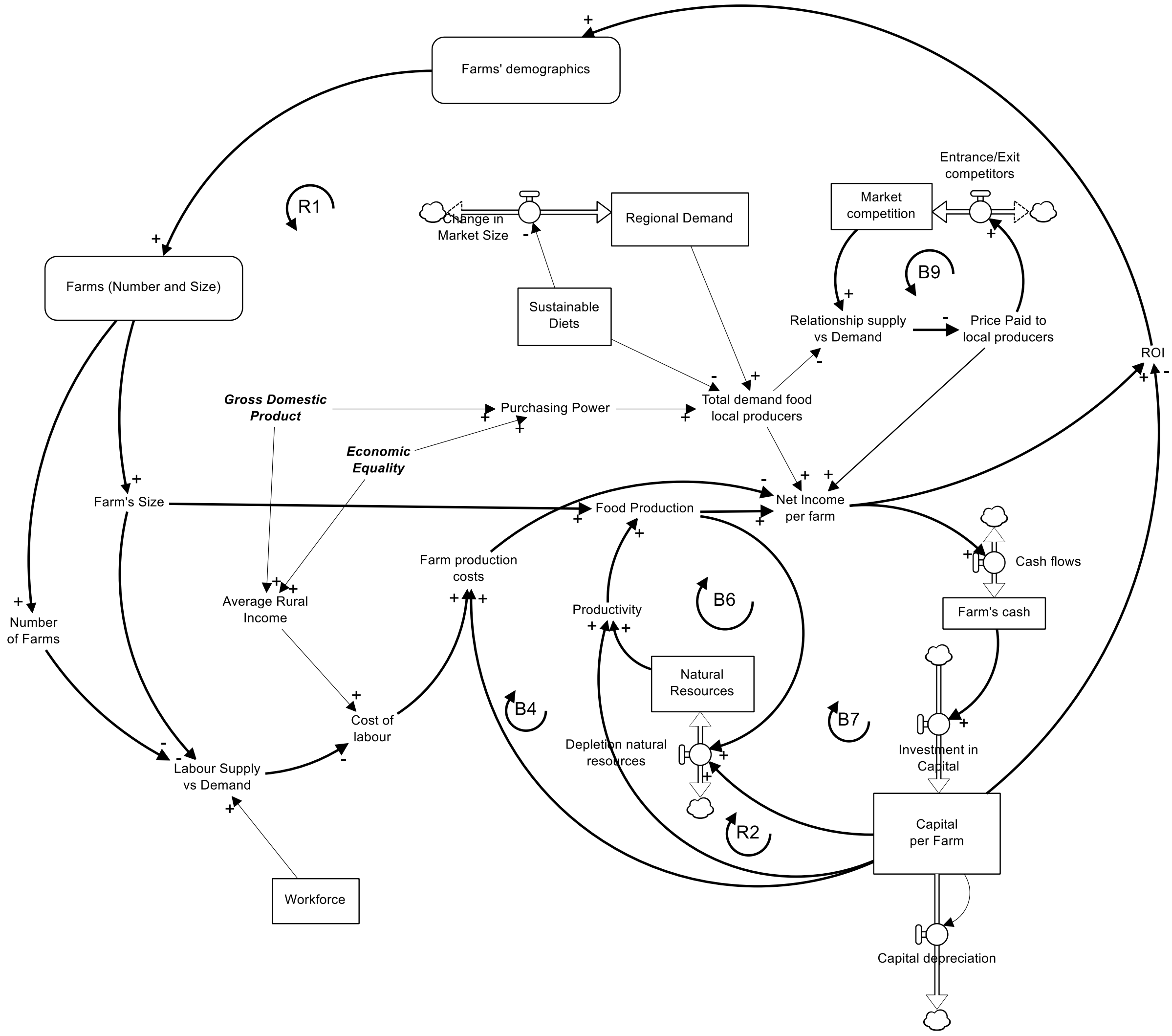


Figure 4.13: A causal loop diagram presenting some important dynamics considered to estimate potential behaviour of European systems for the SSP5-Fossil fuelled development

Highly mechanised farms will be more productive and require less labour, but they will deplete natural resources at a higher rate. Since the markets will be highly interconnected, competition

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

will be high, and prices low and volatile (see B9 in Figure 4.13). The effect of open trade might be mitigated by massive and intensive consumption. This intensive production will have a negative effect on the natural resources (see B6 and B7 Figure 4.13) making the system more dependent on chemical fertilisers and irrigation.

The future of EU farming systems in this scenario SSP5 could be expected to have a high number of large highly mechanised farms producing at low margins. The amount of family farms, small ventures and jobs are likely to decrease and natural resources could be quickly depleted increasing the system dependency on mechanisation, irrigation and fertilisers.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 4.4: Expected performance for European farming systems under each of the EU-Agri-SSP

	Food production	Farm's economic viability	Rural Jobs	Natural Resources
SSP1 Agriculture on sustainable paths	★★☆ The food production per capita is likely to decrease, specially production of animal products.	★★☆ Challenging conditions during the transition. In the long term, farming systems could be expected to be economically viable with relatively low throughputs, high productivity and high prices.	★★☆ Farms are expected to have high productivity reduced size and low throughput resulting overall on a reduction of jobs but and increase on the average wage paid to farmers.	★★★ Lower production, better practices and innovation will help to preserve farms' natural resources.
SSP2 Agriculture on established paths	★★☆ The food production likely to remain as it is since there are not major incentives for increasing productivity.	★☆☆ The viability of farms in Europe could be expected to remain relatively low as it is now..	★★☆ The total amount of jobs will decrease slightly as the amount of farms decreases. Low demand is expected to keep wages low.	★☆☆ Depletion of natural resources will continue. There is an increasing dependence on irrigation systems and fertilisers.
SSP3 Agriculture on separated paths	★★☆ The local food production could be expected to decrease in the short term but will increase in the medium and long term as the trade barriers increase. Conditions favour larger and labour intensive farms.	★★☆ The economic viability could be expected to increase as result of the reduction in the competition. However, conditions might turn challenging as local purchasing power decreases.	★★☆ Jobs in the farming systems could be expected to growth as mechanisation becomes more expensive. Low GDP and demand for skill labour are expected to keep wages low.	★★☆ Lower production and less mechanised practices will reduce the pressure on natural resources and could slow down the depletion of soil and underground water.
SSP4 Agriculture on unequal paths	★☆☆ The local food production for local consumption is likely to decrease as the local demand decreases. Most of the production for regional markets.	★★☆ Overall the low cost of labour and unemployment will keep production costs making farms economically viable.	★★☆ The total amount of jobs will decrease as the amount of farms decreases. Low demand and inequality is expected to keep wages low.	★★☆ Lower production and less mechanised practices will reduce the pressure on natural resources and could slow down the depletion of soil and underground water.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	Food production	Farm's economic viability	Rural Jobs	Natural Resources
SSP5 Agriculture on high-tech paths	★★★ While food demand is likely to increase, the local food production in Europe is likely to decrease due to the competition. Farms concentrate and intensify.	★☆☆ The economic viability of farms will be low. Local farms will require high productivity and economies of scale to compete	★☆☆ The total amount of jobs could be expected to decrease as result of mechanisation and a decrease in the number of farms	☆☆☆ Depletion of natural resources accelerates. There is an increasing dependence on irrigation systems and fertilisers. Biodiversity is lost as consequence of large monocultures.

4.2.2 Assessing future resilience of European farming systems

To assess the potential responses of the system we used our model to explore the elements of thee system that are likely to be affected by a disturbance and which dynamics in the system might be directly affected by the shock. Note that since we focus on the local farming systems, the dynamics we explore are the internal ones rather than external dynamics (e.g. markets balance, effect on the economy, etc.).

For instance, Figure 4.14 shows how we introduce a climate change disturbance (e.g. increasing droughts) in the model. While climate change is likely to have multiple and unpredictable effects in different parts of the system, the obvious effect for farming systems is a likely increase on weather variability with extreme seasons (droughts and flows). The changes in the weather conditions are already affecting yields in many areas and prolonged droughts are reducing the productivity of livestock farms (see Figure 4.14).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

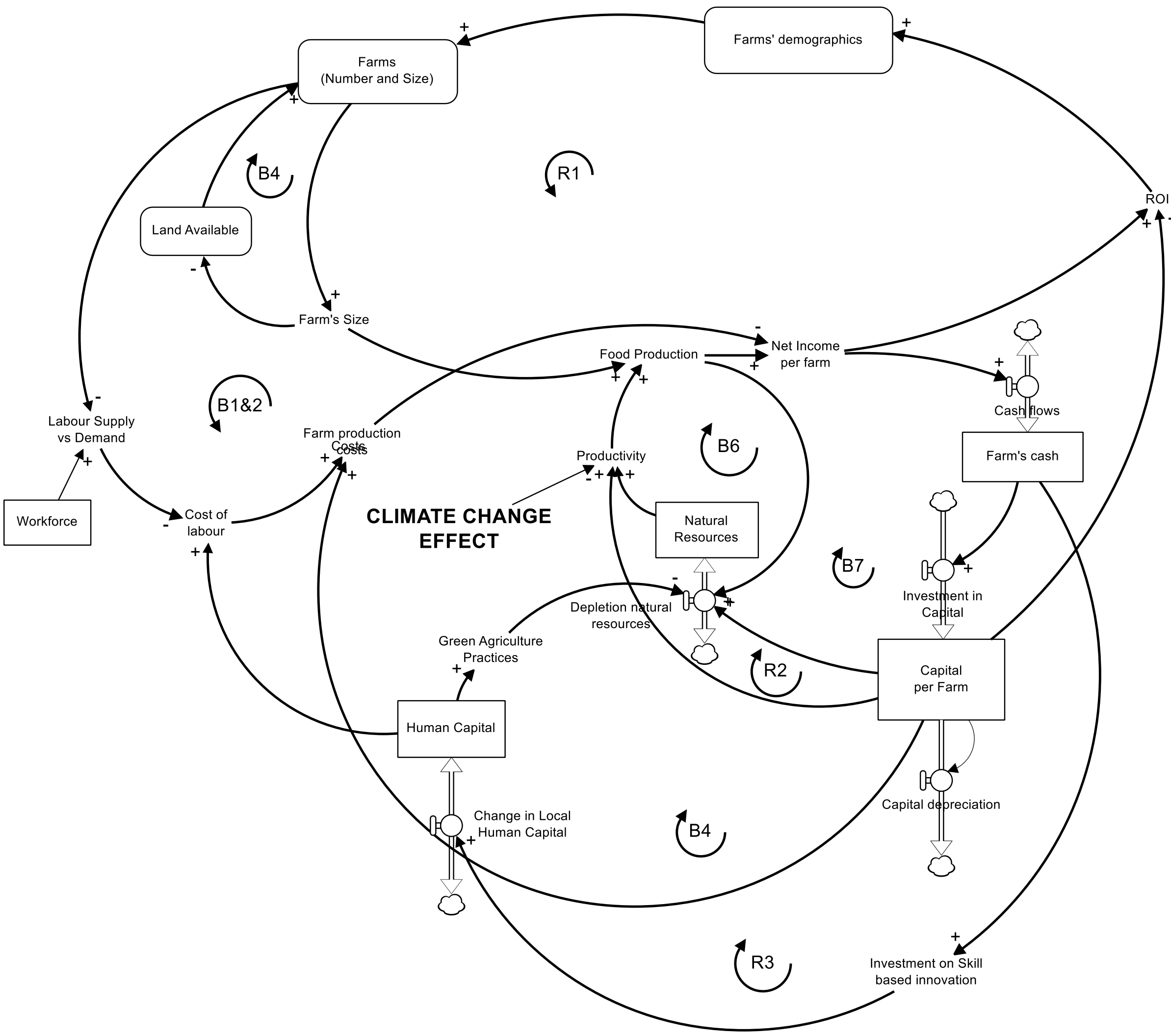


Figure 4.14: Effect of climate change in a farming system

Based on previous studies (e.g. Mall et al., 2017, Van Passel , 2017; More and Lobell, 2014) and in order to keep the analysis simple we have assumed that the effect of climate change will, for farming systems, mainly manifest as a variation of the system productivity. Lower productivities will reduce margins and will make farming less economically attractive bot to new entrants and successors (B1 and B2 in Figure 4.14) pushing the farms to evolve into more efficient configurations.

The conceptual model can then be used to explore what are the pathways towards these more efficient configurations. For the climate change challenge described before we used the conceptual to identify three alternatives developments the system could adopt to respond to disturbance diminishing its outcomes:

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

- A1: Increase in size trying to take advantages of economies of scale (R1). This reconfiguration requires three key resources: land, capital and cash availability.
- A2: Focus on mechanisation and automation (R2). This reconfiguration requires three key resources: farm's capital, farm's cash and workforce availability (to keep costs low).
- A3: Focus on skill based innovation (R3). This reconfiguration requires four key resources: farm's cash, workforce available, natural resources (to support high productivity without mechanisation) and human capital.

In practice, farm systems are likely to pursue a combination of the above rather than a single response. To which extent and how successfully each system could implement these responses depends to a large extent on the resources available in the system at the time the climate change disturbance is introduced . Using the conceptual model, we identified some key resources necessary to implement each one of the responses identified and used our scenario analysis to estimate at which level they might be in each of the EU-Agri-SSPs. The summary of this assessment is presented in Table 3. Note that, while 'farm's cash' is a key enabler for all of the responses, other resources are needed to implement any response.

Table 4.5: Expected status of key resources for each EU-Agri-SSP

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Land available	A1	Low	Moderate	Moderate	High	High
Farms' Capital	A1 A2	Moderate	High	Low	Low	Very High
Farm's cash	A1 A2 A3	Moderate	Low	High	High	Low
Workforce available	A2 A3	Moderate	Moderate	Low	High	High
Natural Resources	A3	Very high	Low	Moderate	Moderate	Low
Human Capital	A3	High	Moderate	Low	Low	Moderate

By looking at the likely state of the key resources in each of the scenarios we can make inferences of how successful farmers could be pursuing each of the three alternative reconfigurations. Increase on size (A1) will be difficult in SSP1 as land regulations will limit the amount of land available for agriculture. Similarly, it will also be difficult to have large farms in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

the SSP3 as capital and technification could be expected to be low as a consequence of having more trade barriers and less regional cooperation and in the SSP2 because there is not enough cash to afford the transition. Alternatively, Rec1 seems to be more feasible in SSP4 and SSP5 where land would be available and probably cheaper than in any other scenario.

To focus on mechanisation and automation (A2) is the natural evolution of farming systems in the SSP2 and SSP5. In these scenarios farmers have already invested in mechanisation and automation. A natural response will be to use technical innovation to overcome climate change challenges (e.g. using genetically modified varieties that require less water, capturing water in new ways, building flood defences, etc.).

For SSP3 and SSP4 it will be difficult to implement A2 as mechanisation and automation are not expected to be high in either scenario. High levels of liquidity and cheap labour make this probably more feasible in the SSP4 than the SSP3 where regional rivalry had constrained access to workforce and new technologies.

The success of this alternative would only be limited by farmers cash and access to credit. In SSP1 this strategy is less appealing as farmers have not focused on technification. However the conditions would be set for making a combination between A2 and A3 developing eco-friendly technologies that help to deal with the challenge.

Skill based innovation (A3) will be difficult in all the other scenarios, with some possibilities in SSP4 and SSP5 where there is a big workforce available and affordable. SSP5 could have the advantage that sense as economic conditions would have helped to create human capital through a more qualified (educated) workforce. On the other hand, in the SSP5, natural resources needed to successfully implement A3 will be scarce after many years of fossil-fuelled growth. Rec3 will a difficult transition in the SSP2 and SSP3, since workforce will be limited in both and human capital will be low SSP3 and natural resources will be depleted in A2.

In short, SSP5 and SSP1 seem to be the scenarios where farms could be expected to be more resilient. The scarcity of natural resources in the SSP5 might compromise its overall sustainability but if technical innovation could keep the pace with it farmers might be able to adapt using a combination of the three responses. The challenge in SSP1 could be the cost of keep pushing skill base innovation further as know-how and labour will become more expensive and the demand for food will keep decreasing. However, a movement towards green technification of farms could open enough opportunities for adaptation.

In the SSP2 farms seem to be kept in an unstable stability domain. Without intervention, climate change is likely to result on an increase on farm's size (A1) and mechanisation (A2) as

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

alternatives for adaptation. If this will be the case, the farms in SSP2 would look a lot like those in SSP5 (if other parts of the economy experience high growth) or SSP4 if economic growth is uneven and social justice neglected.

The lower costs of labour, high prices and margins make us think that farmers in SSP4 could, in theory, be resilient to some extent. The extent to which farmers could be resilient in SSP4 will be driven by the speed at which they could transform their financial liquidity into more efficient systems by pursuing any of the three expected responses. Nevertheless, looking at the wider context, in challenging conditions farmers in the SSP4 would probably move to other industries where the risk is lower rather than strive to keep their farms. This possibility not explored in detail in our model makes SSP4 less resilience.

Finally, farmers resilience to climate change in the SSP3 is likely to be the lower. In this scenario farmers have limited access to technology, labour and know-how, making it difficult to implement A2 and A3. Even more, market conditions could discourage them to keep innovating as they would experience low competition. With trade barrier taking advantage of economies of scale will also be difficult. Local market dependency on local production will keep farmers in the business but food production and prices will have low resilience to climate change.

Next, we perform a similar analysis on sub-set of individual case studies of the SURE-Farm project. For the analysis we use desired alternatives for the system proposed by stakeholders from each case during the FoPIA-SURE-Farm workshop 2. More details regarded FoPIA-SURE-Farm workshop 2 presented in the corresponding chapter of this deliverable.

4.2.3 Assessing future resilience of selected case studies of the SURE-Farm Project

Using stakeholders input and with help of the conceptual model we identified some of the key enabling resources needed to successfully implement the alternatives proposed. Following the same approach than the one illustrated before for climate change alternatives, we used the model to explore how these enabling resources are likely to develop in each scenario. Based on the excepted development of these resources we draw some insights about how feasible alternatives are likely to be and what enabling strategies could contribute to their success.

Next, we present the results of this analysis. It is important to note that during the workshop participant also made an assessment of the compatibility of the proposed strategies against the same scenarios. Their assessment and the analysis presented next are complementary as the latter offers a systemic view that is often difficult to grasp without having a former model and the former offers a level of realism that is not possible to capture in the model.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Mixed farms in the Altmark region Germany

The “Altmark” region is located the North of the German federal state “Sachsen-Anhalt,” which is in the East of Germany, and consists of the two districts “Stendal” and “Altmarkkreis Salzwedel”. The structure of the agricultural production system reflects the large-scale agricultural structures of East German agriculture but also comprises small farm structures. In the Altrmark most of the utilized agricultural area is used by mixed farms, while the highest number of farms are the arable farms.

In addition to the status quo, stakeholders in the Altmark proposed the following alternatives during the FoPIA-SURE-Farm workshop 2: GE-A1 organic farming, GE-A2 better societal appreciation and GE-A3 intensification. The resources identified in the model as key enablers for each of these alternatives and its expected status in each of the EU-Agri-SSPs is presented in Table 6

Table 6: Expected status of key resources for each EU-Agri-SSP in the Altrmark, Germany

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Natural Resources	GE-A1	Very high	Low	Moderate	Moderate	Low
Environmental awareness	GE-A1 GE-A2	Very high	Moderate	Moderate	Moderate	Low
Farms’ Capital	GE-A1 GE-A2	Moderate	High	Low	Low	Very High
Farm’s cash	GE-A1 GE-A2 GE-A3	Moderate	Low	High	High	Low
Human Capital	GE-A1 GE-A2 GE-A3	High	Moderate	Low	Low	Moderate
Food market	GE-A3	Low	Moderate	Low	High	High

By analysing the resources needed for the alternatives proposed by the stakeholders we can hypothesise that the scenario SSP1 is more favourable for all the alternatives proposed. In particular, the SSP1 offer ideal conditions for GE-A1 (organic farming) as natural resources and environmental awareness is expected to be high in these scenarios. GE-A3 (Intensification) is less likely to be successful in the SSP1 as the food consumption is expected to be lower and there will be a preference for locally produced food.

Moderate success could be also expected for the GE-A3 (intensification) in the SSP5. In this scenario, is the lack of liquidity the main constraint for success. Analysing the model liquidity is

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

expected to be low because intense competition is likely to reduce margins. As an alternative, policies increasing farmers access to credit mechanisms could increase the feasibility of GE-A3.

The challenges for successfully pursuing any alternative in SSP2, SSP3 and SSP4 suggest that substantial changes will need to be made in the system. While we don't propose that the alternatives proposed by stakeholders are not feasible external actions will need to be taken to build some of the necessary resources.

Intensive livestock farms in the Bourbonnais, France

The Bourbonnais region (coinciding more or less the department of Allier as shown is located in Central part of France, and traditionally dominated by extensive beef production systems (56% of the farms in the region). The average total size of the beef farms is 88ha, which is quite big for the region. Most of the revenues perceived by these farms has traditionally come from sells of weanlings (male and female) to the Italian market.

In the case of the Bourbonnais it was not possible to get stakeholder together due to the COVID-19 pandemic. As an alternative the case study leaders conducted a desktop study with help of subject matter experts in the region regarding the questions thar were to be answer by stakeholders in the FoPIA-SURE-Farm workshop 2. As part of this exercise they proposed the following alternatives for the system: exporting all production (FR-A1), focusing on the French market (FR-A2) and combining agro-tourism with farming (FR-A3).The resources identified in the model as key enablers for each of these alternatives and its expected status in each of the EU-Agri-SSPs is presented in Table 4.6.

.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 4.7: Expected status of key resources for each EU-Agri-SSP in the Bourbonnais, France

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
International market	FR-A1 FR-A3	Low	Moderate	Low	High	High
Farm's cash	FR-A1 FR-A2 FR-A3	Moderate	Low	High	High	Low
Local market	FR-A2 FR-A3	Moderate	Low	Very High	High	Low
Natural Resources	FR-A3	Very high	Low	Moderate	Moderate	Low
Human Capital	FR-A3	High	Moderate	Low	Low	Moderate

By analysing the resources needed for the alternatives proposed by the stakeholders we can hypothesise that FR-A1 (exporting all production) is likely to be successful in the SSP4 and SPP5 as the key driver is the international demand. Analysing the system development FR-A1 looks like a natural development of the system within those scenarios as all the conditions are ideal for focusing on exporting high quality meat to foreign markets.

Similarly, FR-A2 (focusing on the French market) is a natural alternative in SSP3 and likely to be successful as all conditions favour it. FR-A2 might also be a good alternative in SSP4 if French farmers manage to position their product among elites. However, in SSP4 they will face competition from foreign producers and price could be expected to be more volatile. Moderate success could be also expected for this alternative in the SSP1, mainly because in this scenario meat consumption is low.

Finally, FR-A3 (combining agro-tourism with farming) seems feasible in SSP1 if farmers comply with potential consumer expectations in terms of animal wellbeing. As with FR-A2, sustainable diets and lower consumption of meat is likely to damp FR-A1 success. Moderate results could be also expected for SSP3 and SSP4. In these scenarios, farmers might find challenging to find qualified staff to deliver this alternative.

Extensive livestock farms in Huesca, Spain

The case study area is in the North East of Spain in the province of Huesca. Agriculture accounts for the 12% of the gross added value of the region. The extensive sheep sector is a traditional agricultural practice that is strongly decreasing in the region.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

In addition to the status quo, stakeholders in the Huesca proposed the following alternatives during the FoPIA-SURE-Farm workshop 2: semi-intensive farming (SP-A1), hi-technology extensive farming (SP-A2). The resources identified in the model as key enablers for each of these alternatives and its expected status in each of the EU-Agri-SSPs is presented in Table 4.8.

Table 4.8: Expected status of key resources for each EU-Agri-SSP in the Huesca, Spain

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Farms' Capital	SP-A1 SP-A2	Moderate	High	Low	Low	Very High
Farm's cash	SP-A1 SP-A2	Moderate	Low	High	High	Low
Food international market	SP-A1 SP-A2	Low	Moderate	Low	High	High
Natural Resources	SP-A2	Very high	Low	Moderate	Moderate	Low
Human Capital	SP-A2	High	Moderate	Low	Low	Moderate

By analysing the resources needed for the alternatives proposed by the stakeholders we can hypothesise that SSP1 is overall the scenario where both alternatives (SP-A1 and SP-A2) have higher chances to succeed, however the reduction in meat consumption expected as result of more sustainable diets is the major challenge for the livestock sector in general. Of the two strategies, hi-technology extensive farming (SP-A2) has probably better chances of success if innovation is oriented towards conserving natural resources.

Moderate success could be expected for the SP-A1 (semi-intensive farming) in SSP2 SSP4 and SSP5. In SSP2 and SSP5 farmers will need external support in the form of access to low cost credit as they are unlikely to have enough liquidity to invest in equipment needed for intensive farming. in SSP4 farmers will need to develop their technological capital while labour costs and demand are low. While it is feasible, the analysis suggests SP-A1 is unlikely to be attractive in comparison with other alternative (e.g. specialised and small artisanal farms offering high price products to elites).

Hazelnut farms in Viterbo Italy

The province of Viterbo, located in Lazio (central Italy), is the first Italian province in terms of hazelnut production (*Corylus avellana*). The case study includes most of the Viterbo province, excluding the coastal zones. Hazelnut production is a major economic resource in the province, and

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

it is a traditional activity: the area does not offer favourable conditions for farming, therefore hazelnut cultivation has allowed agriculture to survive, providing an income to farmers. Traditionally, hazelnuts used to be cultivated together with other species (e.g. olive trees, chestnuts, vineyards), in the south-east area of the province and particularly around the Vico lake. In the last few years, the increased market demand and competition (especially with Turkey) has led to an expansion of the cultivated area and to a modernisation of the production, with growing levels of specialisation. Therefore, most cultivations are now hazelnut monocultures, with high planting density of trees, and hazelnut farming has expanded to new areas of the region.

In addition to the status quo, stakeholders in Viterbo proposed the following alternatives during the FoPIA-SURE-Farm workshop 2: sustained demand (IT-A1) , technological innovation (IT-A2), product valorisation (IT-A3), eco-friendly agriculture (IT-A4). The resources identified in the model as key enablers for each of these alternatives and its expected status in each of the EU-Agri-SSPs is presented in

Table 4.9.

Table 4.9: Expected status of key resources for each EU-Agri-SSP in Viterbo, Italy

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Market	IT-A1 IT-A2	Low	Moderate	Low	High	High
Farm's cash	IT-A1 IT-A2 IT-A3 IT-A4	Moderate	Low	High	High	Low
Farms' Capital	IT-A1 IT-A2 IT-A3	Moderate	High	Low	Low	Very High
Human Capital	IT-A2 IT-A3 IT-A4	High	Moderate	Low	Low	Moderate
Natural Resources	IT-A3 IT-A4	Very high	Low	Moderate	Moderate	Low
Environmental awareness	IT-A3 IT-A4	Very high	Moderate	Moderate	Moderate	Low

By analysing the resources needed for the alternatives proposed by the stakeholders we can hypothesise that with the exception of the alternative IT-A1 (sustained demand), all the other

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

three alternatives (IT-A2, IT-A3 and IT-A4) are likely to be successful in SSP1. In fact, IT-A3 (product valorisation) and IT-A4 (eco-friendly agriculture) look like the ideal pathway for this system in the case of SSP1.

Implementing IT-A1 in scenarios like SSP1 and SSP3 will be difficult because the Hazelnut market is a global rather than a local market. However, for the same reasons IT-A1 could be expected to have moderate success in scenarios where there is expected a high demand (SSP4 and SSP5). However, as seen in other cases, farmers will need access to cheap credits or subsidies in order to successfully implement IT-A1 in a highly competitive environment like SSP5.

Moderate results could be expected form IT-A3 and IT-A4 in the SSP2 if farmers manage to implement environmental friendly policies on time and get enough external support. For instance, since Hazelnut has an specific market niche, it could be possible to create environmental awareness among that specific group of consumers even if the global trend goes otherwise.

Starch potato production in the Veenkoloniën, the Netherlands

The farming system in the Veenkoloniën in the Netherlands is characterized by starch potato cultivation in a rotation with cereals and sugar beets. The presence of a starch processing cooperative in the area results in a stable farm gate prices, which influences the stability of supply and demand.

In addition to the status quo, stakeholders in the Veenkoloniën proposed the following alternatives during the FoPIA-SURE-Farm workshop 2: alternative crops (NL-A1), precision agriculture (NL-A2), nature-inclusive agriculture (NL-A3), collaboration & alternative water management (NL-A4). The resources identified in the model as key enablers for each of these alternatives and its expected status in each of the EU-Agri-SSPs is presented in .

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 4.10: Expected status of key resources for each EU-Agri-SSP in the Veenkoloniën in the Netherlands

Resource	Alternative	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Farm's cash	NL-A1 NL-A2 NL-A3	Moderate	Low	Moderate	High	Low
Farms' Capital	NL-A1 NL-A2 NL-A3	Moderate	High	Low	Low	Very High
Human Capital	NL-A1 NL-A2 NL-A3 NL-A4	High	Moderate	Low	Low	Moderate
Natural Resources	NL-A2 NL-A3 NL-A4	Very high	Low	Moderate	Moderate	Low
Consumers environmental awareness	NL-A2 NL-A4	Very high	Moderate	Moderate	Moderate	Low
Farmers Networks	NL-A3 NL-A4	Very high	Moderate	Low	Low	Moderate

By analysing the resources needed for the alternatives proposed by the stakeholders we can hypothesise that all the alternatives have high changes of success in SSP1. Alternatives NL-A3 (nature-inclusive agriculture) and NL-A4 (collaboration & alternative water management) are probably natural development paths for the system within SSP1.

In SSP1, moderate success could be also expected for alternatives NL-A1 (alternative crops) and NL-A2 (precision agriculture). The alternatives NL-A1 and NL-A2 might also a have moderate success in SSP5 and SSP2 if farmers get external support like access to cheap credit and/or qualified staff.

The scenarios SSP3 and SSP4 don't seem to offer the right conditions for implementing any of the alternatives proposed. Additionally, as most of the starch potato produced in the Veenkoloniën is exported the SSP3 might prove to be a difficult environment for farmers overall.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

4.3 Quantitative analysis of future resilience

To perform a quantitative analysis of resilience, causal relationships are operationalize through mathematic equations in a computer simulation model. This model is used to simulate the behaviour over time of system functions (e.g. food production, farm size or farm income).

There is not standard process for turning a diagram into a model (often called quantification) however, there are general steps modellers follow as good practice. The steps we followed to quantify the conceptual model presented before were:

1. Identify and populate parameters or input variables: Input variables are those that are not calculated by the model itself but are provided to the model as an input so that it can calculate the remaining variables. In a system dynamics model there are often only few input factors as must variables are calculated within the model. For our case the input variables were provided by the case study partners and come from historical information available.
2. Define mathematical relationships for remaining variables: The causal relationships indicated by arrows in the model diagram are operationalise through mathematical equations. The type of equation used will depend on the on the nature of these relationships (e.g. linear, exponential, etc.). Equations 3 and 4 show example of the equations used in the model.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

$$UAA\ for\ Livestock\ and\ Grassland = Total\ UAA \times \%UAA\ used\ for\ livestock \quad (3)$$

where:

UAA for Livestock and Grassland: is the utilised agricultural area used to keep and feed livestock

Total UAA: is the total utilised agricultural area used by a farm

%UAA used for livestock: is the percentage of the total utilised agricultural area of a farm used for keeping and feeding livestock

$$Annual\ cost\ per\ LivestockUnit = Annual\ cost\ per\ ha \div LivestockUnits\ per\ ha \quad (4)$$

where:

Annual cost per LivestockUnit: is the average cost of keeping and feeding a livestock unit (LU) for a year

Annual cost per ha: is the average cost of operating a hectare of land in a livestock farm

LivestockUnits per ha: is the average amount of livestock units (LU) per hectare of the farm

3. Initialise stocks: Stocks represent variables that accumulate overtime. In mathematical terms, stocks a stock is the integral of the net flow added to the initial value of the stock, where the integral is calculated using numerical algorithms (see Equation 5). The differential part of the equation is defined by the structure (the inflows and outflows affecting the stock, but the initial value of the stock should be defined separately. More details description on how using numerical methods to calculate stocks can be found in Dugan (2016).

$$Heifers(t) = Heifers(t - dt) + (Maturing - First\_Calving) * dt \quad (5)$$

Defining the initial value of the stock is an important step of the model calibration and can be done a) using input variables (e.g. the known value of a stock at the beginning of the simulation) or, when there is not data available, b) estimating the value of the stock that will represent an equilibrium between the initial inflow and outflow rates.

4. Define simulation settings: The final step is to define the time horizon that will be simulated and the DT or time step to be used in the simulation Timelines need to be selected so that they allow to observe relevant trends for the behaviour studied. The DT is the parameter utilised by a numerical method (commonly the Euler's method) to numerically calculate the value of the stock. A smaller DT increases the accuracy at the expense of lower computational efficiency. Usually social simulations use a time step value of 1/8 or 1/16 of the time unit used (e.g. 1/8 of a year) (Dugan, 2016).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

4.3.1 Case 1: Starch potato farms in the Veenkoloniën, the Netherlands

The Veenkoloniën case study was part of Lilli Schütz's Master Thesis dissertation. This section presents a summary of her findings. For more details please see Schütz (2020).

Background

In the Veenkoloniën farming system all starch potato growers are organised into the agro-industrial cooperative called Avebe. Avebe is the only company in the Netherlands that processes starch from potatoes (Bont et al., 2007). They receive roughly half of all of their starch potato supply from the Veenkoloniën, and represent about one third of the global market share of the starch potato value chain (Strijker, 2008). Starch potato growers own Avebe shares, which come with the obligation to deliver starch potatoes to Avebe (van Dijk et al., 2019). The factories of Avebe process the starch potatoes that are produced by all share-holders and sell the resulting starch or other products for an added value on the world market. The profits of Avebe then get redistributed back to the members according to the volume and quality of starch potatoes they delivered, and the number of shares they own (Avebe, 2018).

However, the region has experienced challenging conditions in the recent past. These challenges have resulted on a significant decrease on the number of farms cultivating starch potato in the region (see Figure 4.15).

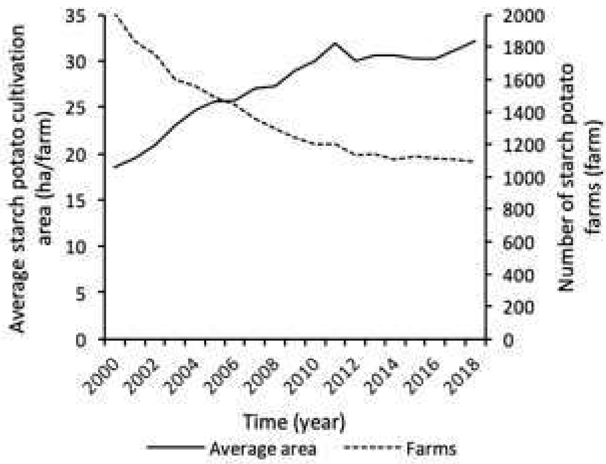


Figure 4.15: The number of specialised starch potato farms in the Veenkoloniën [farms] (dashed line – right axis) and the respective average farm size [ha/farm] (solid line – left axis) (CBS, 2019)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Resilience of what? (Outcome Functions)

In this case the analysis focuses on the resilience of i) the ability of the system to 'deliver healthy and affordable food products' ii) the 'economic viability of farms'. The former was operationalised through the variable 'starch potato production'.

The main variables driving the starch potato production are a) the potato yield, b) the fraction of potato in the crop rotation and c) the total area available for cultivation. While the first two could be considered exogenous factor, the latter is the result of complex dynamics driving farmers decision (see Figure 4.16). Hence, the effects of disturbances affecting starch potato production are not likely to be linear or easy to predict. Similarly, the economic viability of farms was assessed through the 'farms income'. The farms income depend on a) the price of starch potato paid by Avebe, b) the potato yield, c) the profits coming from other arable farms and d) the costs of starch potato farms.

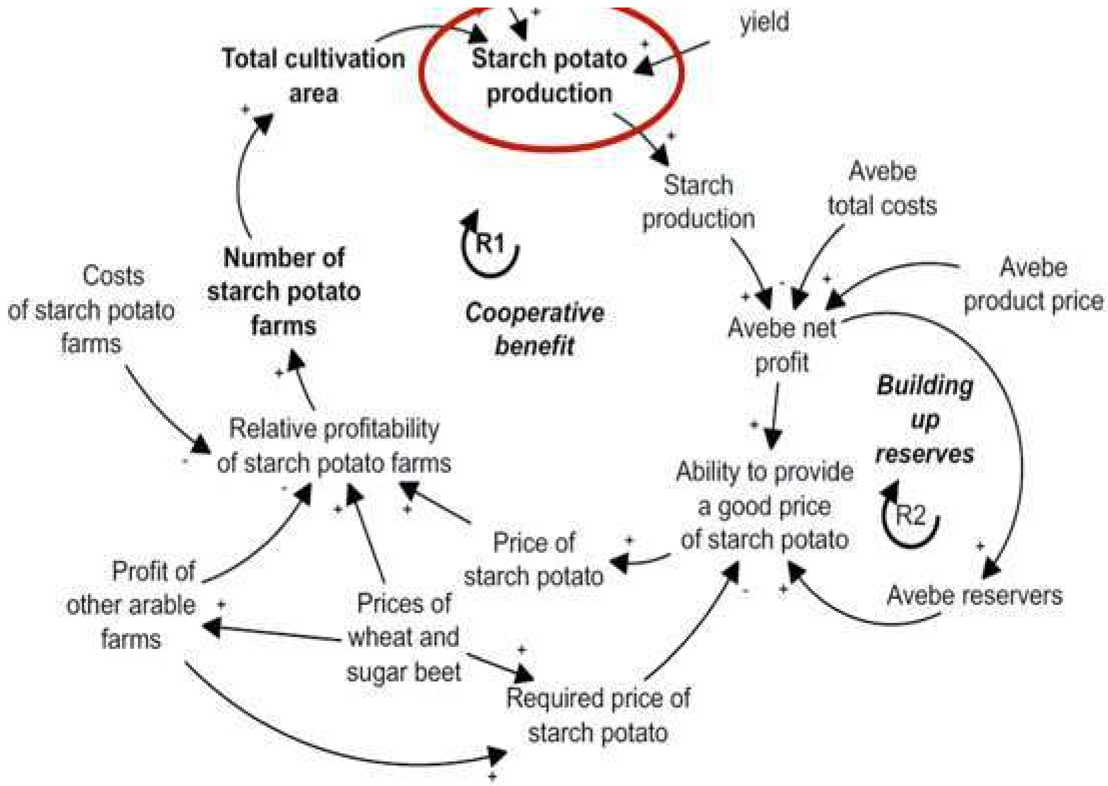


Figure 4.16: A causal loop diagram showing the main dynamics driving/constraining starch production

The model is comprised of two modules that each represent one of the two system actors: the "Starch potato farms" and "Avebe" (see Figure 4.17). The starch potato farms module represents farm number and farm size changes, based on the profitability of starch potato cultivation. The main output of this module is total starch potato production. The Avebe module

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

captures how the supply of starch potatoes from the Veenkoloniën determines Avebe's net profits and therefore Avebe's ability to offer a reasonable starch potato price to their members.

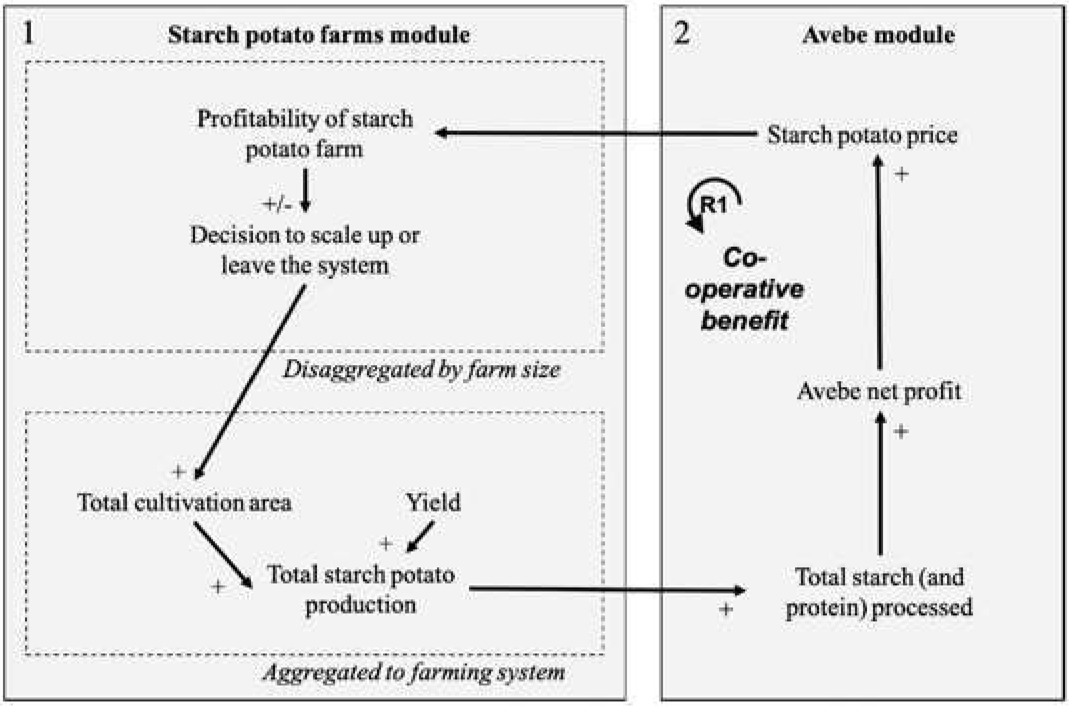


Figure 4.17: A model overview showing the two main modules that were included: (1) A module to capture how profitability of starch potato farms (including the entire crop rotation) drives the decisions of farm to either scale up or leave the system. The decisions of the farms influence the total cultivation area and therefore the total starch potato production. (2) The second module calculates Avebe's net profit (before payment to farmers) and uses this net profit to determine the starch potato price. Only if the net profit is high enough can the starch potato price be kept high enough to ensure adequate profitability of starch potato farms.

The Avebe module captures how Avebe sets the starch potato price according to the price desired by farmers, given high enough net profits. The most important assumption in the Avebe module, is that Avebe has some "reserves" to pay farmers an adequate Starch potato price [EUR/ton] even if Net profits [EUR] in one year are too low. This is possible as long as Net profits were high enough in the preceding years. Avebe's reserves are not captured by a stock. Instead, the Average net profits [EUR] are calculated for the past 3 years at each time step. These Average net profits are used to determine the ability of Avebe to pay farmers the Price of starch potato desired by farmers. The Price of starch potato desired by farmers is equal to the price that will make the profit of being a specialised starch potato farm (in rotation with sugar beet and wheat) equal to the profit of being another arable farm. Yields of starch potatoes, sugar beet and wheat, prices of sugar beet and wheat, costs of starch potato farms and profits of other arable farms are taken into account in the calculation of the desired starch potato price.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

When the Average net profits are below the value needed to pay the Price of starch potato desired by farmers, a lower price is offered. This price adjustment does not occur linearly. The degree to which the actual Price of starch potato differs from the Price of starch potato desired by farmers, is determined by a table function (see Figure 4.18). In this way, Payments to farmers reduce only moderately when Average net profits are only slightly below what would be required to pay the full price. Only when Average net profits are much less than the full desired payment, will starch potato price reduce significantly.

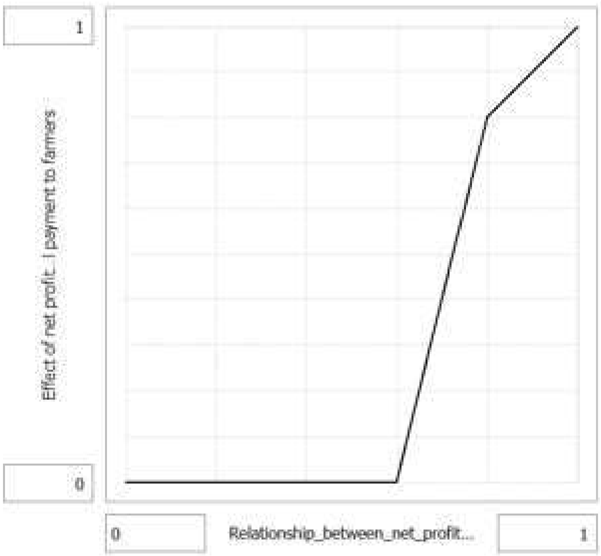


Figure 4.18: The lookup table used by the Effect of net profit on total payment to farmers variable in the Avebe module. The payment to farmers reduces linearly as net profit reduces until average net profit is 80% of the desired payment. Between 60% - 80% the payment decreases more rapidly. When net profits are lower than 60% of the desired payment, the total payment to farmers is equal to zero.

The model was calibrated against historical data following good practice. The results of the model calibration for the five selected indicators is shown in Figure 4.19.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

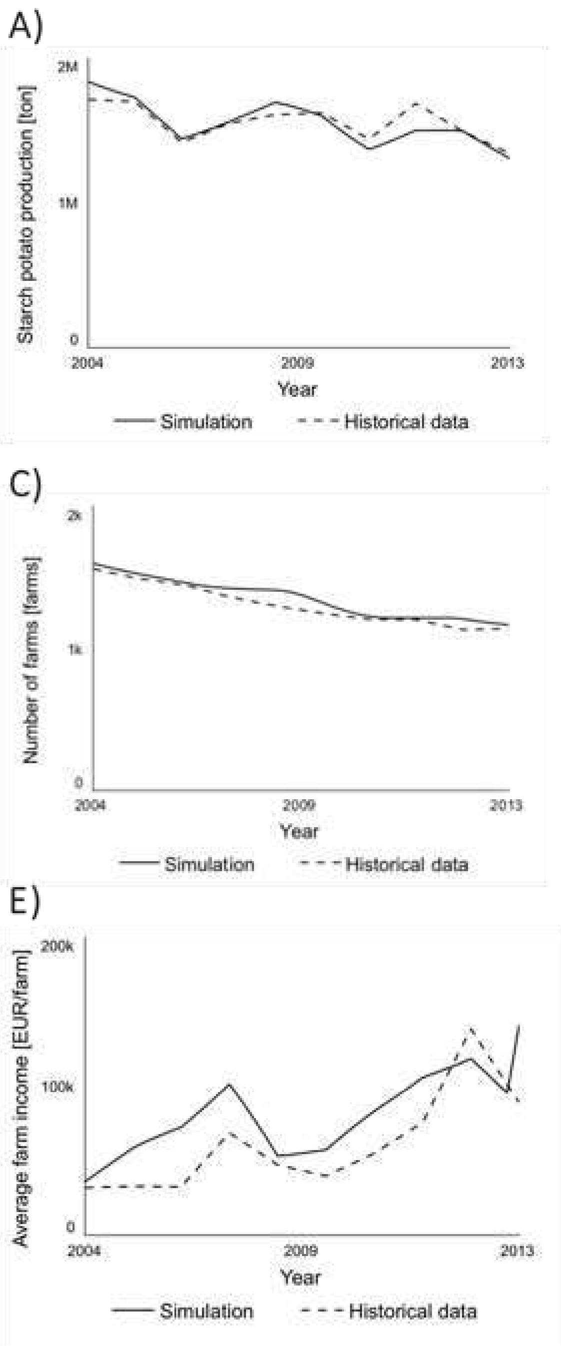


Figure 4.19: Simulated and historical behaviour for A) starch potato production [ton], B) total cultivated area[ha], C) number for farms [farms], D) average farm size [ha/farm] and E) average farm income [EUR/farm]

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Resilience to what? (Challenges)

Some of the challenges faced by starch potato farmers in the Veenkoloniën region were identified by Paas et al. (2019) during the FoPIA -SURE-Farm 1 workshop and are summarised in Table 4.11. For this analysis we focused on the system's response to five of them: C1) nematodes in the soil, C2) decreasing soil quality, C3) low water holding capacity and low drainage capacity, C4) increasing profits from other crops relative to the profits of starch potatoes and C5) high and rising costs of specialised starch potato farms.

Table 4.11: Challenges faced by starch potato farmers in the Veenkoloniën region (adapted from Paas et al., 2019)

Challenges	Economic	Environmental	Social	Institutional
(Non-) permanent shocks	Fluctuation of prices of agricultural products	**Hard winds and wind erosion in fields with young plants** Warm and wet summers increase risk of infection with Erwinia spp. or risk on second growth in potatoes. **Low water holding capacity and low drainage capacity make the region sensitive to extreme drought and rainfall.** Extreme quantities of rain in May - Sep can cause rotting in potatoes.	Mental health of farmer and his/her family	Change in agricultural policies of EC; decoupling of subsidies Ban on certain crop protection products
Long-term pressures	Low economic performance per hectare of land **High land prices and increasing rental prices** **Low prices for sugar beets because of expansion after abolishment sugar beet quota.**	**Nematodes in the soil limit crop rotations** Climate change	Number of farms in the region is going down. Long working days Shortage of farm successors Quality of hired staff is going down	Continuous change in policies and regulations Energy transition

In the model these challenges are operationalised through four disturbances (σ):

σ1: Decrease of starch potato in crop rotation due to nematode pressure (C1)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

σ2: Decrease in average yield (associated with challenges C2 and C3)

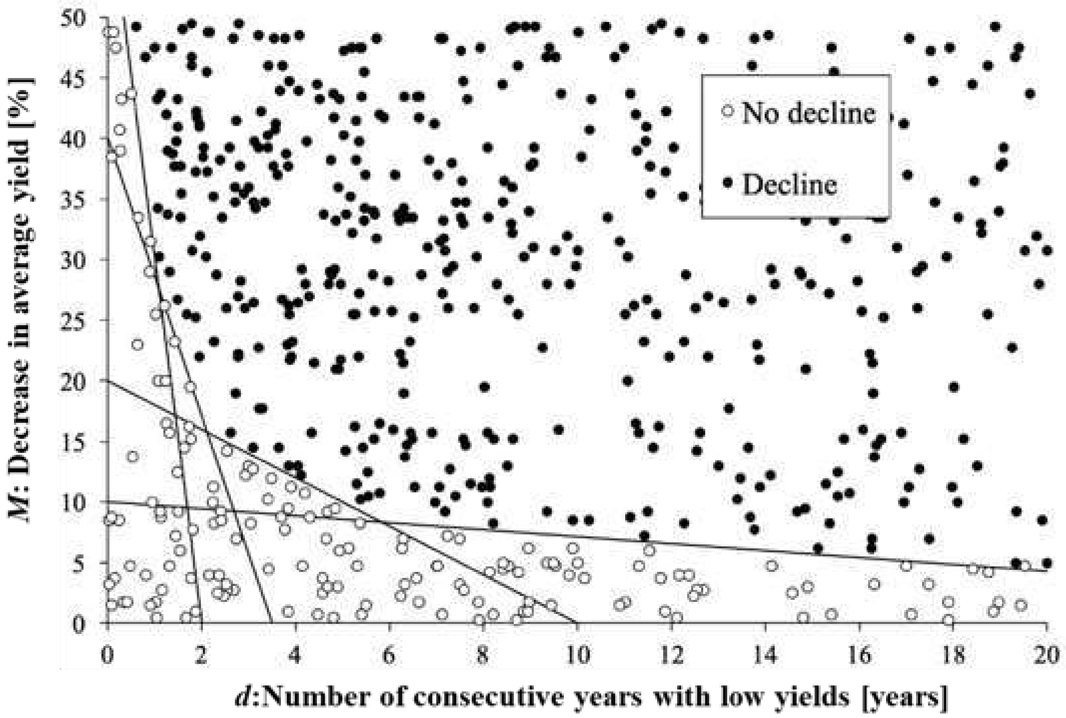
σ3: Increase in profit per ha other crops (associated with challenge C4)

σ4: Increase in production costs starch potato (associated with challenge C5)

For each of these disturbances we varied the magnitude (% of the increase/decrease) from 0% to 50% and the duration (number of years the system is affected by each σ) from 0 to 20 years. The results of testing the behaviour of starch potato production under such conditions is presented next.

Results and analysis

By testing the behaviour of starch potato production to different combinations of magnitude and duration we identify the system elasticity σ_E. As described in Table 4.2**Erreur ! Source du renvoi introuvable.**, σ_E is the magnitude of disturbance that can be absorbed before the system redefines its structure and/or changes shifts to a different stability domain and can be used as an indication of systems resilience (Gunderson, 2000). Figure 4.20 shows an example of the analysis performed for the average yield and Table 12 presents the results for the three disturbances considered.



This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Figure 4.20: The different combinations of decreasing the average yield of starch potato (- % from the average yield base value of 43 ton/ha) and the number of consecutive years of each respective yield, that a) did not cause starch potato to temporary decline up to 10%, b) did cause starch potato to temporary decline more than 10% while the remaining in the same stability domain b) cause starch potato production to decline by more than 20% in 2050.

Table 12: Estimated hardness and elasticity of starch potato production and farm income to different disturbances

	σ1: Decrease of starch potato in crop rotation due to nematode pressure	σ2: Decrease in average yield	σ3: Increase in profit per ha other crops[1]	σ4: Increase in production costs starch potato[1]
Base run value	0.5	43 ton/ha	1,630-1,900 €/ha	2,410-1,970 €/ha
Starch potato production				
Hardness	4.0%	2.5%	7.5%	5.5%
Elasticity *(σ_E)*	5.0%	3.5%	11.0%	8.0%

[1]Profits and costs vary depending on the farm size.

To gain a more holistic view of the system resilience to difference challenges, different disturbances were simulated together to determine their combined threshold elasticity values (see Figure 4.21). All combinations to the left of the threshold line caused no system decline and all combinations to the right of the threshold line caused a decline. The results show that the system is more resilient to economic disturbances than environmental one (see Figure 4.21 B and C).

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

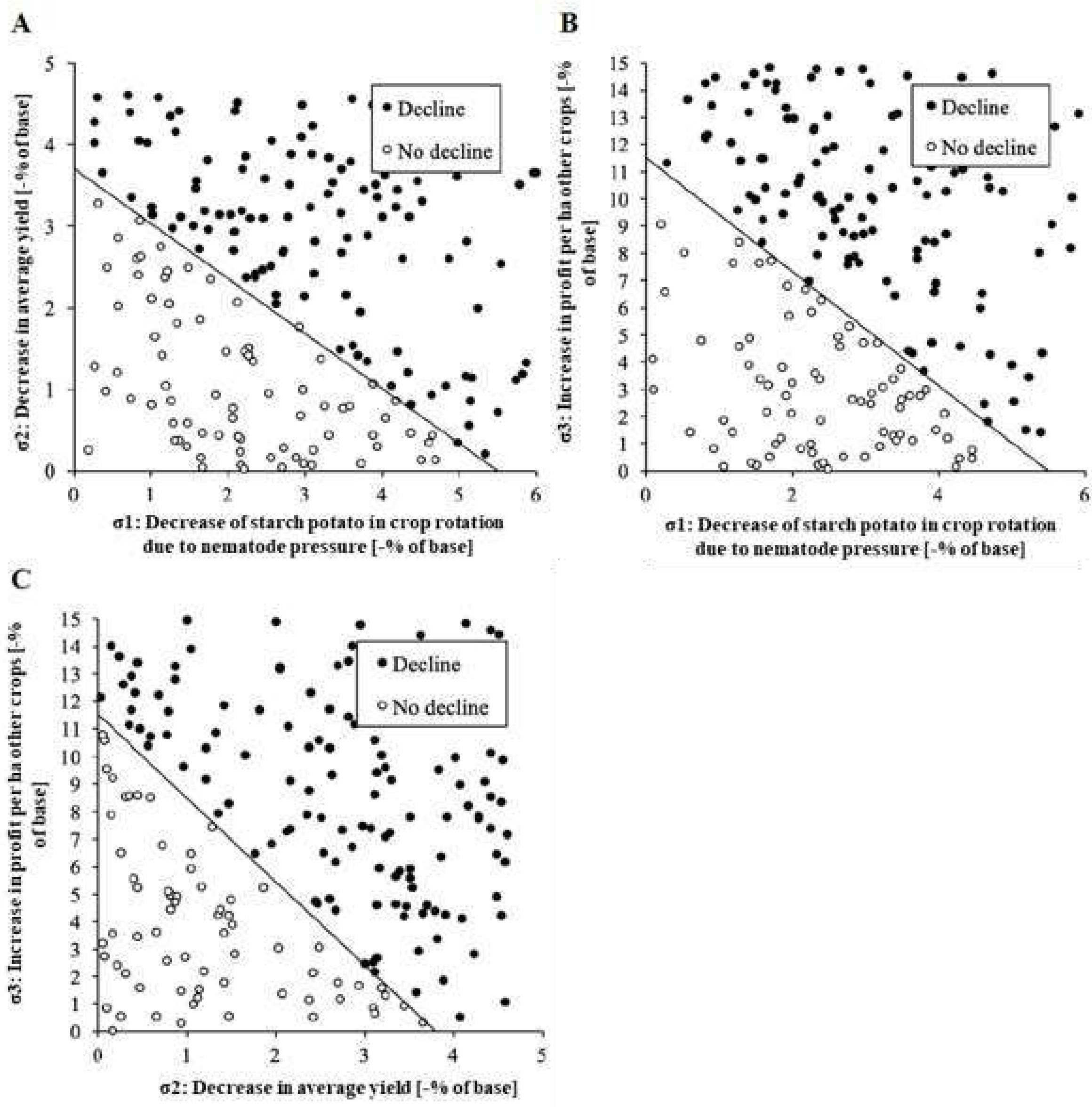


Figure 4.21: The combinations between disturbances σ1, σ2, σ3 that either caused starch potato production to decline by more than 20% in 2050 (black) or that did not cause a decline (white). Each point in the graph represents one simulation. (A) Simulations with σ2 (y-axis) and σ1 (x-axis) (B) simulations with σ3 (y-axis) and σ2 (x-axis) and (C) simulations with σ3 (y-axis) and σ2 (x-axis). Threshold lines cut the axes at approximately the same values found when testing challenges individually

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The resilience shown by the system to economic disturbance is to some extent attributable to the virtuous relationship between the farmers and Avebe. Some strategies taken by farmers and Avebe to respond to external disturbances were identified during the FoPIA-SURE-Farm workshop 1 (Pass et al.,2019). This analysis focuses on three of these strategies:

- *(S1):* Plant breeding to increase starch content.
- *(S2):* Increasing average yields by breeding/using nematode resistant and climate resilient varieties and by improving farm management practices (e.g. irrigation or precision agriculture).
- *(S3):* Increasing value of starch products and also extracting and selling potato protein.

For simplicity the SD model did not model these strategies in detail. Instead, the impact of these strategies was tested separately by modifying parameters (e.g. the starch content) directly in the system. This approach offered flexibility for testing separately contributions of each strategy to the system resilience. The results of these analysis are shown in Figure 4.22.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

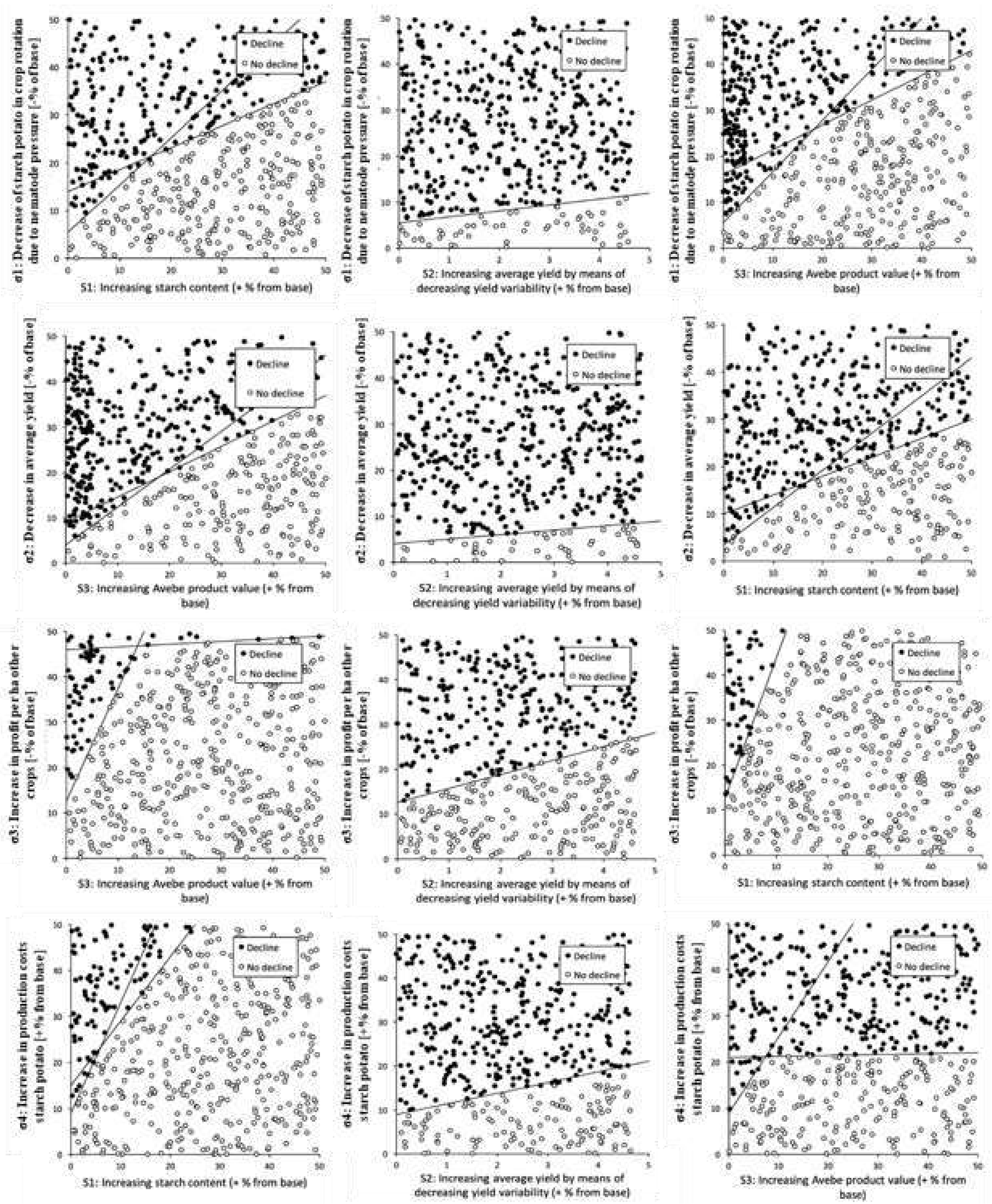


Figure 4.22: Simulation results of strategies (S1, S3) in combination with different disturbances. A threshold line shows the minimum relative change of a strategy parameters that is required to prevent a system decline given a relative change of a challenge parameter. A system decline occurs when starch potato production decreases by more than 20% from the 2020 value in 2050.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

As in the original system, the system is less resilient to environmental disturbances affecting directly potato yield (σ1 and σ2 in Figure 4.22). A decrease of starch potato in the crop rotation by over 40%, or a decrease of the average yields by more than 30%, always resulted in a system decline, regardless of how aggressively/successfully they could be implemented.

Overall the results show S1 and S3 outperform S2 (see Figure 4.22) in their effectiveness increasing resilience to all the disturbance examined with S1 and S3 showing similar performance. The only significant difference between the S1 and S3 was observed when analysing the system resilience to an increase in production costs of starch potato (see σ4 in Figure 4.22). In this case S1 outperform significantly S3 and even moderate increases in the starch content (e.g. less than 20%) increased system's resilience considerably.

4.3.2 Case 2: Resilience of livestock farms in the Bourbonnais region

Background

Livestock farms in the Bourbonnais region have faced a challenging environment in the recent years and the region has seen a consistent reduction in the number of farms (see Figure 4.23). Between 2000 and 2010, the number of farms decreased 25%, with changes of -33% for dairy cows, -17% for beef farms, -52% for beef & dairy farms, -41% for the other herbivores, -42% for polyculture. However, the change in the Utilised Agriculture Area (UAA) has not follow same trends and the average size of the farms have considerably increased during the same period (see Figure 4.23B).

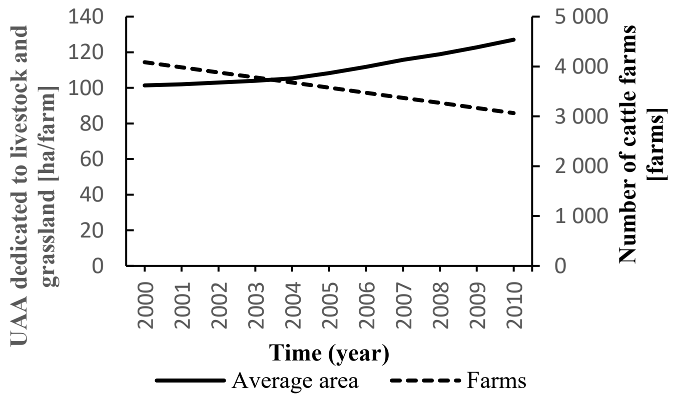


Figure 4.23: The number of cattle farms in the Bourbonnais region [farms] (dashed line – right axis) and the respective average farm size [ha/farm] (solid line – left axis) (source: Agreste FDS_G_0001)

The changes in the past years suggests the system is already undergoing a transformation as farms continue scaling up and moving towards intensified production. Next, we use the conceptual SD model to assess what developments could be expected for the livestock farms in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

the Bourbonnais region in different scenarios and how resilient these scenarios are in comparison to each other.

Resilience of what? (Outcome Functions)

For the analysis of the Bourbonnais region we look at the impact of climate change on three essential functions provided by the livestock farming systems in the region:

- ***Ensure Economic viability:*** We use the farms' 'return on investment' as proxy to estimate farms economic viability. The income is already highly variable due to the volatility of prices.
- ***Ensure that rural areas are attractive places for residence and tourism:*** We use the variable 'rural jobs' as a proxy to estimate farms' contributions to make the rural areas attractive places for residence.
- ***Deliver healthy and affordable food products:*** We use the variable 'meat production' as a proxy.

These three variables are closely interconnected (see Figure 4.24 and Figure 4.25). Economic viability makes farming an attractive and more farmers join, increasing the amount of food produced (R1 in Figure 4.24). Pressures to reduce costs or the desire to increase margins drives economies of scale (see B1 in Figure 4.24). The same motivations make farmers to invest on more efficient technologies (see R2 in Figure 4.24). Nonetheless, the relation between investment and efficiency is not linear and eventually the efficiencies gained don't compensate for the return generated, slowing down the investment (see B2 in Figure 4.24).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

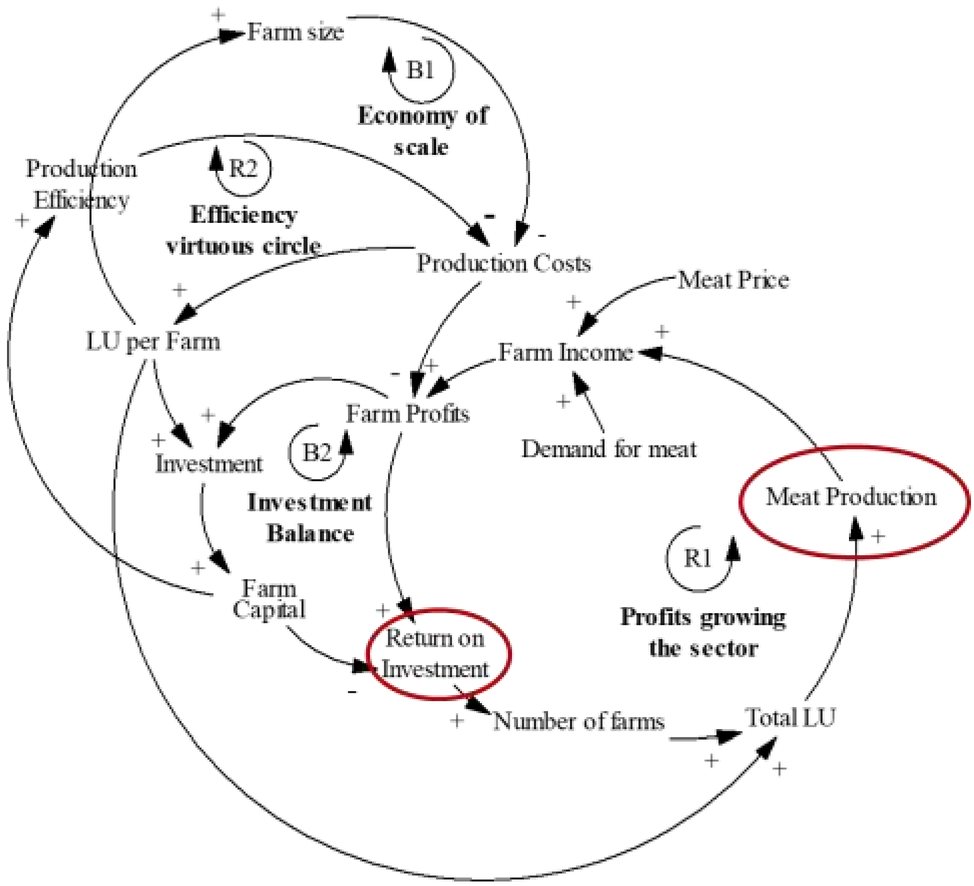


Figure 4.24: A causal loop diagram showing some dynamics driving food production and return on investment in the Bourbonnais

An increase in the number and size of farms increases, all other variables remaining the same, the number of jobs generated by farms. A higher demand for labour might increase competition in the labour market and increase recruitment costs and wages slowing down farms expansion (see B4 in Figure 4.25).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

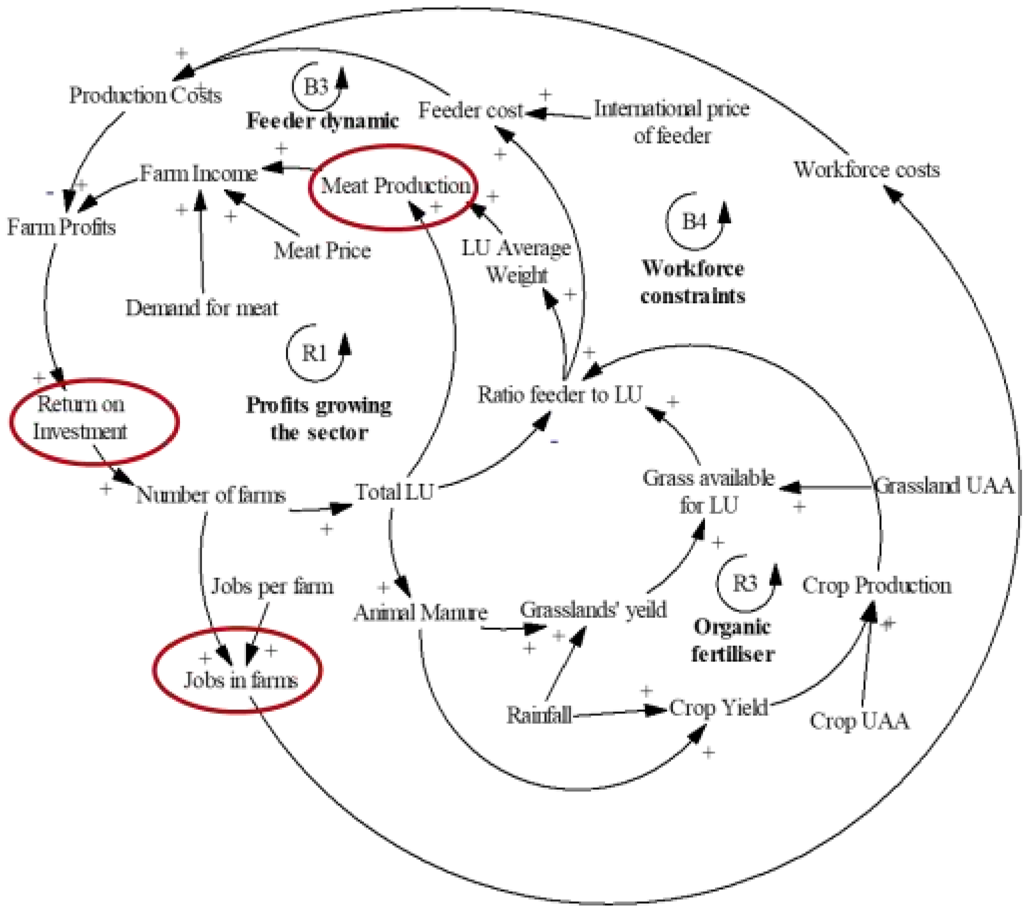


Figure 4.25: A causal loop showing some dynamics driving jobs in farms and return on investment in the Bourbonnais

Another constraint in the system is the amount of feeder available and the cost of it (see B3 in Figure 4.25). More and bigger farms demand more feeder eventually increasing its costs and the dependency on imported feeder. Using the mature as fertiliser might reduce this dependency by increasing grasslands and crop fields yields (see R3 in Figure 4.25), but the relationship is not linear and the system eventually reaches the maximum amount of feeder it can produce locally.

The model was calibrated against historical data following good practice. The results of the model calibration for the selected variables is shown in Figure 4.26.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

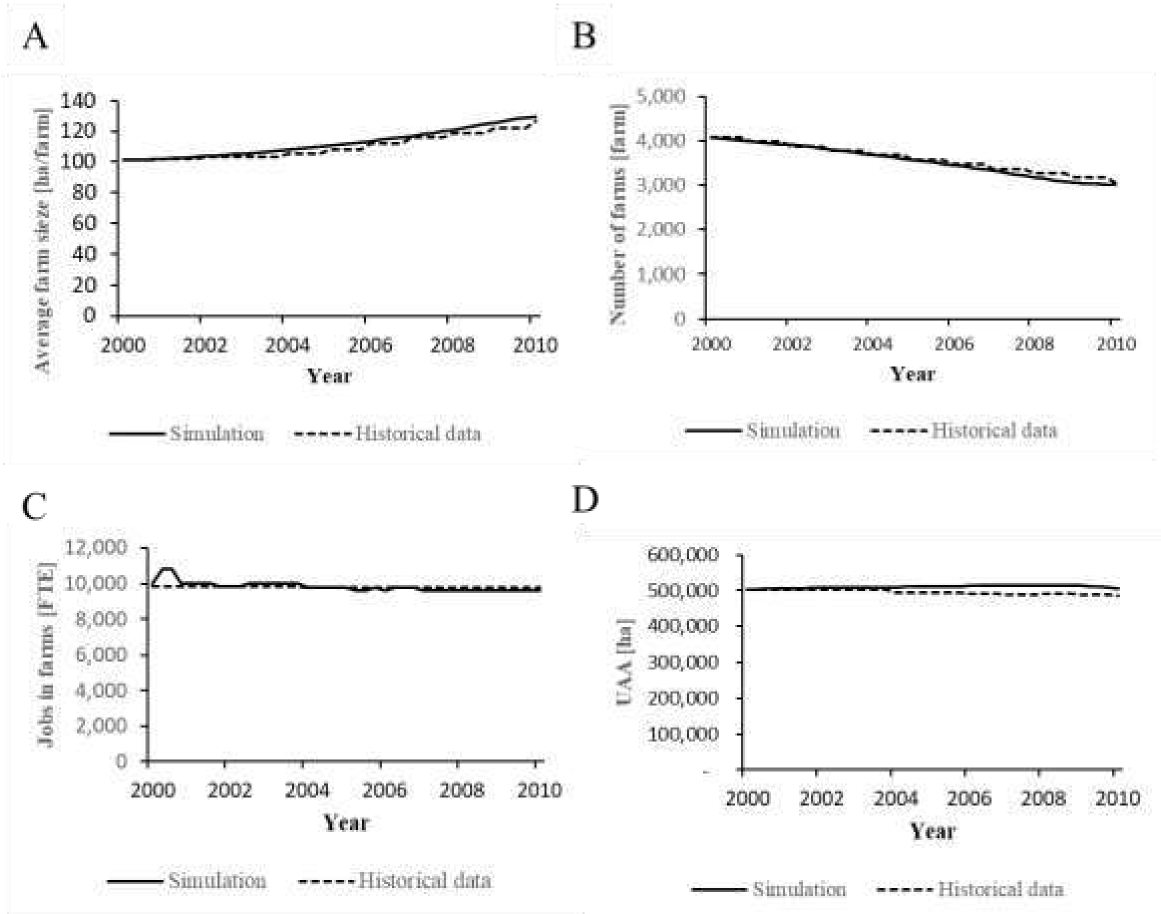


Figure 4.26: Simulated and historical behaviour for A)) average farm size [ha/farm], B) number for farms [farms], C) Jobs in farms [FTE] and D) utilised agriculture area (UAA) [ha]

Future paths for the livestock systems in the Bourbonnais

For the Bourbonnais region, we use first used the model to explore the resilience of the system functions to climate change in the 5 EU-Agri-SSPs. We use our SD model to simulate what the system behaviour will be in the long-term future. Figure 4.27 shows examples of the simulations produced by the model when the current external conditions (e.g. GDP growth, farmers access to markets, sustainable diets) where extrapolated 20 years into the future. For our analysis we considered these conditions to be equivalent to the SSP2 scenario.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

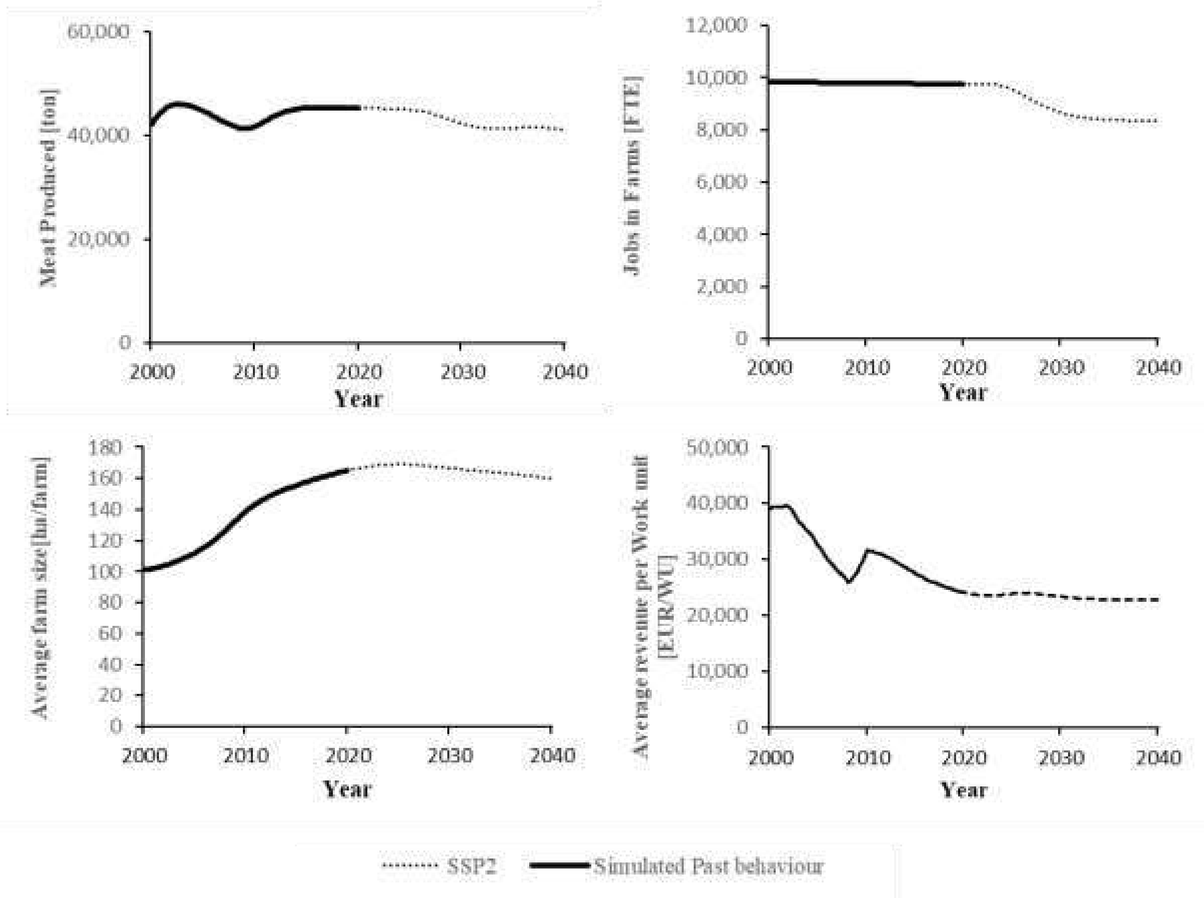


Figure 4.27: Example of simulated results for livestock farming systems in the Bourbonnais region for the 5 EU-Agri-SSP A) for the variation in the return on investment and B) for the average size of farms [ha/farm]

Using the model and the SSP2 as starting point we changed some of the parameters in the model so that they deviate from the current trend aligned to the SSPs narratives. Rather than attempting to estimate precise values for each parameter we work with variations against the SSP2 and describe the trends of these variables as “higher than” or “lower than” SSP2.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table 4.13: Parameters modified in the Bourbonnais SD model to simulate the EU-Agri-SSP scenarios.

	SSP1 Agriculture on sustainable paths	*SSP2 Agriculture on established paths*	*SSP3 Agriculture on separated paths*	*SSP4 Agriculture on unequal paths*	*SSP5 Agriculture on high-tech paths*
Growth per capita	↗ Higher than current trend	As current trend	↘ Lower than current trend	As current trend	↗ Higher than current trend
Equality index	↗ Higher than current trend	As current trend	As current trend	↘ Lower than current trend	As current trend
Meat consumption per capita	↘ Lower than current trend	As current trend	As current trend	↘ Lower than current trend	↗ Higher than current trend
Access to international markets	As current trend	As current trend	↘ Lower than current trend	As current trend	↗ Higher than current trend
Workforce migration	As current trend	As current trend	↘ Lower than current trend	As current trend	↗ Higher than current trend
Land regulations	↗ Higher than current trend	As current trend	As current trend	As current trend	↘ Lower than current trend
Access to technology	As current trend	As current trend	↘ Lower than current trend	As current trend	↗ Higher than current trend

Figure 4.28 shows the results for the 5 EU-Agri-SSP scenarios. The simulation results show that with exception of SSP2 and SSP5, all scenarios could expect to see a reduction on the size of farms and the amount of meat produced. These reduction are result of a decay in the demand for meat. In SSP1 the reduction in the meat demand is expected as a consequence of more sustainable diets, in SSP3 as a result of access to international markets and in SSP4 is a consequence of a decrease of the average purchasing power due to inequality.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

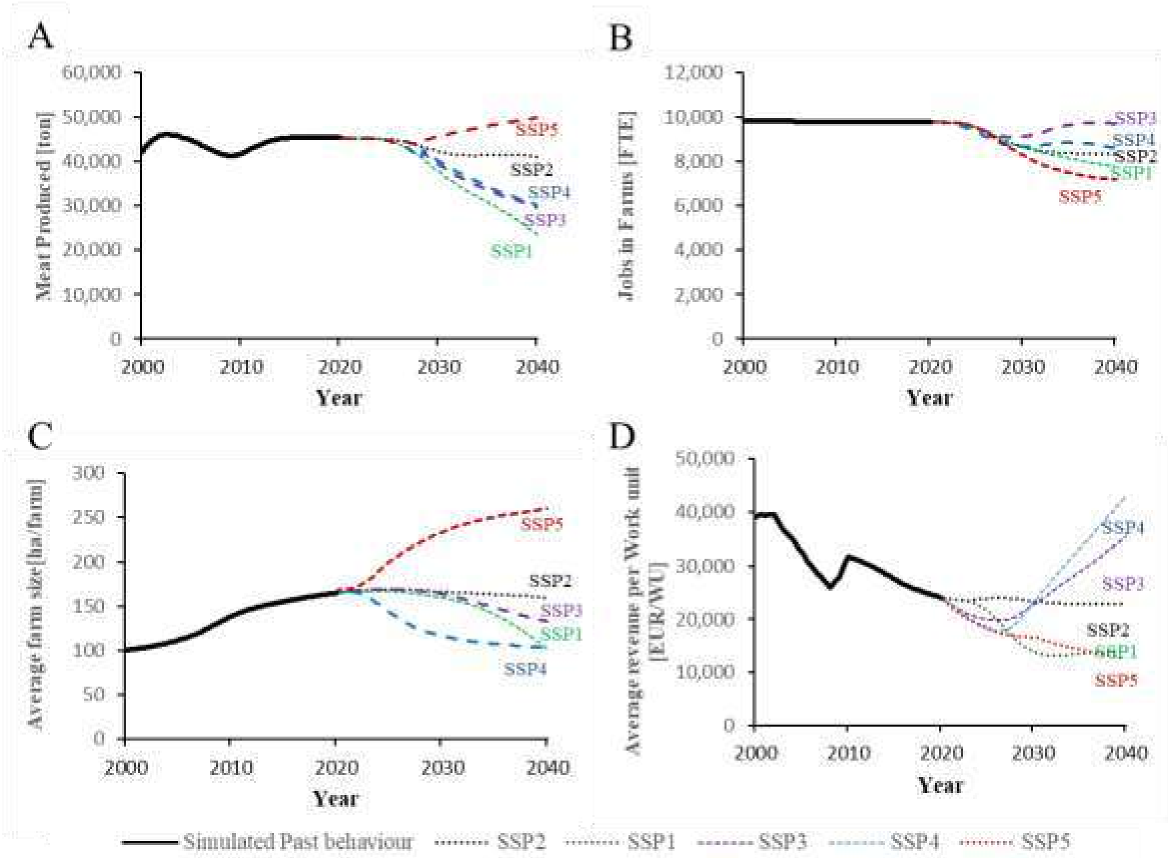


Figure 4.28: Illustrative examples of simulated results of the selected variables: A) meat production, B) jobs generated by farms, c) average farm size and D) average revenue per work unit for each of the five EU-Agri-SSPs

The changes in the demand are meet differently in each scenario. In SSP5 the system is likely to develop into large, low margin high throughput farms (see C and D in Figure 4.28) and smaller specialised farms with higher margins in the SSP4 and SSP3. The environmental constraints and low demand in SSP1 are likely to result on smaller and low profit farms (meat is not a perceived as premium product anymore).

The combination of market and economic conditions are also likely to affect the amount of people working in farms. In SSP4 workforce could be expected to be relatively cheap so the reduction on the farm size will have a moderate effect on the amount of jobs (see SSP4 in B and C in Figure 4.28). Alternatively, the growth in size expected in SSP5 is likely to be accompanied by mechanisation reducing the overall number of jobs (see SSP5 in B and C in Figure 4.28).

Resilience to what? (Challenges)

So far we have presented expected performance of the different functions in different scenarios. The results in Figure 4.28 show that are trade-offs between system functions, for

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

instance between food production and jobs (see SSP5 in B and C in Figure 4.28) or food production and economic viability (see SSP3 and SSP4 in B and C in Figure 4.28). However, we have not explored yet how resilient such performance might be in different scenarios and there might be also trade-offs between performance and resilience to potential challenges affecting the system.

Common challenges faced by many livestock systems in Europe include, price uncertainties, market fluctuation, reduction on red meat consumption and fewer in the new generations wanting to take farms over. Similar challenges were identified by the SURE Farm project (Accatino and Neumeister, 2019), by directly asking stakeholders in the region as part of the FoPIA SURE-Farm workshops. Table 5 summarises the challenges identified by the local stakeholders.

Table 4.14: Challenges in the Bourbonnais region identified as part of the FoPIA-SURE-Farm workshops in the SURE Farm Project

Challenges	Economic	Environmental	Social	Institutional
(Non-) permanent shocks	Low prices	Droughts	High percentage of local inhabitants live below the poverty line Low incomes High unemployment in the area	Change in agricultural policies
Long-term pressures	Lack of investment on capital Increasing operating costs	Climate change Loss of biodiversity	Shortage of farm successors Changes in consumption patterns (low meat diets).	Uncertainty about CAP

In this case we only explore the system resilience to climate change. We focused on climate change, because it is a global phenomenon that is likely to manifest in all the scenarios in the same way. Namely, we looked at the impact that droughts might have in the next 20 years. To do this we tested the system behaviour when exposed to different reductions on rainfall (*M*) from [0mm/year to -200mm/year] lasting from 0 to 15 years (*d*).

Results and analysis

The analysis was done in two dimensions: i) we look at how each outcome function will perform in each scenario in terms of stability and resilience and ii) we look at the aggregated behaviour of the three functions selected for our analysis (food production, jobs generated and return on investment). The first assessment gives insights about some conditions that could improve

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

resilience and, in particular, robustness of specific functions. Alternatively the second assessment offers an overview of the system resilience in each scenario.

The economic viability of the farms, in our analysis assessed through the return on investment (ROI), could be expected to be more stable in the SSP3 (see Table 4.15). The reasons for this robustness is the lack of competition in that scenario. Even if productivity is low, farmers still could pass the cost to the consumer as the demand is less sensitive to price. The same reason is likely to result in a relatively low (in comparison to that in the other scenarios) recover rapidity in the SSP5, where competition is expected to be high (see Table 4.15).

Table 4.15: Resilience measures for the function Return on Investment (ROI) in the Bourbonnais region

	SSP1	SSP2	SSP3	SSP4	SSP5
Recover rapidity (R^{avg}) [%/year]	4.95%	3.65%	5.85%	4.48%	2.63%
Elasticity (σ_E) [- mm]	167	134	140	179	155

In SSP1 the ROI could be expected to be less stable in comparison to other scenarios (see Table 4.15) but the system can be overall quite resilient (see elasticity in Table 4.15). The high elasticity value in the SSP1 is a result of the high productivities resulting from innovation and human capital and the relatively low investment in capital. Similarly, a low capital investment contributes to the higher elasticity for the ROI is observed in the SSP4 (see elasticity in Table 4.15). Low capital costs and access to cheap labour make it easier for the system to bounce back after strong droughts.

The contribution of farms to local livelihoods, in our analysis assessed through the number of jobs generated by farms in the region, could be expected to be more robust in the SSP2 and SSP5 (see Table 4.16). In these scenarios farms are more intensified and automatized than in any other scenario and, hence, already have a relatively low ratio of full time equivalent [FTE] per unit of area [ha]. Same reason result in a high elasticity as those still working in these farms are essential for their operations.

Table 4.16: Resilience measures for the function Jobs generated by farms in the Bourbonnais region

	SSP1	SSP2	SSP3	SSP4	SSP5
Recover rapidity (R^{avg}) [FTE/year]	260	307	300	222	325
Elasticity (σ_E) [- mm]	144	176	115	169	179

Alternatively in the SSP4, where farms could be expected to be more labour intensive and the workforce less specialised, jobs provided by farms shows the lower recover rapidity (see Table 4.16). However, a high elasticity still could be expected in the SSP4 as the unemployment is high

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

and options are limited for non-skilled workers. In the SSP3, jobs provided show relatively high robustness because the pressure for cutting price is low but if disturbances are severe, the system might collapse due to the limited workforce (see elasticity in Table 4.16).

The SSP1 exhibited, surprisingly, low resilience (see both recover rapidity and elasticity in Table 4.16). The low elasticity in this scenario seems to be caused by it high dependence on high-skilled labour. If the disturbance are too high it becomes too expensive to retain the workforce and technical innovation and mechanisation become more attractive.

Finally, the farms' ability to keep providing healthy and affordable food, operationalised in our analysis through the amount of food produced, show very similar results in all the scenarios (see Table 4.17). This is expected as climate change is expected to affect farms productivity directly. There are, however, significant differences in terms of elasticity (see Table 4.17).

Table 4.17: Resilience measures for the function food production in the Bourbonnais region

	SSP1	SSP2	SSP3	SSP4	SSP5
Recover rapidity (R^{avg})[ton/year]	6,661	4,110	5,550	3,350	4,230
Elasticity (σ_E) [- mm]	179	115	144	134	124

The simulation results show higher resilience (indicated by elasticity) in SSP1. Examining the model we hypothesise that resilience in the SSP1 is mainly the result of consumers preferring local producers. In SSP4 and SSP2 competition quickly takes over if the region is disrupted by weather disturbance. The same mechanisms also make food production in the SSP3 more robust than in

4.4 Summary and conclusions

The future resilience of farming systems depends on the combination of several factors enabling or limiting the system ability to bounce back after being affected by severe disturbances and shocks. These factors can be both external (e.g. changes to trade regulations) and internal (e.g. organising farms in cooperatives).

Our analysis suggests that in the future, farms are more likely to be resilient in those scenarios where conditions are favour the development of key resources driving farm productivity. Our exploratory results show that, in the long-term, those resources might be more important for fostering resilience than cash reserves or high profits. For instance, having access to skilled labour (SSP1) and technology (SSP5) seems to help farmers to cope with climate change effects. On the other hand, those scenarios, like SSP3 and SSP4, where there is little pressure to innovate and increase efficiencies could be expected to be less resilient.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

We also observed that innovation, networks and cooperation contribute to building resilience against economic disturbances. For instance, the cooperative Avebe in the Veenkoloniën was identified in our analysis as one of the reasons why starch potato farms might be relatively adaptable to changes in the economic landscape (variations in costs or prices of other crops). Increasing the resilience to environmental factors might be more difficult as our analysis only identified the conditions in the scenarios SSP1 and SSP5 as having a small impact on improving systems resilience to environmental challenges.

While resilience is often used as a characteristic of the whole system, the quantitative analysis show that are differences among different outcome functions. For instance, in the same scenario, farms could simultaneously show a high resilience in terms of offering jobs and low resilience when it comes to food production. There are also trade-offs between resilience and performance, for instance in SSP1 the livestock farms in the Bourbonnais could be expected to produce less food (meat) but this production is expected to be more resilient than in, for example SSP5 where the system is likely to have higher throughputs.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

5 AgriPoliS ASSESSMENT

Franziska Appel

5.1 Introduction of the methodology

AgriPoliS (Agricultural Policy Simulator, see Happe, 2004; Happe et al., 2008; Sahrbacher et al., 2012a; Balmann, 1997) is a spatially explicit and dynamic agent-based model that is able to simulate the evolution of agricultural structures over time. It is mainly used to study the influence of agricultural policies on agricultural structural change. A detailed documentation of the current version can be found in Kellermann et al. (2008). A protocol following the ODD standard (Overview, Design concepts and Details) is available in Sahrbacher et al. (2012b). In AgriPoliS, individual farm agents are assumed to maximize profits or household income by use of a mixed-integer programming model, and are able to react to price or policy changes by renting or leasing land, by changing their production system, or by choosing to quit agriculture. These individual farm agents compete for land with their neighbors by interacting on the land market, which is implemented as a repeated auction. AgriPoliS has been adapted to several regions across the EU based on calibrations to empirically collected data and thus provides results of policy scenarios on structural change in real regions (Sahrbacher et al. 2012).

In the SURE-Farm Impact Assessment toolbox (see D5.1, Herrera et al. 2018), AgriPoliS is especially used to assess the resilience indicators “robustness” above all via the attribute “access to financial resources”. In addition, “adaptability” can be analyzed, especially via the attribute "heterogeneity of farm types". However, AgriPoliS is less suitable for assessing “transformability”(ibid. p. 17, table 7). With regard to the functions of farming systems, AgriPoliS focuses mainly on economic and therefore on the delivery of private goods (structural change – farm closings due to illiquidity or lack of coverage of opportunity costs; production, farm profitability and incomes, regional value added; land prices and Ricardian land rent). Furthermore, AgriPoliS can be used to analyze indicators such as employment, labor income, land rental income, farm household income (social) and land use; livestock figures; crop rotation (environmental), from which the provision of public goods can be derived, albeit to a limited extent (ibid., p. 39, table 24).

5.2 Application on future scenarios: the example of capping direct payments

The common agricultural policy (CAP) aims to support the provision of a decent standard of living farming communities, preserve the food production potential on a sustainable basis

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

throughout the EU and thereby ensure a stable, varied and safe food supply for citizens. It also contributes to the EU's priorities such as creating jobs and economic growth, tackling climate change and encouraging sustainable development (EC 2010; EU 2012).

For the funding period 2021-2027, the European Commission is planning to reform the CAP. In the course of the reform, environmental and climate protection are expected to become a higher priority. Direct payments will still remain an essential part of the CAP. However, the Commission wants to redesign the payment scheme in order to achieve a fairer distribution of funds.

But what does a fairer distribution of direct payments mean in a European context? Since the expansion of the EU, in particular the New Member States of Central and Eastern Europe, the European agriculture became increasingly diverse (see also Pitson et al. 2019). But this had not changed the "European Model of Agriculture" describing the medium-sized family farms which are dominant in Western EU countries (Cardwell, 2004). Calus and Van Huylenbroeck (2010) claim that family farms are essential to the concept of European agriculture. In fact, some 93.7% of all European farms are family farms with family labor (Eurostat, 2015). However, these farms account for only 54.3% of farmland (ibid.) with the expectation that this number will only decrease, based on the current structural changes.

It is the objective of this contribution to model and simulate the proposed capping from 2021 with the agent-based model AgriPoliS. To examine how this affects the heterogeneous agricultural structures in the EU, we have selected a region that is very heterogeneous and thus features both western family farms and large cooperative farms of Central and Eastern European agriculture. To further contribute to the debate on direct payments, we simulate the already discussed capping compared to a complete phasing out of direct payments.

Modeling farms individually allows each farm's payment to be calculated, in addition to the extent it will be capped, as well as how farms react to avoid capping. The analysis focuses on the effects of the capping of direct payment on structural change, farm performance and their implications on production. These results can then be used to assess the implications on farming system resilience.

5.3 Scenarios

The proposed CAP reform includes more flexibility for the member states in the allocation of the payments. The goal is to support the small and mid-sized farms. Farms which previously received between €60,000 and €100,000 in direct payments will receive less, and at €100,000, direct payments will be capped. In both cases, the cost of labor can be deducted, so in theory a

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

farm which spends €200,000 on labor could still receive €300,000 in direct payments. The redistributive payment scheme (extra payment for first hectares), which is currently optional, would become compulsory for all member states. Moreover, it is proposed that at least 2% of the budget has to be used for the support of young farmers. That is more than twice as much as the 0.8% at present (EC, 2018).

Table 5.18 Scenarios and model implementation

Scenario	Description		
Base	50 €/ha extra pay for the first 30 ha, 30 €/ha for the next 16 ha No capping		
Capping	From 2021:		
	Step	Amount of direct payment (per farm annually)	Capping (% of total amount of direct payments)
	1	Up to 60,000 €	0 %
	2	60,000 € to 75,000 €	25 %
	3	75,000 € to 90,000 €	50 %
	4	90,000 € to 100,000 €	75 %
	5	Over 100,000 €	100 %
Phasing out	Gradual phasing out of direct payments over 10 years starting from 2021.		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

5.3.1 Case study region

The simulations are conducted for the Altmark, which is located in the federal state Saxony-Anhalt in the north-east of Germany. The region comprises the two districts Stendal and Altmarkkreis Salzwedel. There are a total of 1,094 farms operating in the region which farm on average 250 ha of land (StaLa, 2019). The Altmark is characterized by a rather heterogeneous farm structure. In terms of numbers of farms, individual full and part-time farms as well as partnerships predominate the Altmark. Although legal entities (mainly limited companies and producer cooperatives) only account for some 10% of the farms, they use almost 45% of the agricultural land. Many of the farms are specialized arable farms or mixed-farming with livestock production. The relative importance of livestock production is emphasized by the fact that as of 2016, some 37% of the dairy cows and 45% of the specialized dairy farms in Saxony-Anhalt were located in the Altmark, though the region covers only 23% of the state's utilizable agricultural area (UAA) (StaLa, 2019). Ostermeyer (2015) provides a detailed description on how the Altmark region is implemented in AgriPoliS.

5.4 Analysis of the results

The simulation is carried out for the period from 2016 to 2041. We simulate without repetitions. The model region comprises 86,834 hectare and 924 farms in 2016. After an initialization phase, the regulation measures become active in the policy scenarios in 2020. The analysis is focused on the period 2020 to 2035. To analyze the impacts of the CAP scenarios on farms and the Altmark region we focus on structural change in the Altmark region in terms of farms and farm size distribution. We further analyze the implications on farm performance, value added from farming as well as on the regional production.

5.4.1 Farm size distribution

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

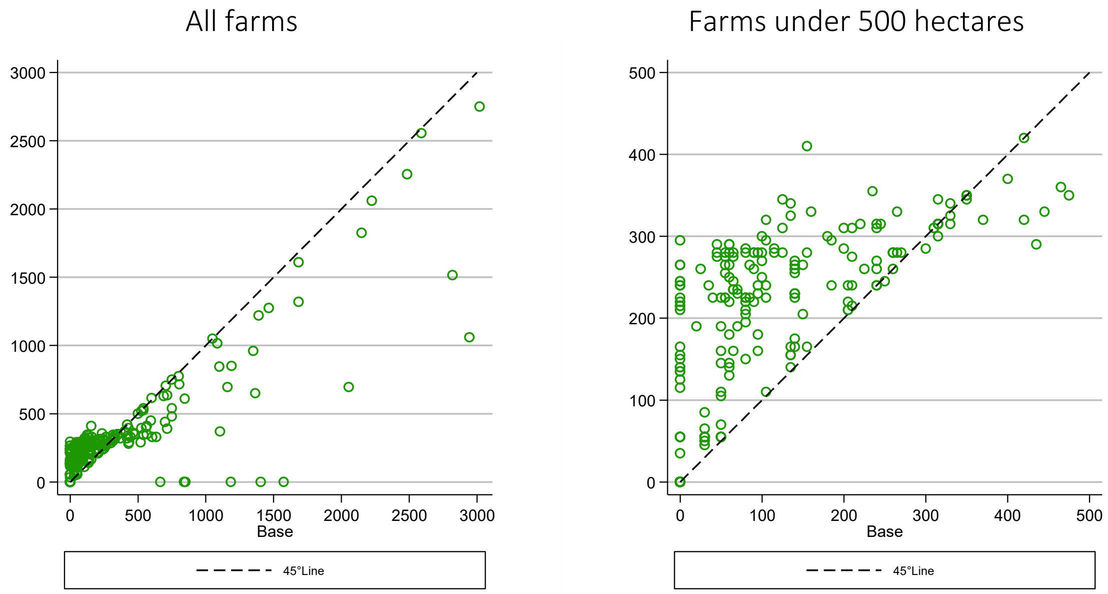


Figure 5.1 Farm size in hectares of single farms in 2031 in the Capping and Base scenarios (model results). Note: Farms that are on the 45° degree line are equally sized in both scenarios. Farms underneath the 45° line are larger in the Base scenario, while farms above the 45° line farm more hectares in the Capping scenario.

For the "Capping" scenario, there is a clear size limit in the range of some 300 hectares (cf. Figure 5.1). Some farms which grow beyond the size of 300 hectares in the "Base" scenario cannot do so in the "Capping" scenario. At the same time, many farms which are below 300 hectares in the "Base" scenario grow to become larger. Although larger farms are disadvantaged by the capping, the farm sizes are less affected the larger the farms are. Another effect of the "Capping" is that fewer farms exit agriculture between 2020 and 2031. 86% of the farms are still operating in 2031 in the "Capping" scenario compared to 78% in the "Base" Scenario.

All farms Farms under 500 hectares

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

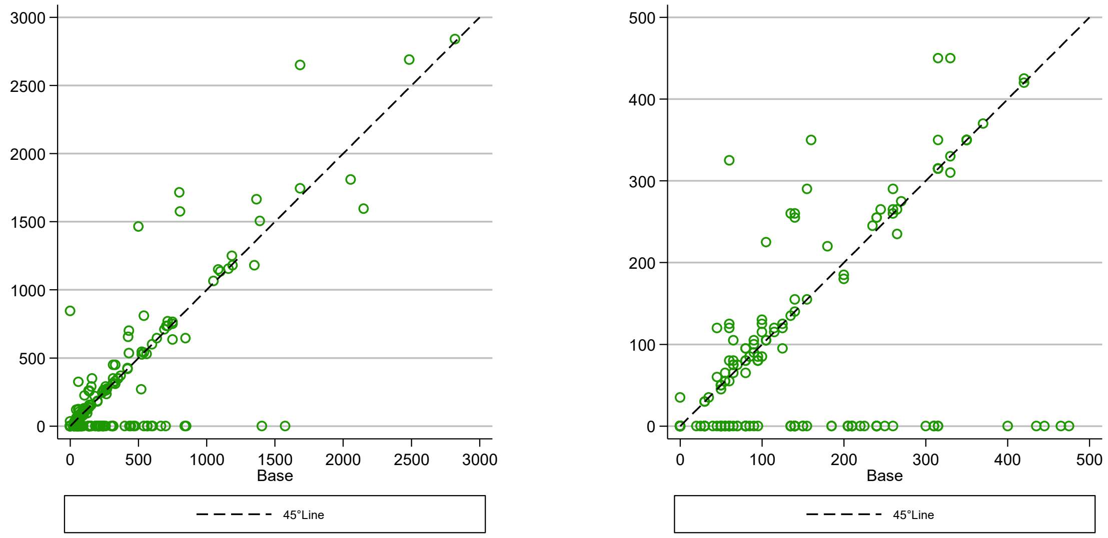


Figure 5.2 Farm size in hectares of single farms in 2031 in the Phasing out and Base scenarios (model results). Note: Farms that are on the 45° degree line are equally sized in both scenarios. Farms underneath the 45° line are larger in the Base scenario, while farms above the 45° line farm more hectares in the Phasing out scenario.

In the “Phasing out” scenario (Figure 5.2), more farms exit. In 2031 48% of the farms of 2020 are still operating. This is considerably less than in “Base” and “Capping” scenario (78% and 86%). On the other hand, some medium to large farms are able to increase their size compared to the “Base” scenario.

With regard to the density of farm sizes (Figure 5.3) the capping leads to a substantial increase in farm sizes of around 300 hectares. In the “Phasing out” scenario the general decline in the number of farms is clearly visible in Figure 5.3. The density curve is flatter overall, but also more evenly across the sizes. The redistribution between farm sizes is substantially lower than in the "Capping" scenario. The highest density is at about 250 hectares. This is more than in the “Base” scenario but is still below the “Capping” scenario. For farm sizes over 700 ha the density in the “Phasing out” scenario is higher than in the other two scenarios.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

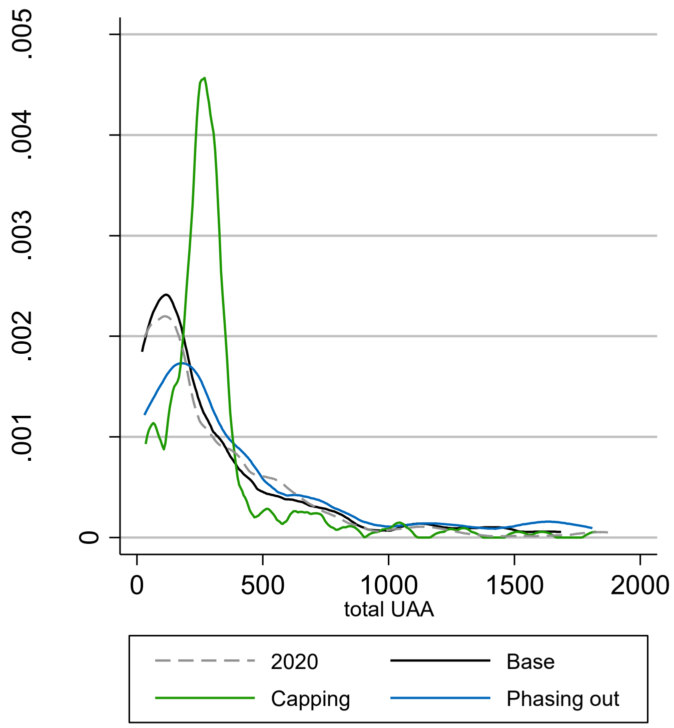


Figure 5.3 Kernel density estimation of farm sizes in 2031 (in hectare UAA)

5.4.2 Farm performance

Compared to 2020, the distribution of profits per hectare (plus wages) shifts to the right in the "Based" and "Capping" scenarios. The highest density is at about 500 €/ha for both and the distribution becomes somewhat narrower. In contrast, the elimination of direct payments in the "Phasing out" scenario shifts the highest density of profits to about 250 €/ha and thus the half of the other two scenarios.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

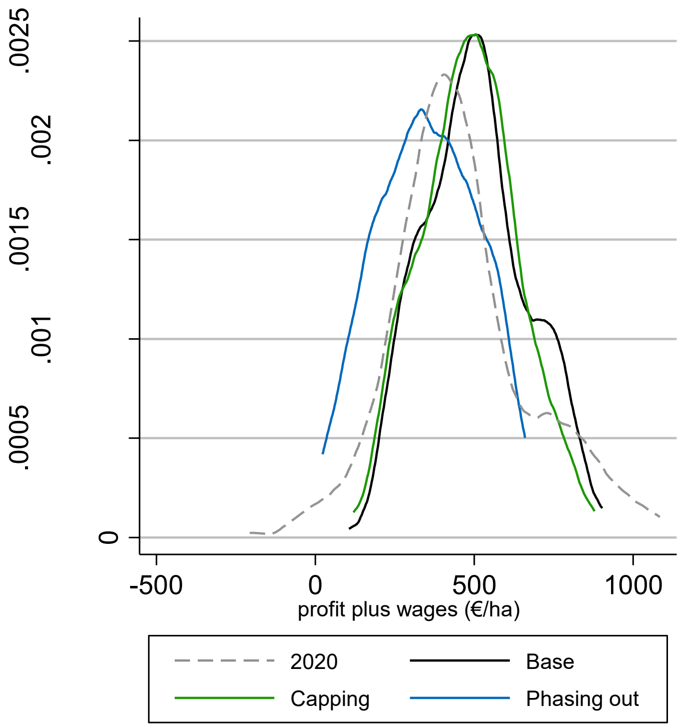


Figure 5.4 Kernel density estimation of the farms' average profit per hectare in 2031 (including wages paid)

Because the profits per hectare give only limited insights regarding the farm performance and efficiency of the agricultural sector in a region, Figure 5.4 shows the evolution of the regional net value added from farming which reflects the overall evolution of efficiency of the sector. Both, “Capping” as well as “Phasing out” scenario, negatively affect the value added from farming in the region (cf. Figure 5.4). The “Capping” scenario leads to a drop at the introduction in 2021, while the “Phasing out” results in a fairly even decline in value added over the 10 years. However, if the direct payments received by the region are subtracted from the value added by agriculture, the value added rises again over time in the "Phasing out" scenario. The sector can adapt and thus compensate for the missing payments. This is due to a selection effect on the farms leaving the sector. As mentioned in the section 5.1, more farms exit and only the more efficient ones remain active and produce in the sector.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

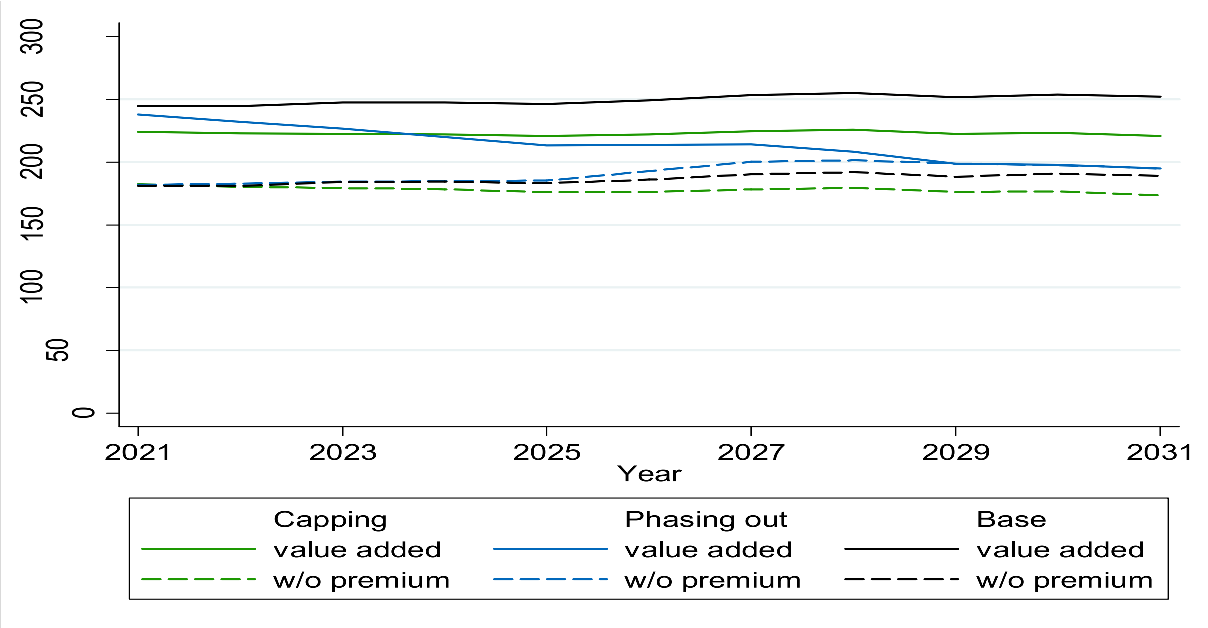


Figure 5.5 Evolution of the net value added from farming with and without direct payments (premium)

The simulated savings in direct payments are also worth mentioning: in the "Phasing out" scenario in 2031, around 63 million euros in direct payments were saved compared to the "Base" scenario. In the "Capping" scenario, the savings are around 23 million euros. In addition, direct payments in the "Capping" scenario even increase slightly again after the introduction of capping. Farms seem to be adapting their size in such a way that they can optimize their direct payments.

5.4.3 Agricultural production

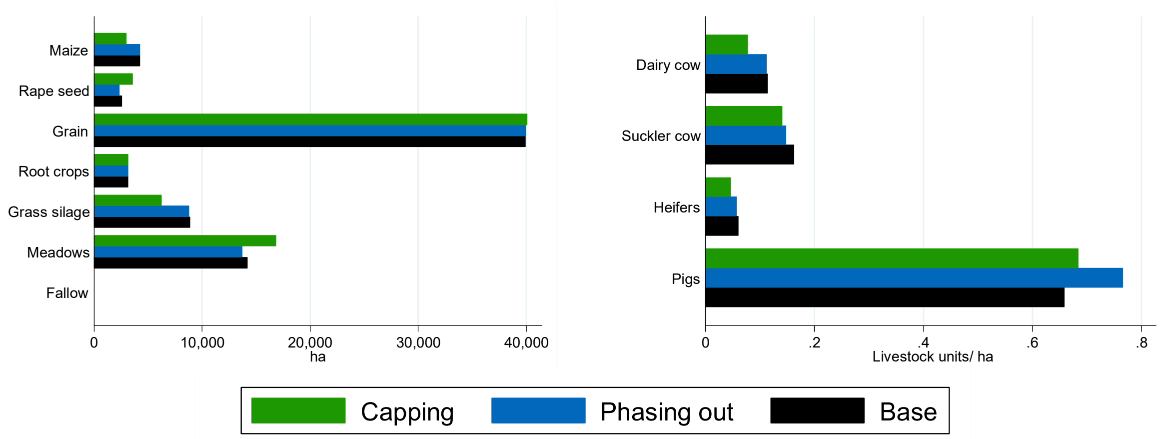


Figure 5.6 Cultivation and livestock production in 2031

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Regarding the Cultivation and livestock production (Figure 5.6), there is a reducing effect on the number of grassland based livestock production in the “Capping” scenario. This effect can be explained by the response of farms slightly above the capping barrier which reduce the less profitable grassland first and lead consequently to a reduction of grassland based livestock. Farms that are below the size limit of capping can rent this grassland at relatively low cost, but tend to use it extensively. As a result, the number of suckler cows declines less than the number of dairy cows. The reduction in sizes of farms with (initially) more than 300 hectares particularly affects dairy farming, which in the Altmark region is mainly practiced in large herds. Grass silage and maize as a feed basis for dairy cows are therefore less cultivated. Most medium-sized farms in the “Capping” scenario specialize in the cultivation of cash crops (increase for rape seed).

The “Phasing out” scenario has less effect on the production structure. There is a smaller decline in the number suckler cows and heifers, together with a slight decrease in grazing land. Somewhat more significant is the increase in pig husbandry. In the absence of the area payment, livestock farming that is more independent of area becomes comparatively more profitable. This effect is also detectable in the “Capping” scenario, but it is stronger the more the payments are reduced.

5.5 Summary and Conclusion

Changes in direct payments schemes not only affect a potentially "fairer" farm size structure, but also the functions of the respective agricultural system and therefore its resilience (Meuwissen et al. 2018). To this end, we have analyzed not only the structural effects but also the effects on farm performance, value added from farming and the regional production.

In summary, it can be concluded that a capping of direct payments results in a higher number of farms but the farm size structure is strongly distorted in favor of a farm size around the cap limit. There are also changes in the structure of cultivation, which affects particularly the dairy production. A complete phasing out of direct payments also influences the agricultural structure. In our simulation, it leads to a strong decline in the number of farms. However, no particular farm size is clearly preferred or disadvantaged. The heterogeneity in the farm size structures is maintained. Similarly, the production and cultivation structure does not change significantly, with the only exception that there is an increase in land-independent production (pigs). Thus, farms seem to be able to adapt and also the exit of farms can increase the resilience of an agricultural region as this enables other farms to grow to economies of scale and thus enhance its potential to absorb shocks. For Appel and Balmann (2018), a “smart exit”, or a farm exiting due to reasons other than illiquidity, enhances the resilience of the farm household.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

What has not been considered so far is what could be done with the funds saved from direct payments. The funds can be spent in other ways to achieve the CAP strategic goals such as creating jobs and economic growth, tackling climate change and encouraging sustainable development. If this money is used specifically for measures of sustainability, biodiversity and landscape conservation, new sources of income for farms in the region are created. In other words, earning money with the production of public goods and shifting the value added into another area that cannot be so well represented by AgriPoliS. The farms in the simulations would have the option of either continuing to operate or transforming themselves into service providers for public goods, which means exit farming but still contribution to the resilience of the farming system.

Instead of trying to establish agricultural structures in accordance with an "ideal European structure" (Cardwell, 2004), the CAP should reflect on their initial aims and spend the money more purposefully. Moreover, a loss of farm structure diversity may also affect the production diversity and therefore be contradictory to the CAP aims.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

6 DISCUSSION OVER RESULTS FROM DIFFERENT METHODS

Francesco Accatino, Franziska Appel, Katarzyna Bańkowska, Jasmine Black, Gordana Manevksa-Tasevska, Wim Paas, Mariya Peneva, Corentin Pinsard, Simone Severini, Bàrbara Soriano, Cinzia Zinnanti, Pytrik Reidsma

6.1 Case-study specific discussions

6.1.1 Comparison of results for the French case study

For the French case study, insights from the FoPIA-SURE-Farm 1 and 2 assessments are compared with the insights from the ecosystem services assessment and from the System Dynamics quantitative analysis.

Importance of reducing (or non increasing) the amount of cattle

In the FoPIA-SURE-Farm 2 desk study, all the alternative systems developed (i.e., *all-export*, *only-French-market*, and *tourism*) envisage a reduction of the amount of cattle. According to the FoPIA-SURE-Farm 2 study, this would make the system more sustainable in the long term, with a reduced pressure on the landscape. In addition, this would reduce greenhouse gas emissions from extensive cattle rearing. This result is largely confirmed by the simulation done with the nitrogen fluxes model of the scenario compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5. The simulation shows that an increase in livestock would render the system more profitable in the short term but definitely less robust in the long term, more dependent on external feed import and on synthetic fertilizer. If a shortage in feed or fertilizer comes, the impact would be more severe with a higher livestock number. It is then recommended for the French case study not to increase cattle number but to increase its coupling with the landscape and in improving the quality of life of farmers.

Importance of non-decreasing permanent grassland

In FoPIA-SURE-Farm 1 (see D5.2, Paas et al., 2019) grassland turned out to be highly valued by stakeholders. There is awareness among stakeholders that beef production is coupled with natural capital and the presence of permanent grassland is important for the system, for beef production in terms of quality and quantity, and for animal health and welfare. In the FoPIA-SURE-Farm 2 desk study experts convey that in all the alternative scenarios the presence of grassland is important for the region and, in alternative systems in which the production would be less coupled with the landscape (i.e., the *all-export* alternative system), some policies for protecting grasslands and hedges should be present or potentiated.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

The results of the land use optimization model highlighted that the grassland can be reduced by extending cropland and forest in order to increase crop production and carbon storage in the region. However, it was remarked in the discussion of these results that this is not a preferred solution for the Bourbonnais. In addition, in the simulation of the Eur-Agri-SSP1 scenario, the production is decreased, as it is completely based on livestock (discouraged in the scenario). The quantitative analysis of the System Dynamics done for the Bourbonnais region highlights that, in the scenario Eur-Agri-SSP1 the economic viability might be more robust. This is in agreement with the scenario Only-French-Market, where the reputation of the region will be increased and consumer will prefer higher quality local beef.

The desk FoPIA-SURE-Farm 2 study highlighted that some processes are already pushing the system towards a reduction of permanent grassland. For example, the increasing frequency of droughts is pushing farmers to cultivate more intensive and temporary forms of grassland, to expand forage cultivation over permanent grassland, or to even expand cereal cultivation for both feed and human consumption. According to the scenario 3 simulated with the nitrogen fluxes model (increase in arable land and livestock number compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5), the increase in arable land (and the increase in cattle number) will push the system to be more and more dependent on external inputs. Therefore, the issue of the reduction of grassland in the Bourbonnais is something to be taken into account and policies of grassland valorization could be promoted to prevent this.

6.1.2 Comparison of results for the Spanish case study

The comparison of the results emerging from the ES and FoPIA-SURE-Farm 2 assessment are discussed: the land use optimization model and the ES assessment of the Nitrogen fluxes model. In turn, we take into consideration the Eur-Agri-SSP scenarios (SSP1, SSP2 and SSP5) and the future systems defined in FoPIA-SURE-Farm 2 assessment. Two alternative future sheep extensive systems emerge from the FoPIA-SURE-Farm 2 assessment: the (i) *semi-intensive alternative system*, mainly characterized by an increased amount of livestock indoor, reduced use of pastures, greater feed dependency and high innovation and level of technology in the animal handling; and (ii) *the high-tech extensive system*, mainly defined by a reduced amount of livestock indoor, an increased use of pastures, lower feed dependency and high innovation and level of technology in pasture and shepherding management.

Land use optimization model

The main conclusion reached in the land use optimization model, defined under the scenario Eur-Agri-SSP1, is that reducing grasslands and expanding annual crops and forest may lead to an increase in both carbon storage and crop production. As explained in the ecosystem service

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

assessment these results do not fit with the extensive sheep farming system, as the Eur-Agri-SSP1 is a scenario in which the reduction in meat production is encouraged.

The *high-tech extensive farming alternative system* is not in line with the results of the land use optimization model. This alternative system foresees that feeding will rely largely on pastures. Therefore, it would require increasing pastures instead of decreasing. The high-tech extensive farming is compatible with the Eur-Agri-SSP1 as it is largely contributing to environmental protection. The SSP1 scenario considers not only a reduced meat production but also a greater environmental awareness. As found in the FoPIA-SURE-Farm 2 workshop, extensive farming is compatible with the SSP1 only when sheep farming continues to provide and reinforce the provision of public goods, such as landscape conservation, biodiversity and animal welfare.

The *semi-intensive alternative system* defined in FoPIA-SURE-Farm 2 may concur with the results emerging from the land use optimization model. The increased amount of livestock indoor would lead to less pastures and more croplands for feeding the herd. In parallel we can expect that abandoned grassland will be invaded by forest. Although this is in agreement with the results of the land use optimization model, this situation would be incompatible with the SSP1 because it fits with no conditions, neither the decreasing meat consumption nor with environment conservation provided by the herd grazing pastures.

Nitrogen fluxes simulation

The first result from the nitrogen fluxes simulation shows that a reduction of the feed-food competition (i.e., replacing fodder with human-edible crops and having the ovine sector more relying on grassland) would increase the net contribution of the region to food provision and would valorize the contribution of grassland to food provision.

This result is clearly in line with results that emerged from the FoPIA-SURE-Farm 2 assessment. *The high-tech extensive alternative system* foresees the increased reliance of feeding the herd by grazing on pastures. It would reduce the feed-food competition and valorize the public goods provided by the sheep extensive farming. On the contrary, the *semi-intensive alternative system* would rely more on fodder. It would lead to an increasing food-feed competition and rivalry with other intensive livestock sectors in the region.

Additional results for the nitrogen fluxes assessment highlight that under the scenarios Eur-Agri-SSP2 and Eur-Agri-SSP5 the configuration of the system is highly dependent on external inputs and therefore poorly robust to decreases in external inputs.

This result is not in line with the *high-tech extensive alternative system* in which reliance on feed decreases, while reliance on pasture increases. No dependency on external inputs is foreseen.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

There is a greater concordance between the *semi-intensive alternative system* and the nitrogen fluxes results. This alternative system will rely largely on feed imports that would lead to greater dependence of external inputs.

The alternative systems in the FoPIA-SURE-Farm 2 assessment shows compatibility with the Eur-Agri-SSP2 scenario and moderate incompatibility with Eur-Agri-SSP5. The compatibility of the alternative systems defined in FoPIA-SURE-Farm 2 assessment with the Eur-Agri-SSP2 scenarios is explained by scenario hypothesis such as: high meat demand, the increasing interest for high standard products and the support for efficiency and productivity by European policies. The compatibility between the alternative systems with the scenario Eur-Agri-SSP5 is explained by scenario hypothesis such encouraged private investments in technology and trade liberalization.

6.1.3 Comparison of results for the Swedish case study

For the Swedish case study, FoPIA-SURE-Farm 2 results are compared with results from the land use optimization and nitrogen fluxes model.

Importance of forests

The land use optimization model highlighted the sharp conflict between land for agriculture and land for forest. If from one side this can be seen as a land-use conflict, the co-presence of both land uses promotes both food production and carbon storage. The stakeholders in the FoPIA-SURE-Farm 2 workshop confirmed that it is in the interest of many farmers to maintain a certain fraction of forest in their land to diversify their income sources. The two forms of activity, agriculture and forestry, are quite compatible as forestry is very adapted to the climate and does not require work on a daily basis.

It is to be noted that, especially for Sweden, forest is an important source of other ecosystem services. A first important service is timber production, although this is in conflict with the storage of carbon. A second important service is related to livestock production, as cattle can graze in mixed grassland-forest lands. It would be therefore interesting to include in the model, at least for Sweden, the multiple ecosystem services provided by forests.

Import reduction and feed-food competition

Two out of three alternative systems formulated in the FoPIA-SURE-Farm 2 workshop are about increasing farm size in order to achieve feed self-sufficiency. This is in line with the scenarios simulated with the nitrogen fluxes model and, indeed, the results highlighted the absence of certain feed items that would make it possible to increase the amount of livestock, and therefore the need to increase the feed self-sufficiency. However, it is pointed out that feed

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

cultivation is not likely to expand over forest but over other forms of agriculture. This would probably enhance the feed-food competition, as highlighted by the nitrogen fluxes simulation (especially scenario 3, compatible with Eur-Agri-SSP3 and Eur-Agri-SSP5)

6.1.4 Comparison of results for the Belgian case study

For the Flemish case study, results and insights from FoPIA-SURE-Farm 1 and 2, ecosystem services modelling, and simulation by agent based modelling (Agripolis) are compared. Results from quantitative modelling approaches can be compared to stakeholders' perceptions and insights from literature (FOPIA2 in Flanders followed an expert and literature based approach, due to COVID-19). We should however note the different focus between quantitative and qualitative approaches. Whereas Agripolis and ecosystem services modelling are focusing on the region as a whole, qualitative approaches have a more narrow focus, namely intensive dairy farming system in Flanders.

Impact of scale enlargement as an ongoing strategy of the farming system

<u>Agripolis:</u>

In D3.5 (Pitson et al., 2020), simulation of different succession rates on structural changes in agriculture have been performed for the Flanders region. Results showed positive effect of decrease in succession. In Flanders, where the majority of producers cannot exploit economies of size because they are too small and the majority of land is farmed by farms with low technological efficiency, a lack of successors can even lead to higher economic prosperity of the agricultural sector. Simulations with Agripolis additionally showed that current measures such as 'young farmer payment' are not effective in increasing succession rates in the region. These results were confirmed during a stakeholder workshop.

"The increasing availability of land allows the surviving farmers in Flanders to better exploit economies of size. The substantial positive effects of the farm exits on factor income in Flanders indicate a lack of efficiency. In other words, the region's current allocation of resources, such as land, technology, and financial and human capital, are such that there is significant waste. Economies of size cannot be exploited when many farms exist and land is scarce. Despite lacking efficiency, many farms continue production. Reasons for this include the sunk costs of existing assets and of human capital, which is particularly relevant in the period before retirement. Another reason points to the existing land market legislation in Flanders which limits the level of rental prices. Accordingly, farms with low competitiveness on the land market can continue to use the land because their actual cost for renting the land are low or because opportunity costs of renting out the owned land to other farmers are low."

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

FoPIA-SURE-Farm 2:

FoPIA-SURE-Farm 2 allowed a more integrated, holistic approach to assess future prospects of scale enlargement as a strategy. It confirms and further elaborates on the boundary conditions hampering scale enlargement in Flanders: a limited availability of land, capital and labour. The lack of labour can be partially tackled through automation of milking and/or feeding the cows. However, the lack of land is a lot more difficult, and the result of competition for land driven by the high population density. If succession rates decreases, land availability for remaining farms might increase. Figures show that in 2016, an average of 18% of specialised dairy farms indicated to have a successor. The share of dairy farms with a successor varies according to the economic dimension, but is highest for the largest farms (Statbel, Statistics Belgium). However, the question whether this succession rate is sufficient to allow scale enlargement and fully exploit economies of scale while maintaining supply of milk production in the region, remains unexplored.

Ecosystems service modelling

However, it should be questioned to what extent current supply of milk production can be maintained. Although maintaining milk production is perceived as an important function of the farming system according to participatory approaches (FoPIA-SURE-Farm 1), the ecosystem modelling exercise shows that the intensive livestock production causes much of the land to be cultivated with fodder, increasing the feed-food competition in the region. In all future scenarios included in the modelling exercise, simulation shows that animal production should be reduced in Flanders

Evaluation of the attributes might be different depending on the observational level across methods. Concerning the attribute ‘diversity’, the ecosystem modelling exercise revealed that in the context of land use optimization for ecosystem services, our case study contributes in providing diversity in ecosystem services. Based on land use evaluation in Flanders, the farming system contributes in providing synergies between crop production and carbon storage. The farming system is well adapted to soften the conflict between those two ecosystem services. However, at the farming system level, evaluated during participatory approaches, functional diversity is scored low due to high specialization rate of the dairy farms in the farming system, making the system less robust to shocks and stresses.

Similarly, in light of the nitrogen fluxes at regional level, the farming system contributes to high nitrogen surplus at the regional level, and is perceived as positive in the light of system reserves in the ecosystem modelling exercise. However, at the farming system level, this nitrogen surplus

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

is rather evaluated negative (FoPIA-SURE-Farm 2), as it contributes to additional costs for processing just as a contributing to low water quality in the region.

6.1.5 Comparison of results for the German case study

AgriPoliS provides an opportunity to further deepen discussion points that emerged, for example, at the FoPIA 2 workshop, but which could not be further elaborated in the methodological and time frame. For example, one of the participants said that he would rather prefer a complete abolition of the direct payment instead of a further adjustment (capping) and other related regulations. Such ideas of possible future scenarios of direct payments and their impact on agricultural regions can be simulated with AgriPoliS (Chapter 4). Further, simulations of AgriPoliS can be used as a discussion basis for participatory approaches (e.g. Deliverable D 3.8).

6.1.6 Comparison of results for the Bulgarian case study

For the Bulgarian case study, insights from the FoPIA-Surefarm assessments are compared with the insights from the ecosystem services assessment

Land use optimization

Crop production is important and has a long tradition in Bulgaria. North-East Bulgaria is known as “the granary of country” and is of crucial importance. The arable farming capacity in the region results from the natural conditions and is defined by the historical developments and transformations, e.g. the most important attributes of the resilience of the large-scale crop production system identified under the FoPIA-Surefarm 1 were “exposed to disturbance” and “coupled with local and natural capital (production)”. The ES assessment confirmed this fact since the Pareto frontier shows that the region has few margin of improvement for crop production, as the region is already well performing in that objective but has some margin of improvement for carbon sequestration. In that sense the important fact revealed during the FoPIA-Surefarm 1 workshop is that the public goods are still not very well recognized by the farming system actors which fact could explain the awareness of ES provision and valuation. So, there is a need of more attention given to the functions related with environment and nature. This conclusion was confirmed during the FoPIA-Surefarm 2 workshop. A very important future strategy stressed by the participants is application of good farming practices as part of the necessity to preserve farming system ability to provide public goods along with private which is in conformity with the demand of the society. All of the stakeholders were convinced that without proper management of natural resources there is no future of any farming system.

The ES assessment suggest that there are points in the Pareto frontier that make it possible to have an increase in production and ES which require an increase in annual crops but also in

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

other forms of agriculture, mostly heterogeneous agriculture, which is more efficient for carbon storage. This conclusion is very much relevant to the FoPIA-Surefarm 2 results about the possible future alternatives for more resilient farming system. The most discussed ones were: "Innovation and technology improvement" and "Crop diversification". The diversification is led by the current challenges (mainly extreme weather conditions - drought) and new crops and varieties which are more suitable for a drier climate are a possible future state and which are in conformity with the local conditions and the state of natural capital. Simultaneously, the diversification process is related to the innovations because new crops may require new machines and ways of tilling the land. Thus, we can say that these two alternative systems are complementary and would better provide ES. Moreover, the adoption of new technology (including machineries as well as crops, fertilizers, and chemicals) would lead to cost reductions with specific focus on the change in tilling technology, respectively simultaneously preserving soil quality and satisfactory level of productivity.

The ES assessment results also inform about the possibility to improve carbon storage with some practices, or giving more space to other forms of heterogeneous agriculture and suggest the future adaptability capacity of the system confirmed under the Eur-Agri-SSP1 scenario under which a simultaneous increase in crop production and other environmental functions are expected.

Farming system simulation

Currently, many challenges are recognized by all the stakeholders as the most critical relate to the climate conditions and preservation of the natural capacity of the resources. FoPIA-Surefarm 1 results also show that the maintenance of „Natural resources" is rated among the most important functions that determine the identity of the system as for the indictor is the nutrient balance both of which directly correspond to the long-term resilience of the system. On the other side is the lowest rate of the "Biodiversity and habitat" and "Animal health and welfare" functions. Actually, there are very weak connections between crop production and animal breeding sectors. The farming system simulation revealed this important issue concerning the resilience of the system, namely the high dependency of the system on external fertilizers since the livestock sector does not give a strong positive feedback on the crop system. Thus, the current farming system will experience shortage in fertilizer at around year 12 because the main sources of mineral fertilization are soil mineralization of organic nitrogen, crop residues and chemical fertilizer. The system resilience is based on the quality of natural resources and agronomic decisions which allow system existence and growth (FoPIA-Surefarm 2) limited by the fact the current crop system is highly dependent on chemical nitrogen fertilization. Therefore,

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

the simulation conclusion that the livestock system is under-developed and has some margin to grow is realistic but it is not considered very much possible for the stakeholders participating in both FoPIA-Surefarm workshops.

The workshop discussions claimed that the preservation of the soil quality may support the robustness of the farming system but it is also a precondition of proper implementation of adaptations of the system which are imposed by the need to overcome negative effects of different challenges. FoPIA-Surefarm 1 showed that the adaptability is the first attempt of the farming system to overcome the environmental challenges. FoPIA-Surefarm 2 confirmed that from the agronomical point of view, the strategy of changes into production technologies and modernisation are compulsory in any of the alternative systems and the adaptability is the most probable way of grain farming system development.

Adaptability has been suggested by the different scenarios developed under the different shared socio-economic pathways for European agriculture (Eur-Agri-SSPs 1-5). The highest compatibility the future alternative systems have with the scenario SSP1 (agriculture encouraged for sustainability) according to the FoPIA-Surefarm 2. Farming simulation results are in conformity with that evaluation. The scenario performance requires a progressive reduction of the agricultural land, an increase in share of land cultivated with oil and protein crops, and a decrease in the share of the other crops which are part of the future strategies of achieving alternative systems. Actually, the high assessment of this scenario is rational since it represents very much the current efforts of the public and private sectors to introduce and mainstream environmental friendly practices and standards, introducing public payments for ecosystem services, pressure for decrease of the artificial inputs level etc. During the FoPIA-Surefarm 2 workshop many participants stated that these are the aims which they support but still the way of their implementation need to be improved.

6.1.7 Comparison of results for the Dutch case study

For the Dutch case study results and insights are compared from the FoPIA-SURE-Farm 2, ecosystem services modelling, and system dynamics. The causal loop diagram used in the system dynamics model was based on available insights from the FoPIA-SURE-Farm 2 workshop, and the quantitative model results can be compared to stakeholders' perceptions.

Potential to increase multiple functions

Potential to moderately improve food production and the maintenance of natural resources was deemed possible by the FoPIA-SURE-Farm 2 participants, and this is confirmed by the land use optimization model (using crop production as indicator for food production and carbon storage for maintenance of natural resources), for which the Pareto frontier indicated that an increase in crop production is possible with also an increase in carbon storage in the region. However, it is to be noted that an increase in both functions would come at the expense of grassland and therefore this has to be carefully evaluated in relation to the dairy system.

The land use optimization model provides solutions mostly in terms of land cover expansions, therefore the solution provided consists in expanding cropland and forest over grassland. In one alternative system where alternative crops would be introduced, participants in the FoPIA-SURE-Farm workshop indeed indicated a lower presence of livestock farmers and thus grassland in the system. For another alternative system, the FoPIA-SURE-Farm 2 participants proposed nature-inclusive agriculture, i.e., with more capacity to increase the synergy with carbon storage. Increase of active organic carbon in the soil would enhance much needed soil structure improvement for better soil structure, resulting in lower vulnerability to wind erosion and drought. The land use optimization model uses the proxy “energy input” and shows that some points of the Pareto frontier can be achieved by decreasing energy input. A low value of energy input can represent an agriculture more based on nature, however we recognize that the proxy “energy input” is quite vague and not precisely representative of certain practices. Moreover, a higher presence of livestock farmers in the nature-inclusive system was seen as a boundary condition, indicating that a reduction of grassland is not likely.

Nitrogen surplus

One of the most important insights from the nitrogen fluxes model is that the Dutch region is characterized by an excess of available nitrogen. When the availability of synthetic fertilizer and feed import would decrease in the future, the Dutch farming system is more robust than other EU case studies, as the historical buildup of nitrogen in the soil due to organic and synthetic fertilizer input ensures the availability of nitrogen for crop growth for a long time. The nitrogen surplus is confirmed to be an issue in the Netherlands as for years the country imported feed and synthetic nitrogen was applied. However, while the large availability of soil nitrogen has ensured high yields in the past, the large import of nitrogen is rather a concern than an asset. Recent policies were aimed at lowering and limiting the amount of nitrogen applications on the fields. As the reduction of nitrogen emissions was not sufficient to avoid biodiversity loss in nature areas, in 2019, a law suit that prescribed that emissions of nitrogen had to be stopped immediately brought the country and the agricultural sector in crisis. New policies have been introduced in 2020, including subsidizing voluntary stopping of livestock farming. While the reduction of livestock and other measures may reduce N surpluses and N emissions, arable farmers in the farming system also see the benefits of livestock farming in their region, which aligns with the nitrogen fluxes modelling. Perceived needs for higher presence of livestock

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

farmers in the future to maintain the status quo and for two out of four alternative systems (FoPIA-SURE-Farm 2), suggest that the excess of nutrients will only slowly decline towards the future.

Tipping points

Both FoPIA-SURE-Farm 2 and the system dynamics quantitative application concluded that starch potato production was close to a tipping point. The system dynamics approach allowed a better understanding of the dynamics making more evident how the short-term strategies could lead to possible collapses in the long term. An added value of the application of system dynamics was the possibility to provide quantifications of the relevant thresholds. Moreover, the system dynamics modelling confirmed that the system is close to thresholds for all the main challenges: decrease of starch potato in crop rotation due to nematode pressure; decrease in average yield due to decreasing soil quality, low water holding capacity and low drainage capacity; relative increase in profit per ha of other crops compared to starch potatoes; increase in production costs of starch potatoes.

Role of the starch processing cooperative (Avebe)

The system dynamics analysis allowed to confirm some findings about the role of Avebe in starch potato production for the Dutch case study. As the cooperative needs a certain production volume to stay profitable and innovative, the farmers producing starch potato in the system are more vulnerable to low yields, compared to increased profits of other crops or higher production costs: low yields mean less volume to sell, but in the long term also lower prices paid by the cooperative as facilities are underutilized and profits are less. As Avebe is dependent on a large starch potato area, it increases the prices of starch potatoes when yields are low, to ensure profitability of starch potato production. This increases the robustness of the system in the short term, but to do this, Avebe has to draw heavily on its financial reserves. Innovation has helped Avebe in the past to sell starch potato products in new markets and also increase prices of the end products. However, if environmental challenges consistently reduce the starch potato yields, Avebe does not earn enough with selling starch potatoes, therefore financial reserves would be depleted and they would not be able to pay high prices for starch potatoes in the long term; as a consequence farm incomes would decrease and the system may collapse, as farms would stop producing starch potatoes.

6.1.8 Comparison of results for the UK case study

For the UK case study, insights are compared and discussed coming from the land use optimization model and the the FoPIA-SURE-Farm 2 workshop. The results of the land use optimization model reveal in the region containing the UK case study a strict conflict between

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

land for agriculture and land for conservation (mainly grassland and forest). The conflict is strict in the sense that an increase in agricultural land results in a degradation of forest or grassland. Possible strategies are the following: (i) intensifying agricultural land in order to prevent agricultural expansion or (ii) little positive changes towards sustainable practices.

Insights from the FoPIA-SURE-Farm 2 revealed that the implementation of strategy (i) is seen as a scenario of system degradation, while strategy (ii) is seen as a desired scenario. The scenario compatible with strategy (i) is a system decline in which farmers would be forced to quit, leading to more intensification and amalgamation of farms, with resulting environmental degradation. On the contrary a likely and desired scenario for the system would be in line with strategy (ii): it would be regenerative, with farming practices causing strong positive change in the resilience of most attributes, most notably the provision of public goods, biodiversity and high welfare standards from their currently low-moderate base. Such a scenario would be transformational, as changes would be radical, long-term and fundamental.

Strategies to get to a diffused environmentally-friendly form of agriculture in the UK case study could promote a virtuous feedback loop between environmental payments and improvement of the natural capital. If environmental payments are increased, farmers are well connected to knowledge exchange networks and outside stakeholders, leading to practices that increase biodiversity, soil health, farmer happiness, animal welfare, and diversity in farm types. However, FoPIA-SURE-Farm stakeholders highlighted some constraining factors to this scenario: pressure from climate change, low prices (with the need to remain profitable), and low political will. These factors might perpetuate a destructive feedback loop leading to strategy (i).

6.1.9 Comparison of results for the Italian case study

For the Italian case study, results and insights from FoPIA-SURE Farm 2, Ecosystem Services (ES) assessment and Stochastic Simulation Models mentioned in D5.3 report (Appendix A and Appendix B) are compared.

Because the present deliverable does not provide the explanation of the Stochastic Simulation models and of their results, we provide here a brief recall. In particular, these models look at the farm economic viability considering the risks farmers face. Observing Gross Margin' levels related to hazelnut production and their variability, the D5.3 report includes two quantitative analyses aimed at assessing:

- profitability and economic risk of hazelnut production;
- effects of the introduction of an innovative risk management tool (as a prospective application) providing whole-income risk management (Income Stabilization Tool - IST).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

In Appendix A of D5.3, a Stochastic Simulation Model has been implemented. It was done through a risk analysis that uses the Value at Risk and Expected Tail Loss as risk indexes. In addition, a sensitivity analysis to assess the contribution of key input variables (e.g. yield, price and product quality) determining the overall risk faced by farmers has been done. In Appendix B, a scenario analysis looking for new strategies has been done simulating the introduction of the sector-specific IST [Regulation (EU) No 2017/2393]. Using the expected utility approach, farmers' willingness to participate and the financial sustainability of this tool have been estimated.

Results of the comparison among methods

The object and the measuring scale of the three methods used are quite different. In contrast with the previously described Stochastic Simulation Models focusing on the farm level, FoPIA-SURE Farm 2 is a qualitative analysis that looks at the whole farming system. The Stochastic Simulation Models have been conducted at the farm level and the ecosystem services assessment at a regional level. All three models refer to the same CS area focusing on the main crop of the system that is hazelnut. In this sense, all the methodologies are related in a complementary way.

FoPIA-SURE Farm 2 results highlight that the farming system is characterized by a strong dependence on the international market: the latter is able to influence hazelnut prices. Stakeholders face several challenges and will continue to do so in the future. Among these, the variability in hazelnut price as well as the increasingly extreme weather events threaten the profitability of farmers, and, in turn, the economic viability of the whole farming system. In such a context, the resilience and sustainability of farms play an important role especially with regard to the robustness of the system. These involve strongly their capacity to survive various risks and shocks that affect their income. In this sense, the results of the Stochastic Simulation approach became useful to provide an overview of the overall risk. Confirming FoPIA-SURE Farm 2 results, the Stochastic Simulation Model shows the farm component of the system to be quite robust. It can withstand the lowering of the prices or other events that affect the production level and quality. The riskiness of income drop by farmers results in a medium-low dimension. This explains the growing interest in the crop leading to the expansion of hazelnut cultivation. Farmers are not worried about the usual short-term fluctuation of their income.

A large part of the risk comes from production (yield), the market (price) and product quality, in descending order. Hence, the challenge raised in FoPIA-SURE Farm 2 and represented by the increasing power of the confectionary industry takes on much more relevance. The critical point, in fact, is the growing demand for products with high quality standards. As confirmed in

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

the Stochastic Simulation approach, the latter is rather variable due to increasing environmental conditions such as extreme climatic events and the increase of new phytopathologies. These have been identified in FoPIA-SURE Farm 2 as two important challenges that the system is facing with and is likely to continue to face with in the future. As confirmed by stakeholders in FoPIA-SURE Farm 2 workshop, the tools to cope with these challenges play a key role. The quantitative analysis showed in D5.3 (Appendix B) allows looking at the future. In particular, by means of stochastic simulations, we assessed the effects of introducing the IST. Results show that it could reduce strongly the income risk. However, public support from the Common Agricultural Policy (CAP) plays a key role in the implementation of the tool. This confirms what stakeholders affirmed during the FoPIA-SURE Farm 2 workshop: moving towards future scenarios, the public contribution is essential to encourage any kind of activity that can stimulate the FS growth.

Regarding the ecosystem services assessment, this addresses environmental issues that we did not consider in the Stochastic Simulation Model. FoPIA-SURE Farm 2 has not been fully dealt with how the hazelnut crop can affect the environment, but this topic has been dealt with much more thoroughly in the ecosystem services assessment. However, in the workshop, the possibility to be fixed more constraints by the public administration were discussed focusing on the possible impacts on the system. Stakeholders mentioned the need of reducing pressures on the environment, e.g. by highlighting the relevance of the organic area, integrated pest control and the safeguarding of water quality and its availability, sometimes forgoing high incomes due to the increasing production costs. Nevertheless, the results of FoPIA-SURE Farm 2 and ES can complement each other. Hazelnut crop, as confirmed in the results of the land use optimization model, play a positive role in CO_2 sequestration. This specific evaluation is not treated in FoPIA-SURE Farm 2. However, the increase of the hazelnut-cultivated surface in this specific environmental dimension could be positive. However, other environmental problems have emerged from FoPIA-SURE Farm 2. They mainly concern water quality, landscape deterioration and loss of biodiversity.

6.1.10 Comparison of results for the Polish case study

For the Polish case study, insights from the FoPIA-SURE-Farm 2 and the ecosystem service assessment modelling are compared.

Increasing the area of fruits and vegetables cultivation

The land use optimization model highlights that the land use corresponding to the Polish case study, based on fruits, vegetables, associations between permanent and annual crops and small parcels mingles with semi-natural elements, thus promoting a synergy between crop production and carbon sequestration. Therefore, the Polish case study has a role in increasing the synergy

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

between crop production and carbon storage in the region. The stakeholder workshop confirmed that the area of the case study is dedicate to horticulture because the terrain is hilly and highly fragmented. In this area, the case study is therefore not in competition with other land uses, especially with large-scale crop cultivation.

One of the alternative systems formulated in the FoPIA-SURE-Farm 2 workshop consists in increasing the cultivation of horticultural crops and to promote quality and diversity. This scenario is expected to increase the coupling with natural capital and, among other good effects, would increase incomes and would attract more people to the area. It is, however, to be noted that, concerning the possible expansion of horticulture, there might be a potential conflict with the land dedicated to linseed and pumpkin oil.

Need to keep intensification under control

The causal loop built for the Polish case study for the FoPIA-SURE-Farm 2 workshop highlighted the following causal loop: an increase in the income would increase the fertilization intensity; soil quality is very sensitive in the region to fertilization and can be very negatively impacted; in the longer term increase the fertilisation would negatively impact for soil quality and for crop yields and therefore on income. An increase in fertilizer input would be detrimental for the system, both in terms of soil fertility (soil quality) and for the yield in the long term. In fact, the soil is composed by loess and it is composed by very small mineral particles rich in calcium, it is an excellent substrate; however it is highly sensitive to erosion and an excessive fertilization can cause its degradation and the perturbation of the delicate bacterial equilibrium. The nitrogen fluxes model shows that the system is not very adapted to an increase in fertilizer and this is in agreement with the causal loop diagram of the FoPIA-SURE-Farm 2 workshop. The system is therefore more adapted to an expansion but with a low level intensification.

6.1.11 Comparison of results for the Romanian case study

Insights from the ecosystem service modelling highlighted that the Romanian case study is exposed to disturbance in the sense that it is characterized by shortage in fertilizers. Indeed, in the FoPIA-SURE-Farm workshop, the participants moderately scored "Exposed to disturbance" and confirmed that the system is currently underperforming. The region is historically characterized by low fertilizer inputs (and consequently low yields), with small farms that do not apply high amount of fertilizers as it would be expensive. Part of the production is used for animal feed and only a small part is sold. The simulations of the nitrogen model for the scenario Eur-Agri-SSP1 show that the impact of a decrease in fertilizer is lower because of the system diversification (use of legume crops), more in general, the diversity of the Romanian case study was argued as an attribute enhancing its resilience. The FoPIA-SURE-Farm 2 scenario "organic

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

farming" and "alternative crops / livestock" go in the direction of fertilizer reduction and diversification. The scenario "Organic farming" goes obviously in the direction of chemical fertilizer reduction. "Alternative crops / livestock", goes also in this direction as the alternative crops would need less fertilizer and would have a greater ability to use lower quality soils, examples are perennials such as sea buckthorn (*Hippophae rhamnoides*), cramberries and paulownia. Stakeholders are also expressing willingness to further improve diversification with alternative livestock, such as quails, bee farming and wild animals grown in agro-forestry systems (e.g., deers, wild pigs), promoting high-quality meat products. Concerning the scenarios "Commercial specialization of family mixed farms" and "cooperation/multifunctionality", the diversification would decrease, as the participants to the workshop argued that those scenarios would rely on small farms becoming medium-size (through land concentration) more economically viable and more intensified (although still relying on a mixed production).

The nitrogen fluxes model showed that the Romanian case study is in line with Eur-Agri-SSP3 and Eur-Agri-SSP5 as it has room for increasing land and increasing the livestock sector. However, all the scenarios proposed in the FoPIA-SURE-Farm 2 showed incompatibility with the Eur-Agri-SSP3 scenario. A reason for this point of non-convergence between the two results is that the nitrogen fluxes model only considers land use, land cover and nitrogen, whereas in the FoPIA-SURE-Farm methodology also other socio-economic factors are considered. In the case of "organic farming" there is even strong incompatibility: a possible explanation is that organic products are mostly exported to the EU and the farming system is very much dependent on subsidies coming from the CAP, and cereals and oilseed are the major export agricultural products in Romania.

The nitrogen fluxes model highlights also that the Romanian case study has room for increase the livestock sector as it would have the possibility to sustain it with internal feed resources. This conclusion is in line with the conclusion of the FoPIA-SURE-Farm 2 workshop regarding the alternative scenarios "Commercial specialization of mixed family farms" and "cooperation/multifunctionality". In these scenarios agricultural productions (crops and livestock) are expected to increase. In addition, the stekaholders expressed that these scenarios are the most likely to occur.

6.2 General cross-methods discussion

Short-term vs long-term resilience

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

One of the most important differences emerged from the comparison between the FoPIA-SURE-Farm assessments and the quantitative simulation models is that stakeholders are mostly focused on shorter-term resilience (mostly robustness), while simulation models can provide insights on the longer-term resilience. The short-term resilience to which stakeholders are more concerned is based on known and specific challenges, usually in the economic domain. On the contrary, models can provide a complementary focus on other challenges more in the long term and more based on the provision of public goods. In particular, system dynamics can provide insights about possible collapses in the long term.

Extensive livestock systems in Eur-Agri-SSP1

Both the French and the Spanish case study insights convey that a reduction of grassland is not in line with the Eur-Agri-SSP1 scenario for their specific production, strongly specialized in livestock. In both case studies the insights from the land use optimization model promote a transformation of the system based on the reduction of permanent grassland, however, the alternative systems considered in line with the Eur-Agri-SSP1 scenarios are not in line with such a reduction of permanent grassland.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

7 CONCLUDING REMARKS: LESSONS LEARNT AND FUTURE PERSPECTIVES

Francesco Accatino, Franziska Appel , Hugo Herrera, Wim Paas, Pytrik Reidsma

7.1 Framework for assessing future resilience

The resilience assessment framework of Meuwissen et al. (2019) was applied extensively in D5.3 (Reidsma et al., 2019) for studying the past and current resilience of the 11 SURE-Farm case study regions. In the context of this deliverable, we could reflect on the eligibility of this framework for assessing future resilience. After the modelling and workshop activities of this deliverable, we can say that the framework is quite adapted for the study of future resilience of farming systems. There were two main differences for studying future resilience compared to the resilience assessment of past and present resilience:

i) the high degree of reliance on simulation models
ii) the presence of multiple possible futures and, thus, the need to consider more possible alternative scenarios and possible challenges.

We believe that the SURE-Farm resilience assessment framework gave a robust scheme that helped to account for these two differences.

The first three blocks of the framework, i.e., system definition, challenges, and functions, were of fundamental importance because they were useful to define the possible futures and the domain of investigation.

Firstly, these blocks formalized the possible future in which resilience is tested. In the definition of the challenges it is important to specify which future challenges could be considered. In the FoPIA-SURE-Farm 2 methodology, the notion of "System decline" scenario was considered, i.e., stakeholders were invited to think about the likely impact of increase of challenges (beyond certain thresholds) on the delivery of functions. In the simulation models, future challenges were given as model input and the response of the system was simulated. For future resilience, along with these three steps we introduced the notion of *future scenario*, which was defined as a context in which the system can be in a possible future. For this deliverable we considered the Eur-Agri-SSP (Mathijs et al., 2018; Mitter et al., under review) scenarios describing possible future pathways for European agriculture and, for the AgriPoliS assessment we considered scenarios of changes in direct payments. The notion of scenario is different to the notion of challenge, as the scenario includes a set of context elements, some of which can be considered as additional challenges for a system, whereas others can be considered as opportunities. Secondly, the first three steps of the resilience framework helped in describing the system as schematized in the model. Each model has assumptions and specific aims, and clarifying these

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

elements with the first three blocks of the resilience assessment framework helped to define the boundaries of the models, e.g., what could be simulated and under which hypotheses.

Concerning resilience capacities (robustness, adaptability, and transformability), they could be assessed differently with qualitative and quantitative methods. With FoPIA-SURE-Farm 2, it was possible to draw conclusions about resilience capacities by discussing the strategies proposed by the stakeholders to reach alternative systems, by evaluating the performance of resilience attributes in alternative systems, by evaluating the compatibility of alternative systems to Eur-Agri-SSP scenarios, and by reflecting on whether alternative systems, formulated by stakeholders were adaptations or transformations. With quantitative methods, only specific capacities to specific challenged could be addressed. Not all resilience capacities could be addressed, but only the specific capacities that could be defined with clear metrics in the models.

A special mention should be made about transformability. We already highlighted the difficulty to measure transformability with quantitative and simulation models, because models cannot transform its own assumptions and the elements simulated. We also highlighted that, on the contrary, participants of workshop could think "out-of-the-box" and conceive alternative systems that constitute "transformations" of the current one. However, we noticed in the 9 FoPIA-SURE_Farm 2 workshops that stakeholders tend to take into consideration alternative system not so different from the current ones, in other words, conceiving transformations is not easy task, neither with stakeholders. This is in line with the low capacity to transform as pointed out in D5.3 (Reidsma et al., 2019), but could also possibly be explained by path-dependent thinking of workshop participants.

Resilience attributes are about the concept of general resilience, and, put in the context of future resilience assessment, they enhance the likelihood of the system to be resilient whichever is the future challenge (known or unknown) and whichever is the future scenario. Therefore, if the other blocks of the resilience assessment framework are more targeted on specific scenarios and future challenges, resilience attributes are an indication of general resilience in all possible futures.

7.2 Messages from the different methods concerning future resilience

Messages originating from FoPIA-SURE-Farm 2

The participatory workshops on future resilience revealed that most farming systems are close to at least one critical threshold. When critical thresholds of challenges are exceeded, important farming systems indicators, mainly related to food production, economic viability and

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

maintenance of natural resources, are perceived to moderately decline in performance. In all case studies, decline is expected to be realized by a chain of interacting threshold. Economic viability of farms is an important factor in this chain, which (in)directly interacts with another important factors related to the attractiveness of the farming system for living and working. This brings us directly to the importance of the complementarity of model simulations in WP5. In the systems dynamics modelling, closeness to critical thresholds can be evaluated, e.g. minimum production levels and/or minimum economic viability levels; in AgriPolis, economic viability and farmer population size, important indicators for rural attractivity, are simulated, making it possible to assess impacts of strategies on farm demographics. Both Systems Dynamics modelling and AgriPolis allow for ex-ante assessments on important system indicators involved in mechanisms that can lead to the seemingly irrevocable process of farming system decline, i.e. in the sense of a shrinking rural population.

When it comes to explorations towards the future, modelling ecosystem services gives insight for the room for maneuver to improve productivity while improving also the natural resource base. Room for improving productivity and improving the maintenance of natural resources was suggested by both the eco-system service assessment as well as by the proposed alternative systems in FoPIA-SURE-Farm 2. Proposed alternative systems could be seen as illustrations of possible alternatives as proposed in the eco-system service assessment. Where the latter can be used to triangulate the perceptions of participants that might over- or underestimate the potential for improvement.

Compared to maintaining the status quo, boundary conditions and strategies for proposed alternative systems in FoPIA-SURE-Farm 2 are increasingly in the social and institutional domain and less so in the economic and agronomic domain. Especially the boundary conditions and strategies in the institutional domain cannot be realized with help from actors outside the farming system. This requires farming systems to be connected with actors outside the farming system, which is currently not perceived to be the case (D5.2; Paas et al. 2019; FoPIA-SURE-Farm 1). Moreover, alternative systems are most adaptations to current systems and are at most moderately, but often only weakly compatible with Eur-Agri-SSPs. This suggest that even more radical system changes might be necessary, which probably requires the realization of more boundary conditions in the institutional domain.

Messages originating from the ecosystem services assessment

The land use optimization model highlighted that some farming systems, more than others, have the role to promote synergies between ecosystem services. This is the case e.g., for hazelnut cultivations in Italy and vegetable and fruit cultivation in Poland, as they promote both

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

carbon storage and crop production. The capacity to promote multiple ecosystem services gives to the farming system the important role of promoting more ecosystem services in the region. Although the weak point of the land use optimization model used in this deliverable is that only two ecosystem service indicators were considered, it is possible to refer to the analysis of ecosystem services provision in D5.3, in which, for each case study, we gave an index of multifunctionality and discussed their capacity to enhance ecosystem service multifunctionality provision with respect to the surrounding region. With this in mind, the multifunctional farming system could be promoted over more mono-functional land uses in the regions. Other farming systems, instead, were focused only on food production. For example, the Swedish case study is mostly focused on the production of crops, forage, and animal-source food and it is in clear contrast with the surrounding region, which provides other ecosystem services. In case of clear separation between food production and the provision of other ecosystem services, possible scenarios to be discussed with the stakeholders can range between these two extremes: either improve the efficiency of the food production system (for example via technology) so that agricultural land could be reduced (land sparing strategy); or to promote practices that improve the provision of other ecosystem services in the agricultural land (land sharing strategy).

As pointed out in D5.3, indices of ecosystem services (we used the data provided by the Joint Research Center, Maes et al., 2012) can be different from what was observed at a finer scale by stakeholders and experts. In many cases, this was due to a set of elements that either improve or worsen the information given by the index (which is calculated at a higher scale). In light of this, we recommend that indices should be considered carefully, and the results obtained with the land use optimization model should be discussed more in detail with stakeholders.

The nitrogen fluxes model highlighted that there are some elements that could improve the robustness of the system to a progressive reduction in external input availability, in other words, there are some systems that are more advantaged in case they need to become progressively more and more self-sufficient. Whereas a more complete list is given in the apposite section (Section 3.13), here we list three resilience-enhancing attributes indicators and two resilience-constraining attribute indicator. A first important attribute enhancing resilience is the integration of crops and livestock. Such integration can be already occurring at the farming system level (e.g., see the Romanian and the German case study), or it can happen that a farming system is focalized only on crop or on livestock and it is well connected with the complementary part in the same region (e.g., the French and the Dutch case study). A second important resilience-enhancing attribute is the low dependency on synthetic fertilizer, and this is the case of hazelnut cultivation in the Italian case study. A third resilience-enhancing attribute is crop diversification (see the Romanian case study), as it makes it possible to provide a varied array of necessary food and feed items for human and animal consumption. On the side of

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

resilience-constraining attributes, the competition between feed and food reduces the possible outputs of the system, as a part of the land that could be used for producing food is needed to feed livestock.

Messages originating from the AgriPoliS assessment

With AgriPoliS we have simulated the influence of policy measures on the resilience of farming systems. For the funding period 2021-2027, the European Commission wants to redesign the payment scheme in order to achieve a fairer distribution of funds. But what does a fairer distribution of direct payments mean in a European context? Since the expansion of the EU, in particular the New Member States of Central and Eastern Europe, the European agriculture became increasingly diverse (see also Pitson et al. 2019). But this had not changed the “European Model of Agriculture” describing the medium-sized family farms which are dominant in Western EU countries (Cardwell, 2004). To examine how the proposed changes in the direct payments would affect the heterogeneous agricultural structures in the EU, we simulate the proposed capping from 2021 with the agent-based model AgriPoliS for the German case study region Altmark that is very heterogeneous and thus features both western family farms and large cooperative farms of Central and Eastern European agriculture.

From the simulation of the Altmark region with AgriPoliS it can be concluded that a capping of direct payments results in a higher number of farms but the farm size structure is strongly distorted in favor of a farm size around the cap limit. Further, a capping of direct payments have implications on the structure of cultivation, which affects particularly the dairy production. In contrast to the proposed capping of direct payments a hypothetical complete phasing out of direct payments leads to a strong decline in the number of farms. However, no particular farm size is clearly preferred or disadvantaged. The heterogeneity in the farm size structures is maintained. Similarly, the production and cultivation structure does not change significantly, with the only exception that there is an increase in land-independent production (pigs). Thus, farms seem to be able to adapt and also the exit of farms can increase the resilience of an agricultural region as this enables other farms to grow to economies of scale and thus enhance its potential to absorb shocks.

The simulation with AgriPoliS highlights that changes in direct payments schemes not only affect the farm size structure, but also the functions of the respective farming system and therefore its resilience. Instead of trying to establish agricultural structures in accordance with an “ideal European structure” (Cardwell, 2004), the CAP should reflect on their initial aims and spend the money more purposefully. Moreover, a loss of farm structure diversity may also affect the production diversity and therefore be contradictory to the CAP aims.

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Messages originating from the System Dynamics assessment

System dynamics was used to do qualitative and quantitative analysis of selected case studies for different alternatives futures outlined in the Eur-Agri-SSP. The qualitative analysis was used to identify some resources that could help the system to be less vulnerable to external shocks in the future by fostering its ability to adapt to challenging circumstances. Among the key resources identified in the analysis were: farms' capital, human capital, workforce available and natural resources in the form of water available and soil nutrients.

From the qualitative analysis it could be concluded that alternatives to enhance resilience proposed by stakeholders during FoPIA –SURE-Farm 2 are, in all the cases analysed suited for the SSP1. In all the cases the stakeholders proposed alternatives that are likely to be successful and easy to implement in a future where there is high environmental awareness accompanied by economic growth and wealth distribution. In most cases, all but the Netherlands, the stakeholder also proposed at least one alternative that is highly compatible with the SSP5.

The results show that farmers are not considering alternatives aligned with the other scenarios. This could be expected as it is easier to think about aspirational futures, like SSP1 and SSP5. However, since it is likely that the future will be a mix of the different scenarios rather than any of them, farmers should consider a wider range of strategies that could help them to be more flexible.

The qualitative results are supported by our quantitative analysis using system dynamics simulations. When we tested resilience of the current system to stressors in the different scenarios, the system showed overall a higher resilience in the scenarios SSP1 and SSP5 than for the rest. This highlights the need to develop resources that could increase the farmers flexibility and resilience (e.g. access to cheap credit, local research and development and local markets).

Moreover, while resilience is often used as a characteristic of the whole system, the quantitative analysis also shows that are differences among different outcome functions. For instance, in the same scenario, farms could simultaneously show a high resilience in terms of offering jobs and low resilience when it comes to food production.

Finally the quantitative analysis of the system dynamics simulations highlights that innovation, networks and cooperation contribute to building resilience against economic disturbances. In particular , the cooperative Avebe in the Veenkoloniën was identified in our analysis as one of the reasons why starch potato farms are resilient to changes in the economic landscape (variations in costs or prices of other crops).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Probably because economic shocks are something farmers have learnt to plan for, building resilience to environmental challenges at the scale that could be expected due to climate change it is more difficult and require further intervention. The analysis presented in this deliverable has already highlighted some of the leverage points where interventions could be introduced. Further research is needed regarding which interventions could be conceived and which their impact might be in the future resilience of farming systems.

7.3 Methodological considerations and possible future perspectives

As highlighted in the presentation of the Integrated Assessment (IA) toolbox (D5.1, Herrera et al., 2018), the array of models and methods used serve to provide a complete vision on the system and to assess the resilience under different angles. While FoPIA –SURE-Farm 2 allowed to have a holistic view on the system, simulation models are more specific on certain aspect (although System Dynamics can maintain a relatively holistic view). Chapter 6 showed that for a number of case studies it was possible to make considerations involving the results coming from different models. Comparison was not always easy as, for example, in order to compare results from FoPIA-SURE-Farm 2 and the land use optimization model, it was necessary to consider the impact on land use and land cover that different alternative system might have.

The complementarity between qualitative (participatory) and quantitative (simulation) approaches allowed having wide array of indicators calculated and challenges considered. Participatory approaches made it possible to enlarge the array of elements considered, as generally models are very specific on certain elements. The added value of simulation models was that, for certain indicators, a quantification could be provided. Other than that, we found that stakeholders tended to focus on short-term socio-economic challenges and functions. On the contrary, the models used made it possible to explore the system on a longer-term view, and this relates mostly natural resources (e.g., the depletion of organic matter in the soil). Therefore, the model can provide a different view to stakeholders, also for the elements that do not concern the stakeholders directly or on the short term.

We argued that models cannot provide transformative scenarios that changed their own assumptions and field of investigations. However, it is possible to re-formulate the models (i.e., changing their assumptions, the elements and the relationships included) so that it is possible to include the alternative systems provided by stakeholders. In this way it could be possible to have a more detailed assessment on the impact of alternative systems on different system functions, it would be possible to simulate the implementation of strategies mentioned by stakeholders under different scenarios. In this way, the complementarity between approaches could be brought to the next level, i.e., using the ability of stakeholders and researchers to conceive alternative scenarios, and using models to have a quantified and detailed assessment of the

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

impact on different functions. At moment, this was done for the AgriPoliS assessment (originating from the activity done for D3.8 on farming system demography), but still has not been done systematically for all case studies. Causal loop diagrams were developed per case study in the FoPIA-SURE-Farm 2 approach, showing how challenges, function indicators, attributes and strategies were related. The qualitative system dynamics model synthesized these causal loops at EU farming system level. The quantitative system dynamics models focused on strategies that were adaptive instead of transformative, but transformative strategies can be further explored using the causal loop diagrams.

One of the outcomes of D5.3 is that the stakeholders tend not to notice opportunities for transformation in the current system. One of the outcomes of this deliverable is that stakeholders, when proposing alternative systems, remain attached to the present system and without really conceiving transformative alternative systems. It is part of "resilience thinking" to acknowledge that change is part of the normal dynamics of a system and a system should be ready to face even unknown and unpredicted challenges and go through transformations (Darnhofer, 2014). This leads to the necessity of encouraging of "thinking the unthinkable" for conceiving transformative alternatives to the current state. Models can be a starting point for trigger some thinking in this sense, some strategies (different that those already applied in the past) can be simulated and results can be presented to stakeholders to make them aware about new possible strategies that would lead to transformative systems.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

REFERENCES

Accatino, F., Neumeister, D. 2019. FoPIA-Surefarm case-study report France. In: Paas, W., Accatino, F., Antonioli, F., Appel, F., Bardaji, I., Coopmans, I., Courtney, P., Gavrilescu, C., Heinrich, F., Krupin, V., Manevska-Tasevska, G., Neumeister, D., Peneva, M., Rommel, J., Severini, S., Soriano, B., Tudor, M., Urquhart, J., Wauters, E., Zawalinska, K., Meuwissen, M., Reidsma, P., 2019. D5.2 Participatory impact assessment of sustainability and resilience of EU farming systems. Sustainable and resilient EU farming systems (SureFarm) project report, EU Horizon 2020 Grant Agreement No. 727520. https://doi.org/10.13140/RG.2.2.25104.25601

Accatino, F., Tonda, A., Dross, C., Léger, F., Tichit, M. 2019. Trade-Offs and Synergies between Livestock Production and Other Ecosystem Services. Agricultural Systems 168: 58–72. https://doi.org/10.1016/j.agsy.2018.08.002.

Antonini, C., Argilés-Bosch, J.M., 2017. Productivity and environmental costs from intensification of farming. A panel data analysis across EU regions. Journal of cleaner production, 140, 796-803.

Antunes, P., Santos, R., Videira, N., 2006. Participatory decision making for sustainable development—the use of mediated modelling techniques. Land use policy, 23(1), 44-52.

Arnoldi, J. F., Bideault, A., Loreau, M., Haegeman, B., 2018. How ecosystems recover from pulse perturbations: A theory of short-to long-term responses. Journal of theoretical biology, 436, 79-92.

Aubin, J.P., 1991. Viability theory. Systems and control: foundations and applications. Birkhauser, Boston, USA.

Balmann, A., 1997. Farm-based modelling of regional structural change: a cellular automata approach, European review of agricultural economics Found. Eur. Rev. Agric. Econ., 24 (1), pp. 85-108

Bender, E. A., Case, T. J., Gilpin, M.E., 1984. Perturbation experiments in community ecology: theory and practice. Ecology, 65(1), 1-13.

Biggs, R., Peterson, G.D., Rocha, J.C., 2018. The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. Ecol. Soc. 23. https://doi.org/10.5751/ES-10264-230309

Brzezina, N., Kopainsky, B., Mathijs, E., 2016. Can organic farming reduce vulnerabilities and enhance the resilience of the European food system? A critical assessment using system dynamics structural thinking tools. Sustain. https://doi.org/10.3390/su8100971

Buitenhuis, Y., Candel, J., Feindt, P.H., Termeer, K., Mathijs, E., Bardají, I., Black, J., Martikainen, A., Moeyersons, M., Sorrentino, A., Improving the resilience-enabling capacity of the Common Agricultural Policy: policy recommendations for more resilient EU farming systems. Submitted.

Cabell, J.F., Oelofse, M., 2012. An Indicator Framework for Assessing Agroecosystem Resilience. Ecol. Soc. 17, 18. https://doi.org/10.5751/ES-04666-170118

Chapin III, F. S., Kofinas, G. P., Olke, C., 2009. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. Environmental Conservation, 37(2), 223.

Clivot, H., Mouny, J.-C., Duparque, A., Dihn, J.-L., Denoroy, P., Houot, S., Vertès, F., Trochard, R., Bouthier, A., Sagot, S., Mary, B., 2019. Modeling soil organic carbon evolution in long-term arable experiments with AGM model. Environmental modelling & software, 118, 99-113.

Coopmans I., Dessein, J., Bijttebier, J., Antonioli, F., Appel, F., Berry, R., Bertolozzi, D., Bohateret, V.M., Bruma, I.S., Courtney, P., Casonato, C., Dinulescu, C., Dinu-Vasiliu, C., Dobay, K.M., Dolleans, E., Fiorini, E., Florian, V., Gavrilescu, C., Gradziuk, P., Heinrich, F., Izvoranu, A.M., Johansson, S., Klein, K.G., Matei, D.M.T., Meuwissen, M., Neumeister, D., Paolini, G., Peneva, M., Pettit, A., Pineau, C., Pitson, C., Severini, S., Slijper, T., Soriano, B., Tanasa, L., Toma, C., Tudor, M., Urquhart, J., Zawalińska, K., Wauters, E., 2019. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Daily, G.C., 1997. Nature's services (Vol. 3) Island Press, Washington, DC.

Darnhofer I., Resilience and why it matters for farm management. European Review of Agricultural Economics, 41: 461-484.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.A.M.T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6(2), 182-197.

De Boer, I.J.M., Van Ittersum, M.K., 2018. Circularity in agricultural production

Delmotte, S., Lopez-Ridaura, S., Barbier, J.M., Wery, J., 2013. Prospective and participatory integrated assessment of agricultural systems from farm to regional scales: Comparison of three modeling approaches. J. Environ. Manage. 129, 493–502. https://doi.org/10.1016/j.jenvman.2013.08.001

Diehl, E., Sterman, J. D., 1995. Effects of Feedback complexity on Dynamic Decision Making. Organizational Behavior and Human Decision Processes, 62, 196–215.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Dodgson, J.S., Spackman, M. Peraman, A., Philips, L.D., 2009. Multi-criteria analysis: a manual. London: Department of Environment, Transport, and the Regions

Fagerholm, N., Torralba, M., Burgess, P.J., Plieninger, T., 2016. A systematic map of ecosystem services assessments around European agroforestry. Ecological Indicators 62, 47–65

Finger, R., Swinton, S.M., El Benni, N., Walter, A., 2019. Precision Farming at the Nexus of Agricultural Production and the Environment. Annu. Rev. Resour. Econ. https://doi.org/10.1146/annurev-resource-100518-093929

Fischer, J., Abson, D.J., Butsic, V., Chappell, M.J., Ekroos, J., Hanspach, J., Kuemerle, T. Smith, H.G., von Wehrden, H., 2013. Land sparing vs land sharing: moving forward. Conservation Letters, 7, 149 – 157.

Ford, J.D., 2009. Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. Regional Environmental Change, 9: 83-100.

Forrester, J., 1961. Industrial Dynamics.

Gunderson, L. H. 2000. Ecological resilience—in theory and application. Annual review of ecology and systematics, 31(1), 425-439.

Gunderson, L.H., Holling, C.S., 2002. Panarchy: Understanding transformations in human and natural systems. Island Press, Washington D.C., USA.

Happe, K. 2004: Agricultural policies and farm structures - agent-based modelling and application to EU-policy reform Stud. Agric. Food Sect. Cent. East. Eur., 30 (IAMO)

Happe, K., Balmann, A., Kellermann, K. and Sahrbacher, C. 2008: Does structure matter? The impact of switching the agricultural policy regime on farm structures J. Econ. Behav. Organ., 67 (2), pp. 431-444

Herrera-de-Leon, H. J., Kopainsky, B. 2019. Do you bend or break? System dynamics in resilience planning for food security. System Dynamics Review, 35(4), 287-309.

Herrera, H., 2017. From Metaphor to Practice: Operationalizing the Analysis of Resilience Using System Dynamics Modelling. Syst. Res. Behav. Sci. 34, 444–462. https://doi.org/10.1002/sres.2468

Herrera, H., Kopainsky, B., Appel, F., Balmann, A., Accatino, F., Tichit, M., Antonioli, F., Severini, S., Paas, W., Reidsma, P., 2018. D5.1 Impact assessment tool to assess the resilience of farming systems and their delivery of private and public goods. Sustainable and resilient EU farming systems (SureFarm) project report, EU Horizon 2020 Grant Agreement No. 727520.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Herrera,H., Kopainsky,B., 2020. Using system dynamics to support a participatory assessment of resilience. Environment Systems and Decisions, 1-14.

Henry, D., Ramirez-Marquez, J. E., 2012. Generic metrics and quantitative approaches for system resilience as a function of time. Reliability Engineering & System Safety, 99, 114-122.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4(1),1–23.

Holling, C.S., Gunderson, L.H., 2002. Panarchy: Understanding transformations in human and natural systems.

Hou, Y., Bai, Z., Lesschen, J.P., Staritsky, I.G., Sikirica, N., Ma, L., Velthof, G.L., Oenema, O., 2016. Feed use and nitrogen excretion of livestock in EU-27. Agric. Ecosyst. Environ. 218, 232–244. https://doi.org/10.1016/j.agee.2015.11.025

Hristov, J., Clough, Y., Sahlin, U., Smith, H.G., Stjernman, M., Olsson, O., Sahrbacher, A., Brady, M.V. 2020. Impacts of the EU's Common Agricultural Policy „greening“ reform on agricultural development, biodiversity, and ecosystem services. Applied Economic Perspectives and Policy

Kellermann, K., Happe, K., Sahrbacher, C., Balmann, A., Brady, M. Schnicke, H., Osuch, A. 2008: AgriPoliS 2.1 – Model Documentation.

Kinzig, A.P., Ryan, P., Etienne, M., Allison, H., Elmqvist, T., Walker, B.H., 2006. Resilience and regime shifts: Assessing cascading effects. Ecol. Soc. 11, 20. https://doi.org/10.5751/ES-01678-110120

Le Noë, J., Billen, G., Garnier, J., 2017. How the structure of agro-food systems shapes nitrogen, phosphorus, and carbon fluxes: The generalized representation of agro-food system applied at the regional scale in France. Science of The Total Environment 586, 42–55. https://doi.org/10.1016/j.scitotenv.2017.02.040

Levin, S. A. 1998. Ecosystems and the biosphere as complex adaptive systems. Ecosystems 1:431–436.

Maes, J., Nina F., Grazia Z., Ana B., Pilar V., Ivits, E., Polce, C., et al. 2015. Mapping and Assessment of Ecosystems and Their Services: Trends in Ecosystems and Ecosystem Services in the European Union between 2000 and 2010. Luxembourg: Publications Office. http://bookshop.europa.eu/uri?target=EUB:NOTICE:LBNA27143:EN:HTML.

Mall, R. K., Gupta, A., Sonkar, G. 2017. Effect of climate change on agricultural crops. In Current developments in biotechnology and bioengineering (pp. 23-46). Elsevier.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Mathijs, E., Deckers, J., Kopainsky, B., Nitzko, S., Spiller, A., 2018. D1.2 Scenarios for EU farming. Sustainable and resilient EU farming systems (SURE-Farm) project report.

Mathijs, E., Wauters, E., Components of a resilience-enabling environment for Europe's farming systems. Submitted.

Meadows, D. 1976. The unavoidable A Priori. Pegasus Communications, 488.

Meuwissen, M., Feindt, P., Spiegel, A., Termeer, C., Mathijs, E., de Mey, Y., Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalinska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, M., Candel, J., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.J., Peneva, M., Gavrilescu, C., Reidsma, P., 2019. A framework to assess the resilience of farming systems. Agric. Syst.

Mitter, H., Techen A., Sinabell, F., Helming, K., Kok, K., Priess, J.A., Schmid, E., Bodirsky, B.L., Holman, B.L., Lehtonen, H., Leip, A. 2019. A protocol to develop shared socio-economic pathways for European agriculture. Journal of Environmental Management, 252, 109701.

Mitter, H., Techen, A.-K., Sinabell, F., Helming, K., Schmid, E., Bodirsky, B.L., Holman, I., Kok, K., Lehtonen, H., Leip, A., Le Mouël, C., Mathijs, E., Mehdi, B., Mittenzwei, K., Mora, O., Øistad, K., Øygarden, L., Priess, J.A., Reidsma, P., Schaldach, R., Schönhart, M., n.d. Shared Socio-economic Pathways for European agriculture and food systems: the Eur-Agri-SSPs. Under review.

Morecroft, J.D.W. 2015. Strategic Modelling and Business Dynamics. A feedback systems approach.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2

Paas, W., Accatino, F., Antonioli, F., Appel, F., Bardaji, I., Coopmans, I., Courtney, P., Gavrilescu, C., Heinrich, F., Krupin, V., Manevska-Tasevska, G., Neumeister, D., Peneva, M., Rommel, J., Severini, S., Soriano, B., Tudor, M., Urquhart, J., Wauters, E., Zawalinska, K., Meuwissen, M., Reidsma, P., 2019. D5.2 Participatory impact assessment of sustainability and resilience of EU farming systems. Sustainable and resilient EU farming systems (SureFarm) project report, EU Horizon 2020 Grant Agreement No. 727520. https://doi.org/10.13140/RG.2.2.25104.25601

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Pantera, A., Burgess, P.J., Mosquera Losada, R., Moreno, G., López-Díaz, M.L., Corroyer, N., McAdam, J., Rosati, A., Papadopoulos, A.M., Graves, A., Rigueiro Rodríguez, A., Ferreiro-Domínguez, N., Fernández Lorenzo, J.L., González-Hernández, M.P., Papanastasis, V.P., Mantzanas, K., Van Lerberghe, P., Malignier, N., 2018. Agroforestry for high value tree systems in Europe. Agroforest Syst 92, 945–959.

Pimm, S.L. , Lawton, J.H. , 1977. Number of trophic levels in ecological communities. Nature 268, 329–331 .

Pitson, C., Appel, A., Dong, C., Balmann, A. (2019). D3.4 Open-access paper on the formulation and adaptation of AB models to simulate generational renewal. Sustainable and resilient EU farming systems (SureFarm) project report, EU Horizon 2020 Grant Agreement No. 727520. https://doi.org/10.13140/RG.2.2.25104.25601

Pitson, C., Appel, A., Heinrich, F., Bijttebier, J. 2020. D3.5 Report on future farm demographics and structural change in selected regions of the EU. Sustainable and resilient EU farming systems (SureFarm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Power, Alison G. 2010. 'Ecosystem Services and Agriculture: Tradeoffs and Synergies'. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365 (1554): 2959–71. https://doi.org/10.1098/rstb.2010.0143.

Pretty, J., Bharucha, Z. P. 2014. Sustainable intensification in agricultural systems. Annals of botany, 114(8), 1571-1596.

Reidsma, P., Ewert, F., Lansink, A. O., Leemans, R. 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. European journal of agronomy, 32(1), 91-102.

Reidsma, P., Spiegel, A., Paas, W., Accatino, F., Antonioli, F., Appel, F., Bardají, I., Berry, R., Bertolozzi, D., Bijttebier, J., Black, J., Buitenhuis, Y., Coopmans, I., Courtney, P., Feindt, P., Gavrilescu, C., Hansson, H., Jendrzejewski, B., Khafagy, A., Krupin, V., Lagerkvist, C., Larson, S., Lievens, E., Mathijs, E., Manevksa-Tasevska, G., Maye, D., Ollendorf, F., Peneva, M., Pettitm A., Pinsard, C., Rommel, J., Senni, S., Severini, S., Slijper, T., Soriano, B., Urquhart, J., Valchovska, S., Vlgani, M., Weuters, E., Zawalińska, K., Meuzissen, M., 2019. D5.3 Resilience assessment of current farming systems across the European Union. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Resilience Alliance, 2010. Assessing resilience in social-ecological systems. Workbook for practitioners. Version 2.0. Online: http://www.resalliance.org/3871.php.

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Richardson, G.P. 2011. Reflections on the foundations of system dynamics. System Dynamics Review, 27(3), 219–243.

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., Woznicki, S. A. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management, 16, 145-163.

Schütz, L. 2020. Analysing the resilience of an arable farming system in the Veenkoloniën, NL, using system dynamics modelling.

Sieber, S., Amjath-Babu, T.S., Reidsma, P., Koenig, H., Piorr, A., Bezlepkina, I., Mueller, K., 2018. Sustainability impact assessment tools for land use policy advice: A comparative analysis of five research approaches. Land use policy 71, 75–85. https://doi.org/10.1016/j.landusepol.2017.11.042

Silva, J.V., P. Reidsma, M.K. van Ittersum, 2017. Crop yields gaps in Dutch arable farming systems: Analysis at crop and crop rotation level. Agricultural Systems 158, 78–92. Available at: https://doi.org/10.1016/j.agsy.2017.06.005.

Soriano, B., Bardají, I., Bertolozzi, D., San Martín, C., Spiegel, A., Slijper, T., Meuwissen, M., Rommel, J., Hansson, H., Severini, S. Antonioli, F., Berry, R., Khafagy, A., Urquhart, J., Harizanova, H., Stoyanova, Z., Coopmans, I., Wauters, E., Bijttebier, J., neumeister, D., Accatino, F., Pinsard, C., Tudor, M., Gavrilescu, C., Luca, L., Izvoranu, A.M., Zawalińska, K., Jendrzejewski, B., Gradziuk, P., Bańkowska, K., Krupin, V., Ollendorf, F., Appel, F., Garrido, A. D2.6 Report on state and outlook for risk management in EU agriculture. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Soussana, J.F. Lemarie, G., 2014. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grassland and crop-livestock systems. Agriculture, Ecosystems and Environment, 190, 9-17.

Spiegel, A., Slijper, T., De Mey, Y., Poortvliet, M., Rommel, J., Hansson, H., Vigani, M., Soriano, B., Wauters, E., Appel, F., Antonioli, F., Harizanova, H., Gavrilescu, C., Gradziuk, P., Neumeister, D., Meuwissen, M. 2019. D2.1 Report on farmers' perceptions of risk, adaptive capacity and resilience. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Sterman, J.D. 1994. Learning in and about complex systems. System Dynamics Review, 10, 291–330.

Sterman, J., Fiddaman, T., Franck, T. R., Jones, A., McCauley, S., Rice, P., et al., 2012. Climate interactive: the C-ROADS climate policy model.

Sterman, J.D., Sweeney, L. 2002. Cloudy skies: assessing public understanding of global warming. System Dynamics Review, 18(2), 207–240.

Strijker, D. 2007. Globalization of a potato starch co-operative: the case of AVEBE. In International business geography (pp. 185-201). Routledge.

Stoate, C., Boatman, N. D., Borralho, R. J., Carvalho, C. R., De Snoo, G. R., Eden, P. 2000. Ecological impacts of arable intensification in Europe. Journal of environmental management, 63(4), 337-365.

Termeer, K., Candel, J., Feindt, P.H., Buitenhuis, Y., 2018. D4.1 Assessing how policies enable or constrain the resilience of farming systems in the European Union: the Resilience Assessment Tool (ResAT). Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, L. 2009. Quantifying sustainability: resilience, efficiency and the return of information theory. Ecological complexity, 6, 27-36.

Unay-Gailhard I., Balmann, A., Appel, F., 2018. D1.3 Dimensions of SURE-Farm Farm typology for farm resilience assessment. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Urquhart, J., Accatino, F., Appel, F., Antonioli, F., Berry, R., Bertolozzi, D., Bijttebier, J., Black, J., Bohateret, V.M., Bruma, I.S., Coopmans, I., Courtney, P., Baskiewicz, H., Dinculsecu, C., Dinu-Vasiliu, C., Dobay, K.M., Gavrilescu, C., Gradziuk, P., Heinrich, F., Izvoranu, A.M., Johansson, S., Klein, K., Matei, D., Maye, D., Peneva, M., Pettit, A., Pitson, C., Severini, S., Slijper, T., Soriano, B., Tanasa, L., Toma, C., Tudor, M.M., Vigani, M., Zawalińska, K. 2019. D2.3 Report on farmers' learning capacity and networks of influence in 11 European case studies. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Van Passel, S., Massetti, E., Mendelsohn, R. 2017. A Ricardian analysis of the impact of climate change on European agriculture. Environmental and Resource Economics, 67(4), 725-760.

Vaidya, A., Mayer, A.L., 2014. Use of the participatory approach to develop sustainability assessments for natural resource management. Int. J. Sustain. Dev. World Ecol. 21, 369–379. https://doi.org/10.1080/13504509.2013.868376

Van Der Bolt, B., Van Nes, E.H., Bathiany, S., Vollebregt, M.E., Scheffer, M., 2018. Climate reddening increases the chance of critical transitions. Nat. Clim. Chang. https://doi.org/10.1038/s41558-018-0160-7

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R., 2002. Resilience management in social-ecological systems: A working hypothesis for a participatory approach. Ecol. Soc. 6, 14.

Walker, B. H., Carpenter, S. R., Rockstrom, J., Crépin, A. S., Peterson, G. D. 2012. Drivers," slow" variables," fast" variables, shocks, and resilience. Ecology and Society, 17(3).

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A. 2004. Resilience, adaptability and transformability in social--ecological systems. Ecology and Society, 9(2), 5.

Weltin, M., Zasada, I. 2018. Farmers' choices of adopting and coupling strategies of sustainable intensification–Evidence from European farm level data. In 13th European International Farming Systems Association (IFSA) Symposium, Farming systems: facing uncertainties and enhancing opportunities, 1-5 July 2018, Chania, Crete, Greece (pp. 1-11). International Farming Systems Association (IFSA) Europe

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Appendix A. List of supplementary material

Supplementary Materials A: Guidelines for FoPIA-SURE-Farm 2: future resilience

Supplementary Materials B: FoPIA-SURE_Farm 2 Case Study Report Flanders

Supplementary Materials C: FoPIA-SURE_Farm 2 Case Study Report Bulgaria

Supplementary Materials D: FoPIA-SURE_Farm 2 Case Study Report Germany

Supplementary Materials E: FoPIA-SURE_Farm 2 Case Study Report Spain

Supplementary Materials F: FoPIA-SURE_Farm 2 Case Study Report France

Supplementary Materials G: FoPIA-SURE_Farm 2 Case Study Report Italy

Supplementary Materials H: FoPIA-SURE_Farm 2 Case Study Report The Netherlands

Supplementary Materials I: FoPIA-SURE_Farm 2 Case Study Report Poland

Supplementary Materials J: FoPIA-SURE_Farm 2 Case Study Report Romania

Supplementary Materials K: FoPIA-SURE_Farm 2 Case Study Report Sweden

Supplementary Materials L: FoPIA-SURE_Farm 2 Case Study Report United Kingdom

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Appendix B. Detailed results FoPIA-SURE-Farm 2

Table B1. Position of system functions relative to identified thresholds per case study.

	Position relative to threshold						
System function per case study	Not close	Somewhat close	Close	At threshold or beyond	No threshold defined	Not discussed	Grand Total
BG-Arable		**1**	**1**	**1**	**3**		**6**
Food production			1	1			2
Economic Viability		1					1
Biodiversity & habitat					2		2
Attractiveness of the area					1		1
DE-Arable&Mixed		**5**	**2**				**7**
Food production		1					1
Economic Viability			1				1
Natural Resources		2	1				3
Attractiveness of the area		2					2
ES-Sheep		**1**		**2**			**3**
Food production				1			1
Economic Viability		1					1
Quality of life				1			1
IT-Hazelnut		**2**	**2**				**4**
Economic Viability			2				2
Natural Resources		1					1
Attractiveness of the area		1					1
NL-Arable		**1**	**2**	**1**			**4**
Food production			1				1
Economic Viability			1				1
Natural Resources		1		1			2
PL-Horticulture			**3**	**1**			**4**
Food production			1				1
Economic Viability			2	1			3
RO-Mixed	**1**	**1**	**1**	**1**			**4**
Food production			1				1
Bio-based resources				1			1
Economic Viability		1					1
Biodiversity & habitat	1						1

Position relative to threshold
System function per case study | Not close | Somewhat close | Close | At threshold or beyond | No threshold defined | Not discussed | Grand Total

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

SE-Poultry			**1**	**1**		**2**	**4**
Food production				1			1
Economic Viability			1				1
Natural Resources						1	1
Animal health & welfare						1	1
UK-Arable	**1**		**2**	**1**		**2**	**6**
Food production						1	1
Economic Viability						1	1
Natural Resources				1			1
Biodiversity & habitat			1				1
Animal health & welfare			1				1
Quality of life	1						1
Grand Total	**2**	**11**	**14**	**8**	**3**	**4**	**42**

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B2. Position of resilience attributes relative to identified thresholds per case study.

Resilience attributes per case study	Position relative to threshold Not close	Somewhat close	Close	At threshold or beyond	No threshold defined	Not discussed	Grand Total
BG-Arable			**2**	**1**	**1**		**4**
Exposed to disturbances			1				1
Infrastructure for innovation				1			1
Production coupled with local and natural capital					1		1
Socially self-organized			1				1
DE-Arable&Mixed		**2**	**1**				**3**
Infrastructure for innovation			1				1
Response diversity		1					1
Support rural life		1					1
ES-Sheep				**1**	**1**		**2**
Diverse policies				1			1
Production coupled with local and natural capital					1		1
IT-Hazelnut	**1**	**1**	**2**	**1**			**5**
Diverse policies				1			1
Infrastructure for innovation			1				1
Production coupled with local and natural capital			1				1
Socially self-organized	1						1
Support rural life		1					1
NL-Arable		**1**	**1**		**2**		**4**
Infrastructure for innovation					1		1
Production coupled with local and natural capital		1					1
Reasonably profitable			1				1
Socially self-organized					1		1
PL-Horticulture		**1**	**1**		**2**		**4**
Functional diversity					1		1
Production coupled with local and natural capital		1					1
Reasonably profitable			1				1
Response diversity					1		1

Position relative to threshold

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Resilience attributes per case study	Not close	Somewhat close	Close	At threshold or beyond	No threshold defined	Not discussed	Grand Total
RO-Mixed	**1**	**1**	**2**				**4**
Appropriately connected with actors outside the farming system	1						1
Heterogeneity of farm types			1				1
Legislation coupled with local and natural capital		1					1
Support rural life			1				1
SE-Poultry			**1**		**1**	**3**	**5**
Exposed to disturbances						1	1
Functional diversity						1	1
Infrastructure for innovation					1		1
Reasonably profitable			1				1
Response diversity						1	1
UK-Arable		**1**			**3**	**2**	**6**
Appropriately connected with actors outside the farming system					1		1
Heterogeneity of farm types					1		1
Infrastructure for innovation					1		1
Production coupled with local and natural capital						1	1
Reasonably profitable						1	1
Socially self-organized		1					1
Grand Total	**2**	**7**	**10**	**3**	**10**	**5**	**37**

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B3.. Position relative to identified thresholds.

Challenges per case study	Not close	Position relative to threshold Somewhat close	Close	At threshold or beyond	No threshold defined	Not discussed	Grand Total
BG-Arable		**1**	**3**				**4**
Low prices and price fluctuations			1				1
Extreme weather			1				1
Continuous change of laws and regulations		1					1
Low labor availability			1				1
DE-Arable&Mixed		**1**	**1**	**3**			**5**
Low prices and price fluctuations				1			1
Extreme weather			1				1
Continuous change of laws and regulations		1					1
Lack of infrastructure				1			1
Low attractiveness				1			1
ES-Sheep				**3**	**1**		**4**
High production costs				1			1
Wildlife attacks					1		1
Low labor availability				1			1
Changes in consumer preferences				1			1
IT-Hazelnut	**2**	**2**	**1**				**5**
Low prices and price fluctuations		1					1
Extreme weather	1						1
Pests & diseases		1					1
Economic laws & regulations	1						1
Environmental laws & regulations			1				1
NL-Arable		**2**	**2**				**4**
High production costs			1				1
Extreme weather		1					1
Pests & diseases		1					1
Continuous change of laws and regulations			1				1

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Challenges per case study	Position relative to threshold						
	Not close	Somewhat close	Close	At threshold or beyond	No threshold defined	Not discussed	Grand Total
PL-Horticulture		**3**	**1**				**4**
Low prices and price fluctuations		1					1
Extreme weather		1					1
Continuous change of laws and regulations			1				1
Low labor availability		1					1
RO-Mixed	**1**	**2**		**1**			**4**
Low prices and price fluctuations	1						1
Extreme weather				1			1
Continuous change of laws and regulations		1					1
Economic laws & regulations		1					1
SE-Poultry			**1**	**2**		**1**	**4**
Change in technology			1				1
Economic laws & regulations				1			1
Environmental laws & regulations				1			1
Changes in consumer preferences						1	1
UK-Arable		**1**	**2**	**1**			**4**
Low prices and price fluctuations			1				1
High production costs			1				1
Economic laws & regulations				1			1
Environmental laws & regulations		1					1
Grand Total	**3**	**12**	**11**	**10**	**1**	**1**	**38**

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B4. Compatibility scores of future systems with Eur-Agri-SSPs. Where values -1 to -0.66: strong incompatibility, -0.66 to -0.33: moderate incompatibility, -0.33 – 0: weak incompatibility, 0-0.33 weak compatibility, 0.33-0.66: moderate compatibility, and 0.66-1: strong compatibility. Colors reflect compatibility categories.

Alternative systems per case study	Eur-Agri-SSPs SSP1 "Sustainability"	SSP2 "Status quo"	SSP3 "Regional rivalry"	SSP4 "Inequality"	SSP5 "Technology"
BG-Arable	**0.65**	**0.21**	**-0.77**	**0.20**	**0.21**
Status quo	0.63	0.29	-0.76	0.09	0.12
Diversification	0.63	0.10	-0.76	0.11	0.12
Technology	0.65	0.24	-0.74	0.33	0.30
Collaboration	0.65	0.14	-0.84	0.13	0.18
Product valorization	0.68	0.29	-0.77	0.32	0.32
DE-Arable&Mixed	**0.80**	**0.34**	**-0.74**	**0.06**	**0.32**
Status quo	0.79	0.43	-0.76	0.24	0.46
Intensification	0.78	0.34	-0.75	0.13	0.36
Organic / nature friendly	0.82	0.23	-0.76	-0.05	0.20
Attractive countryside	0.81	0.36	-0.69	-0.09	0.24
NL-Arable	**0.72**	**0.22**	**-0.79**	**0.13**	**0.19**
Status quo	0.65	0.21	-0.76	0.18	0.31
Diversification	0.76	0.17	-0.76	0.02	0.05
Technology	0.61	0.19	-0.77	0.32	0.36
Collaboration	0.72	0.26	-0.79	0.13	0.19
Organic / nature friendly	0.86	0.27	-0.88	0.01	0.04
UK-Arable	**0.69**	**0.20**	**-0.78**	**0.02**	**0.10**
Status quo	0.60	0.11	-0.74	0.07	0.23
Diversification	0.70	0.18	-0.78	-0.05	0.02
Organic / nature friendly	0.78	0.31	-0.83	0.03	0.05
RO-Mixed	**0.54**	**0.41**	**-0.64**	**0.23**	**0.37**
Status quo	0.43	0.49	-0.61	0.27	0.45
Specialization	0.52	0.37	-0.64	0.22	0.35
Collaboration	0.51	0.37	-0.64	0.22	0.36
Organic / nature friendly	0.68	0.42	-0.66	0.19	0.32
ES-Sheep	**0.62**	**0.47**	**-0.71**	**0.19**	**0.25**
Status quo	0.51	0.32	-0.83	0.14	0.21
Intensification	0.63	0.66	-0.62	0.35	0.38
Technology	0.73	0.44	-0.67	0.07	0.17
SE-Poultry	**0.63**	**0.48**	**0.54**	**0.18**	**0.23**
Status quo	0.55	0.40	0.44	0.00	0.19
Intensification	0.61	0.43	0.50	0.15	0.09
Diversification	0.86	0.44	0.58	0.08	0.26
Technology	0.50	0.63	0.63	0.50	0.38

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Alternative systems per case study	Eur-Agri-SSPs SSP1 "Sustainability"	SSP2 "Status quo"	SSP3 "Regional rivalry"	SSP4 "Inequality"	SSP5 "Technology"
IT-Hazelnut	**0.50**	**0.34**	**-0.65**	**0.13**	**0.31**
Status quo	0.35	0.22	-0.62	0.19	0.31
Diversification	0.15	0.51	-0.49	0.64	0.75
Technology	0.70	0.15	-0.72	-0.10	0.06
Product valorization	0.67	0.23	-0.82	-0.31	0.12
Organic / nature friendly	0.63	0.60	-0.61	0.24	0.29
PL-Horticulture	**0.51**	**0.33**	**-0.70**	**0.21**	**0.34**
Status quo	0.48	0.31	-0.69	0.18	0.31
Specialization	0.48	0.34	-0.69	0.25	0.39
Technology	0.56	0.28	-0.72	0.19	0.29
Organic / nature friendly	0.52	0.37	-0.69	0.21	0.35
Grand Total	**0.63**	**0.33**	**-0.59**	**0.15**	**0.26**

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B5. Expected developments of function performance in future systems. → implies no change, ↗ implies moderate positive change, ↑ implies strong positive change, ↘ implies moderate negative change, ↓ implies strong negative change

CS	Indicator name	Function	Current level	Status quo	System decline	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
BG-Arable	Productivity (t/ha)	Food production	Moderate to high	↗	↗|↓	↗	→	→	→
BG-Arable	Net farm income	Economic viability	Low to moderate	↘	↓	↗	↗	↗	↗
BG-Arable	Nutrient balance	Natural resources	Low	↘	↓	↗|→	→	↗	→
BG-Arable	Diversity of production	Biodiversity & habitat	Low	→	↗	↗	↑	↑	→
BG-Arable	Level of services in rural areas	Attractiveness of the area	Low	→	↓	→	↗	→	→
DE-Arable&Mixed	Cereal production (t/ha)	Food production	Moderate	→|↘	↘|↓	↘	→	→	
DE-Arable&Mixed	Profitability (Euro/ha)	Economic viability	Moderate	→|↘	↘|↓	→	↑	↗	
DE-Arable&Mixed	Availability of successors	Attractiveness of the area	Low	↘	↘|↓	→	↑	↗	
DE-Arable&Mixed	Availability of workers	Economic viability	Low	↘	↘|↓	→	↑	↗	
DE-Arable&Mixed	Soil quality	Natural Resources	Good	→	→	→|↗	→	→	
DE-Arable&Mixed	Production of biogas	Bio-based resources	Good	→	↘|↓	↓	→	→	
DE-Arable&Mixed	Water availability	Natural Resources	Good	↘	↘|↓	→	→	↗	
ES-Sheep	Gross margin	Economic viability	Low	→	↘|↓	↗	↗		
ES-Sheep	Sheep census	Food production	Low	↓	↓	↗	↑		
ES-Sheep	Number of farms	Attractiveness of the area	Low	↓	↓	↗	↗|→		
IT-Hazelnut	Gross Saleable Production	Food production	High	↗	↘	↗	↗	↗	↘|↗
IT-Hazelnut	Gross Margin	Economic viability	High	→	↘	↗	↗	↗	↘|↗
IT-Hazelnut	Organic farming (Ha)	Biodiversity & habitat	Low	↗	→	↘	→	↗	↑

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

<table>
<tr><th>Case Study</th><th>Indicator name</th><th>Function</th><th>Current level</th><th>Status quo</th><th>System decline</th><th>Alter-native 1</th><th>Alter-native 2</th><th>Alter-native 3</th><th>Alter-native 4</th></tr>
<tr><td>NL-Arable</td><td>Starch potato production</td><td>Food production</td><td>Moderate</td><td>→</td><td>↘|↓</td><td>→</td><td>↗</td><td>↗</td><td>→|↗</td></tr>
<tr><td>NL-Arable</td><td>Profitability</td><td>Economic viability</td><td>Moderate</td><td>↗</td><td>↘|↓</td><td>↗</td><td>↗</td><td>↗</td><td>↗</td></tr>
<tr><td>NL-Arable</td><td>Soil quality</td><td>Natural Resources</td><td>Low</td><td>↗</td><td>↘|↓</td><td>↗|↘</td><td>↗</td><td>↑</td><td>↗</td></tr>
<tr><td>NL-Arable</td><td>Water availability</td><td>Natural Resources</td><td>Moderate</td><td>↗</td><td>↘|↓</td><td>→|↘</td><td>↗</td><td>→|↗</td><td>↗</td></tr>
<tr><td>PL-Horticulture</td><td>1) Utilised agricultural area</td><td>Food production</td><td>Moderate</td><td>→</td><td>↘|↓</td><td>↗</td><td>→</td><td>→</td><td></td></tr>
<tr><td>PL-Horticulture</td><td>2) Purchase prices for agricultural products</td><td>Economic viability</td><td>Low</td><td>↘</td><td>↘|↓</td><td>→|↗</td><td>→|↗</td><td>↑</td><td></td></tr>
<tr><td>PL-Horticulture</td><td>3) Income dynamics</td><td>Economic viability</td><td>Moderate</td><td>↘</td><td>↘|↓</td><td>→|↗</td><td>→|↗</td><td>→|↗</td><td></td></tr>
<tr><td>PL-Horticulture</td><td>4) Labour costs</td><td>Economic viability</td><td>Low</td><td>↘</td><td>↘|↓</td><td>→|↗</td><td>→|↗</td><td>→</td><td></td></tr>
<tr><td>RO-Mixed</td><td>Agricultural production</td><td>Food production</td><td>Moderate</td><td>→</td><td>↗</td><td>↑</td><td>↗</td><td>↘</td><td>↗</td></tr>
<tr><td>RO-Mixed</td><td>Sales of agricultural products</td><td>Bio-based resources</td><td>Low</td><td>→</td><td>→</td><td>↑</td><td>↑</td><td>↗</td><td>↗</td></tr>
<tr><td>RO-Mixed</td><td>Subsidies</td><td>Economic viability</td><td>Moderate</td><td>→</td><td>↗</td><td>→</td><td>↑</td><td>↑</td><td>↗</td></tr>
<tr><td>RO-Mixed</td><td>Awareness of biodiversity importance</td><td>Biodiversity & habitat</td><td>Moderate to low</td><td>↗</td><td>→|↘</td><td>↗</td><td>→</td><td>↑</td><td>↗</td></tr>
<tr><td>SE-Poultry</td><td>Viable income</td><td>Economic viability</td><td>Low/Moderate</td><td>→</td><td>↘|↓|↑</td><td>↗|↓</td><td>↗|↓</td><td>↗|↓</td><td></td></tr>
<tr><td>SE-Poultry</td><td>Healthy and affordable products</td><td>Food production</td><td>Moderate/High</td><td>↗</td><td>↗|↘</td><td>→</td><td>→</td><td>↗</td><td></td></tr>
<tr><td>SE-Poultry</td><td>Maintain natural resources in good conditions</td><td>Natural Resources</td><td>High</td><td>↗</td><td>↘|↗</td><td>→</td><td>→</td><td>→</td><td></td></tr>
<tr><td>SE-Poultry</td><td>Animal health and welfare</td><td>Animal health & welfare</td><td>Moderate</td><td>↗</td><td></td><td>→|↘</td><td></td><td>↗</td><td></td></tr>
<tr><td>UK-Arable</td><td>Soil health</td><td>Natural Resources</td><td>Low</td><td>↘</td><td>↓</td><td>↑</td><td>→</td><td></td><td></td></tr>
<tr><td>UK-Arable</td><td>Biodiversity</td><td>Biodiversity & habitat</td><td>Low</td><td>↘</td><td>↓</td><td>↑</td><td>↘</td><td></td><td></td></tr>
</table>

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Indicator name	Function	Current level	Status quo	System decline	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
UK-Arable	Happiness index of farmers	Quality of life	Low	↘	↓	↑	↘		
UK-Arable	Percent of products certified higher welfare standards	Animal health & welfare	Moderate	→	→	↗	→		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B6. Expected developments of resilience attribute presence in future systems. → implies no change, ↗ implies moderate positive change, ↑ implies strong positive change, ↘ implies moderate negative change, ↓ implies strong negative change

Case study	Resilience attribute	Current level	Status quo	System decline	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
BG-Arable	Production coupled with local and natural capital	Moderate	→	↓	↗	→	↗	↗
BG-Arable	Exposed to disturbance	Moderate	→	↗	↗	↗	↗	↗
BG-Arable	Socially self-organized	Low	→	↗	→	→	→	↑
BG-Arable	Infrastructure for innovation	Low	→	↑	↑	↗	↗	→
DE-Arable&Mixed	Response diversity	Moderate	→	↘|↓	→	↗	→	
DE-Arable&Mixed	Infrastructure for innovation	Low	→	↘|↓	→	↑	↑	
DE-Arable&Mixed	Support rural life	Low	→	↘|↓	→	↑	→	
ES-Sheep	Production coupled with local and natural capital	Low	↘	↘|↓	↘	↑		
ES-Sheep	Diverse policies	Low	→	↘|↓	↘	↗		
ES-Sheep	Socially self-organized	Low	→	↘|↓	→	↑		
ES-Sheep	Support rural life	Low	↘	↘|↓	→|↗	↗		
ES-Sheep	Infrastructure for innovation	Low	↘	↘|↓	↗	↗		
ES-Sheep	Reasonable profitable	Low	↘	↘|↓	↗	↗		
IT-Hazelnut	Socially self-organized	Moderate	→	↘|→	↗	↗	↗	↑
IT-Hazelnut	Production coupled with local and natural capital	Low	↗	↘|↓	↑	↗	↑	↑
IT-Hazelnut	Support rural life	Moderate	↗	↘|→	↗	↗	↗	↗
IT-Hazelnut	Infrastructure for innovation	Moderate	↗	→|↗	↗	↗	↑	↗
IT-Hazelnut	Diverse policies	Low	→	→	→	↗	↗	↑
NL-Arable	Reasonable profitable	Low	→	↘|↓	↗	↗	↗	↗
NL-Arable	Socially self-organized	Moderate	→	↘|↓	↗|→|↘	→	↗	↑
NL-Arable	Infrastructure for innovation	Moderate	→	↘|↓	→|↗	↑	↗	↗
NL-Arable	Production coupled with local and natural capital	Moderate	→	↘|↓	↗	↗	↑	↗
PL-Horticulture	Production coupled with local and natural capital	Moderate	↘	↘|↓	↗	↗	↗|↑	
PL-Horticulture	Functional diversity	Low	→	↘|↓	↘|→	→	↘|→	
PL-Horticulture	Response diversity	Low	→	↘|↓	→|↗	↘|→|	↘|→	

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

↗

Case study	Resilience attribute	Current level	Status quo	System decline	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
PL-Horticulture	Reasonable profitable	Low	↘	↘|↓	→	→|↗	↘|→|↗	
RO-Mixed	Spatial and temporal heterogeneity (farm types)	Good	↗	↗	→	↘	↗	↗
RO-Mixed	Support rural life	Good	↗	→|↗	↗	↗	→	→
RO-Mixed	Appropriately connected with actors outside the farming system	Low	→	↗	↗	↑	↗	↗
RO-Mixed	Coupled with local and natural capital (legislation)	Low	→	→	↗	↗	↗	↗
SE-Poultry	Response diversity	Low	→			↗		
SE-Poultry	Reasonable profitable	Low	→	↘|↓|↑	↗|↓	↗|↓	↗|↓	
SE-Poultry	Functional diversity	High	→		↗	↗		
SE-Poultry	Exposed to disturbance	High	↗	↗|↑	→	→	→	
SE-Poultry	Infrastructure for innovation	Moderate	↗	↗|↑	↗	↗	↗	
UK-Arable	Spatial and temporal heterogeneity (farm types)	Low	→	→	↗	↘		
UK-Arable	Socially self-organized	Moderate	→	↓	↑	↘		
UK-Arable	Appropriately connected with actors outside the farming system	Moderate - low	↘	↓	↑	→		
UK-Arable	Infrastructure for innovation	Low	↘	↓	↑			

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B7. Expected performance development in future systems per case study. Scores close to -2 imply strong negative, -1 moderate negative, 1 moderate positive, 2 strong positive developments. Scores close to 0 imply no to weak positive or negative developments.

	Case studies									
Indicator/resilience attribute per alternative system	BG-Arable	NL-Arable	ES-Sheep	UK-Arable	DE-Arable& Mixed	RO-Mixed	SE-Poultry	IT-Hazel-nut	PL-Horti-culture	Mean
Indicator (mean)	**0.5**	**0.8**	**0.3**	**0.2**	**0.1**	**1.0**	**0.2**	**0.8**	**0.2**	**0.5**
Status quo	-0.2	0.8	-1.3	-0.8	-0.6	0.3	0.8	0.8	-0.8	-0.1
Intensification			1.0		0.6		-0.3			0.4
Specialization						1.3			0.6	0.9
Diversification	0.8	0.1		-0.5		1.0	-0.2	0.5		0.3
Technology	0.7	1.0	1.2				0.4	1.0	0.4	0.8
Collaboration	0.2	0.9				1.3				0.7
Product valorization	0.8							0.8		0.8
Organic / nature friendly		1.1		1.8	-0.4	1.0		0.8	0.6	0.7
Attractive countryside					0.9					0.9
Resilience attributes (mean)	**0.7**	**0.7**	**0.3**	**0.3**	**0.6**	**0.7**	**0.4**	**1.1**	**0.1**	**0.6**
Status quo	0.0	0.0	-0.7	-0.5	0.0	0.5	0.4	0.6	-0.5	0.0
Intensification			0.1		0.7		0.4			0.3
Specialization						0.8			0.3	0.5
Diversification	0.8	0.6		-0.7		0.8	0.5	1.0		0.6
Technology	1.0	0.8	1.3				0.2	1.4	0.4	0.9
Collaboration	1.0	0.9				0.8				0.9
Product valorization	0.5							1.0		0.8
Organic / nature friendly		0.9		1.8	0.0	0.8		1.6	0.1	0.9
Attractive countryside					1.7					1.7
Mean	**0.5**	**0.7**	**0.3**	**0.2**	**0.3**	**0.8**	**0.3**	**1.0**	**0.1**	**0.5**

Table B8. Overview of boundary conditions mentioned in each case study.

Case Study	Boundary condition	Future system					
		Domain	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
BG-Arable	Satisfactory level of productivity	Agronomic	1	1	1	1	
BG-Arable	Satisfactory level of income	Economic	1	1	1	1	1
BG-Arable	Diversity of production	Economic		1	1	1	
BG-Arable	Exposed to disturbances	Environmental	1	1	1	1	1
BG-Arable	Coupled with local and natural capital (production)	Environmental		1		1	
BG-Arable	Public policy	Institutional	1	1	1	1	1
BG-Arable	Public policy - favoring national production	Institutional		1	1	1	
BG-Arable	Legislation – land tenure regulation	Institutional	1	1	1	1	1
BG-Arable	Administrative requirements	Institutional	1		1		1
BG-Arable	Access to know how	Institutional		1	1	1	
BG-Arable	Access to finance	Institutional		1	1		
BG-Arable	Labor availability	Social	1		1		
BG-Arable	Acquisition of new knowledge	Social	1	1	1	1	
BG-Arable	Access to innovation ideas	Social	1	1	1	1	
BG-Arable	Social self-organization	Social		1			1
DE-Arable&Mixed	Demand	Agronomic		1			
DE-Arable&Mixed	Labelling (certificates and standards)	Agronomic			1		
DE-Arable&Mixed	Agglomeration areas	Economic		1		1	
DE-Arable&Mixed	Independent generation of income (without subsidies)	Economic				1	
DE-Arable&Mixed	Political incentives	Institutional	1	1		1	
DE-Arable&Mixed	Research & Development	Institutional			1	1	
DE-Arable&Mixed	Educational system	Institutional			1		
DE-Arable&Mixed	Consistency of regulations	Institutional		1		1	
DE-Arable&Mixed	Access to internet and other infrastructure	Institutional	1		1	1	
DE-Arable&Mixed	CAP has to set right incentives	Institutional				1	
DE-Arable&Mixed	De-bureaucratization	Institutional			1		
DE-Arable&Mixed	Culture of trust	Social			1		
DE-Arable&Mixed	Improved societal perception of Agric.	Social			1	1	
DE-Arable&Mixed	Societal dialogue / new social contract	Social			1	1	
ES-Sheep	New technology applied to sheep sector farm management	Agronomic		1	1		
ES-Sheep	Farmers training in new technology	Agronomic		1	1		
ES-Sheep	Improved sanitary conditions	Agronomic	1	1	1		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case Study	Boundary condition		Future system				
		Domain	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
ES-Sheep	Improved animal handling	Agronomic	1	1	1		
ES-Sheep	Geo-localization technology	Agronomic			1		
ES-Sheep	Use of sub-products	Agronomic		1			
ES-Sheep	New financial products	Economic	1	1	1		
ES-Sheep	New commercialization channels	Economic	1	1	1		
ES-Sheep	Public aids for public goods provision	Economic	1		1		
ES-Sheep	Broader access to pastures and stubble fields	Environmental	1		1		
ES-Sheep	Sustainable pastures management	Environmental	1		1		
ES-Sheep	Research relationship nature-ovine sector	Environmental		1	1		
ES-Sheep	Reduced bureaucracy control	Institutional	1	1	1		
ES-Sheep	Sector oriented legislation (sanitary, environmental and urban)	Institutional	1	1	1		
ES-Sheep	Rural development	Institutional	1		1		
ES-Sheep	Public awareness of the contribution of sector	Social	1	1	1		
ES-Sheep	Improved cooperation among actors	Social	1		1		
IT-Hazelnut	Growing demand	Economic	1	1			
IT-Hazelnut	Prices linked to the real cost	Economic				1	1
IT-Hazelnut	Hazelnut prices decline	Economic	1	1			
IT-Hazelnut	Concentration of the confectionery industry	Economic	1	1			
IT-Hazelnut	New markets	Economic		1	1		
IT-Hazelnut	Short supply chain	Economic			1		1
IT-Hazelnut	Brands with high local value	Environmental			1		1
IT-Hazelnut	Extreme weather events: drought	Environmental	1				1
IT-Hazelnut	Greater eco-friendly requirements	Environmental	1				1
IT-Hazelnut	CAP support	Institutional	1			1	1
IT-Hazelnut	Duty-Free Markets	Institutional		1			
IT-Hazelnut	Cultural changes	Social	1		1		1
IT-Hazelnut	Research	Social				1	1
IT-Hazelnut	More young people in the system	Social	1			1	
IT-Hazelnut	Information flow	Social				1	
NL-Arable	Higher presence of livestock farmers in the region	Agronomic	1			1	1
NL-Arable	Lower presence of livestock farmers in the region	Agronomic		1			
NL-Arable	Less root and tuber crops	Agronomic				1	

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case Study	Boundary condition			Future system			
		Domain	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
NL-Arable	Starch potato as most profitable crop	Economic	1	1	1	1	1
NL-Arable	Good business model	Economic		1	1	1	
NL-Arable	More local economy	Economic		1			
NL-Arable	Lower cultivation costs	Economic			1		
NL-Arable	Financial rewards for services to nature and society	Economic				1	
NL-Arable	Low presence of nematodes	Environmental	1	1	1	1	1
NL-Arable	Limited number of extreme weather events	Environmental	1		1	1	
NL-Arable	Maintain or improve soil quality	Environmental	1	1			1
NL-Arable	Consistent policies for greening and water retention	Institutional				1	
NL-Arable	Changes in norms for water management	Institutional					1
NL-Arable	Better laws and regulations for collaboration	Institutional					1
NL-Arable	Technological innovation	Social	1		1	1	1
NL-Arable	Awareness of water management issues	Social	1				1
NL-Arable	Good infrastructure		1	1	1		1
PL-Horticulture	Stability in prices of agricultural products	Economic	1	1	1	1	
PL-Horticulture	Expansion of UAA	Economic		1		1	
PL-Horticulture	Increase of profit margin	Economic		1	1	1	
PL-Horticulture	Limited number of extreme weather conditions	Environmental	1	1		1	
PL-Horticulture	Locally suited organic crop varieties	Environmental				1	
PL-Horticulture	Transparent and consistent regulations	Institutional	1		1	1	
PL-Horticulture	Accessibility of agricultural land (physical and value terms)	Institutional		1		1	
PL-Horticulture	Increase implementation of origin labelling	Institutional		1		1	
PL-Horticulture	Availability of seasonal workers	Social	1	1		1	
PL-Horticulture	Increase of horizontal cooperation (producer groups, joint storage facilities)	Social		1	1	1	
PL-Horticulture	Improve consumer preferences and raise awareness	Social		1		1	
PL-Horticulture	Increase of vertical cooperation (sorting, processing)	Social		1	1	1	
RO-Mixed	Level of support	Economic	1			1	1
RO-Mixed	Adequate financial instruments	Economic	1		1		
RO-Mixed	Input prices	Economic	1			1	1

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case Study	Boundary condition	Future system					
		Domain	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
RO-Mixed	Extreme weather events: drought	Environmental	1	1	1	1	1
RO-Mixed	Eco regulations	Environmental	1			1	1
RO-Mixed	Adequate legislation	Institutional	1			1	1
RO-Mixed	Bureaucracy simplification	Institutional	1			1	1
RO-Mixed	Access to information	Institutional	1			1	1
RO-Mixed	Representation at political decision level	Institutional	1	1	1	1	1
RO-Mixed	Unbiased quality standards	Institutional	1			1	
RO-Mixed	Better agricultural education, knowledge and know-how	Social	1	1	1	1	1
RO-Mixed	Openness to cooperation	Social	1				
RO-Mixed	Labor availability	Social	1	1		1	
RO-Mixed	Acceptance of foreign workers	Social	1	1	1		
SE-Poultry	Balance between production costs and farm gate prices	Economic	1	1		1	
SE-Poultry	Access to land and capital	Economic	1	1	1	1	
SE-Poultry	Technological innovation	Economic	1	1		1	
SE-Poultry	Effective bureaucracy	Institutional	1	1	1		
SE-Poultry	Knowledge management	Social	1	1	1	1	
SE-Poultry	Qualified labor	Social	1	1	1	1	
UK-Arable	Keep or increase farm diversity	Environmental	1	1			
UK-Arable	% farmers in socially self-organized groups	Social	1	1	1		
UK-Arable	% of farmers collaborating with outside stakeholders	Institutional	1	1	1		
UK-Arable	Advisors per farm	Institutional	1	1	1		
UK-Arable	Soil health maintained or increased and the % of cover crops, % spring crops, rotation length and seedbed preparation techniques (till / soil disturbance)	Environmental	1	1			
UK-Arable	minimum % of crops which require pollinators, minimum 5-year rotations, hedgerows and field margins maintained	Environmental	1	1			
UK-Arable	Minimum 5-10-year tenancies	Environmental		1			
UK-Arable	% or scale of farmer feeling valued in that they are contributing positively to society	Social	1	1	1		
UK-Arable	% produce in higher welfare standards	Environmental	1	1	1		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B9. Number of mentioned boundary conditions per future system category per case study per domain

	Domains				
Future system per case study	Agronomic	Economic	Environmental	Institutional	Social
Status quo					
BG-Arable	1	1	1	3	3
NL-Arable	1	1	3	0	2
UK-Arable			4	2	2
ES-Sheep	2	3	2	3	2
DE-Arable&Mixed	0	0		2	0
RO-Mixed		3	2	5	4
SE-Poultry		3		1	2
IT-Hazelnut		3	2	1	2
PL-Horticulture		1	1	1	1
Intensification					
ES-Sheep	5	2	1	2	1
DE-Arable&Mixed	0	2		5	2
SE-Poultry		3		1	2
Specialization					
RO-Mixed		0	1	1	3
PL-Horticulture		3	1	2	4
Diversification					
BG-Arable	1	2	2	4	2
NL-Arable	1	3	2	0	0
UK-Arable			1	2	2
RO-Mixed		2	2	4	1
SE-Poultry		1		1	2
IT-Hazelnut		4	0	1	0
Technology					
BG-Arable	1	2	2	5	3
NL-Arable	0	3	2	0	1
ES-Sheep	5	3	3	3	2
SE-Poultry		3		0	2
IT-Hazelnut		1	0	1	3
PL-Horticulture		2	0	1	2
Collaboration					
BG-Arable	0	1	1	3	1
NL-Arable	1	1	2	2	2
RO-Mixed		1	1	1	2

Domains

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Future systems per case study	Agronomic	Economic	Environmental	Institutional	Social
Product valorization					
BG-Arable	1	2	1	6	3
IT-Hazelnut		2	1	0	1
Organic / nature friendly					
NL-Arable	2	3	2	1	1
UK-Arable			5	2	2
DE-Arable&Mixed	1	1		2	0
RO-Mixed		2	2	5	2
IT-Hazelnut		2	3	1	2
PL-Horticulture		3	2	3	4
Attractive countryside					
DE-Arable&Mixed	1	0		4	3

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B10. Overview of strategies mentioned in each case study.

Case study	Strategy	Domain	Current system	Future systems				
				Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
BG-Arable	Changes into production technologies and modernization	Agronomic	1	1	1	1	1	1
BG-Arable	Diversification of crops	Agronomic	1		1		1	
BG-Arable	Increase of the farmed land	Economic	1	1				
BG-Arable	Preservation of the marketing of the products	Economic	1			1		1
BG-Arable	Introduction of insurances	Economic	1		1			
BG-Arable	Preservation of soil quality	Environmental			1	1	1	
BG-Arable	Application of good farming practices	Environmental	1	1	1	1	1	1
BG-Arable	Policy support	Institutional	1		1	1		1
BG-Arable	Better cooperation with research institutions and universities	Institutional			1	1		
BG-Arable	Marketing/production/processing cooperatives	Social				1		1
BG-Arable	Stimulating succession and improved attractiveness of the sector	Social	1	1	1	1		
BG-Arable	Better information exchange and field visits	Social			1	1	1	1
DE-Arable &Mixed	Extend knowledge on local varieties and climate smart techniques	Agronomic			1		1	
DE-Arable &Mixed	Better varieties (drought resistant)	Agronomic			1		1	
DE-Arable &Mixed	Precision agriculture	Agronomic	1	1			1	
DE-Arable &Mixed	Integrate knowledge from R&D	Agronomic	1	1	1	1	1	
DE-Arable &Mixed	Cost leadership through cost reduction	Economic					1	
DE-Arable &Mixed	Increase value of raw materials	Economic			1		1	
DE-Arable &Mixed	Increase share of profit in value chain	Economic			1			

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Strategy	Domain	Current system	Future systems				
				Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
DE-Arable &Mixed	New varieties with climate services (tree crops)	Environmental			1	1		
DE-Arable &Mixed	Improve efficiency of irrigation schemes	Environmental	1	1	1		1	
DE-Arable &Mixed	Improve rural infrastructure	Institutional	1	1	1	1	1	
DE-Arable &Mixed	Create alternative jobs and social/cultural offers	Institutional			1	1	1	
DE-Arable &Mixed	Stronger regulation of international agricultural trade system	Institutional			1			
DE-Arable &Mixed	Simplify system of labelling and certification	Institutional			1	1	1	
DE-Arable &Mixed	De-bureaucratization (duration of approval, frequency of controls, paper work for new investments)	Institutional			1		1	
DE-Arable &Mixed	Fair prices instead of direct payments	Institutional			1	1	1	
DE-Arable &Mixed	Align funding with locally specific conditions	Institutional			1	1	1	
DE-Arable &Mixed	Improve marketing of farms and the whole sector	Institutional			1	1	1	
DE-Arable &Mixed	Improve culture of trust	Social			1	1	1	
DE-Arable &Mixed	Better cooperation between all stakeholders	Social			1	1	1	
ES-Sheep	Use of technology for management efficiency improvement (electronic readers, blood test, etc.)	Agronomic			1	1		
ES-Sheep	Research in more prolific and productive breeds.	Agronomic	1	1	1			
ES-Sheep	Research for sanitary conditions of the ovine sector (new vaccines, medicaments, etc.)	Agronomic			1	1		

Case study	Strategy	Domain	Current	Future systems

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Strategy	Domain	Current system	Future systems				
			system	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
ES-Sheep	Implementation of sanitary conditions (hygiene, spaced animals, etc.)	Agronomic	1	1	1	1		
ES-Sheep	Use of technology for animal positioning (GPS, mobile phone, etc.)	Agronomic				1		
ES-Sheep	Farmers training in new technology	Agronomic			1	1		
ES-Sheep	Financial products to cover market volatile prices	Economic	1	1	1			
ES-Sheep	Financial products to cover droughts	Economic	1	1		1		
ES-Sheep	Opening up a foreign market	Economic	1	1	1	1		
ES-Sheep	Short channel boost	Economic	1	1		1		
ES-Sheep	Openness of local slaughterhouses	Economic				1		
ES-Sheep	Diversification (on-farm)	Economic	1	1	1			
ES-Sheep	Alternative income sources (off-farm)	Economic	1	1		1		
ES-Sheep	Investment in the farm assets	Economic	1	1	1	1		
ES-Sheep	Costs reduction and flexibility	Economic	1	1	1	1		
ES-Sheep	Sales contracts	Economic	1	1	1	1		
ES-Sheep	Access to market information	Economic	1	1	1	1		
ES-Sheep	Improvement of the access to pastures and stubble fields	Environmental	1	1		1		
ES-Sheep	Use of technology for control of grazed pastures	Environmental				1		
ES-Sheep	Research in methane emissions from ovine sector	Environmental			1	1		
ES-Sheep	Use of technology for real-time communication with administration	Institutional			1	1		
ES-Sheep	Trained administration staff in region specificities	Institutional			1	1		
Case study	Strategy	Domain	Current system	Future systems				

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Strategy	Domain	Current system	Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
ES-Sheep	Reduce bureaucracy and excessive and specific regulations	Institutional			1	1		
ES-Sheep	Tailored legislation in environmental management	Institutional				1		
ES-Sheep	Tailored legislation in sanitary conditions	Institutional			1	1		
ES-Sheep	Remuneration to the sector for contribution to public goods	Institutional				1		
ES-Sheep	Improve legislation in relation to wild fauna	Institutional	1	1		1		
ES-Sheep	Innovation of laws for products origin and certification	Institutional			1	1		
ES-Sheep	Promote generational renewal (early retirements, access to land, etc.)	Institutional			1	1		
ES-Sheep	Creation of shepherd schools	Institutional				1		
ES-Sheep	New urban legislation	Institutional				1		
ES-Sheep	Promotion of lamb meat consumption	Social	1	1	1	1		
ES-Sheep	Promotion of local breeds outside the region	Social				1		
ES-Sheep	Improvement awareness of sector contribution to public goods	Social	1	1	1	1		
ES-Sheep	Associations and cooperatives	Social	1	1	1	1		
ES-Sheep	Improvement of quality of live (work intensity reduction with technology)	Social	1	1	1	1		
FR-Livestock								
IT-Hazelnut	Mechanization	Agronomic	1	1	1		1	1
IT-Hazelnut	Open international markets	Economic			1			
IT-Hazelnut	Agro-environmental policies	Environmental	1					1
Case study	**Strategy**	**Domain**	**Current system**			**Future systems**		
				Status	Alter-	Alter-	Alter-	Alter-

				quo	native 1	native 2	native 3	native 4
IT-Hazelnut	Control of environmental requirements	Institutional						1
IT-Hazelnut	Consortia for technical advise	Institutional	1	1			1	1
IT-Hazelnut	Promotional policies	Institutional			1	1		
IT-Hazelnut	CAP support	Institutional	1				1	1
IT-Hazelnut	Training activity	Social					1	
IT-Hazelnut	Value chain activities – cooperation among stakeholders	Social	1	1	1	1	1	1
NL-Arable	Extend knowledge on soil & varieties	Agronomic	1	1	1	1	1	1
NL-Arable	Better varieties (starch content, nematode resistance)	Agronomic	1	1	1	1	1	1
NL-Arable	Precision agriculture	Agronomic	1	1		1	1	1
NL-Arable	Exchange land with dairy farms	Agronomic	1	1		1	1	1
NL-Arable	Changing crop rotation	Agronomic		1	1		1	
NL-Arable	Protein crops for animal and human consumption	Agronomic			1			
NL-Arable	Different way of fertilizing (alternative) crops	Agronomic			1			
NL-Arable	Increasing water use efficiency	Agronomic			1			1
NL-Arable	Applying drones (for early risk detection and damage assessment)	Agronomic				1		
NL-Arable	Improve circularity	Agronomic		1	1	1	1	
NL-Arable	Scaling up	Economic	1	1		1		
NL-Arable	Increase value of starch products	Economic	1	1	1	1	1	1
NL-Arable	Reduce costs (in general)	Economic	1	1				
NL-Arable	Reduce crop inputs	Economic	1			1	1	
NL-Arable	Have land available outside contract farming	Economic	1	1				
NL-Arable	Developing new business models	Economic			1	1	1	
NL-Arable	Introduction of new value chains	Economic			1			
NL-Arable	Having a good marketing strategy	Economic			1			
Case study	Strategy	Domain	Current system			Future systems		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Strategy	Domain	Current system	Future systems: Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
NL-Arable	High value products	Economic			1	1		
NL-Arable	Improve soil quality	Environmental	1	1	1	1	1	1
NL-Arable	Maintain water locally in canals	Environmental						1
NL-Arable	Take lower laying lands out of production	Environmental						1
NL-Arable	Actively replenishing ground water levels	Environmental						1
NL-Arable	Land consolidation / redesign of the landscape	Environmental					1	1
NL-Arable	Nature friendly interventions at field level (buffer strips, strip cropping, green manures etc.)	Environmental					1	
NL-Arable	Customized water levels	Institutional						1
NL-Arable	Relax constraining regulations (water management, collaboration, taxes)	Institutional						1
NL-Arable	Rewarding services with regard to nature	Institutional			1		1	1
NL-Arable	Adapting trading policies	Institutional					1	
NL-Arable	Allowing genetic improvement techniques (Crispr-Cas)	Institutional				1		
NL-Arable	Raising awareness about soil quality	Social	1	1	1	1	1	1
NL-Arable	Raising awareness about water availability	Social	1	1				1
NL-Arable	More contact between consumers and producers	Social			1			
NL-Arable	Precision agriculture as shared responsibility of processors and farmers	Social				1		
NL-Arable	Collective action	Social			1			1
PL-Horticulture	Diversifying outlets (entering new markets)	Economic					1	
PL-Horticulture	Marketing	Economic	1		1	1	1	
PL-Horticulture	Insurance	Economic	1					

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Case study	Strategy	Domain	Current system	Future systems: Status quo	Future systems: Alter-native 1	Future systems: Alter-native 2	Future systems: Alter-native 3	Future systems: Alter-native 4
PL-Horticulture	Enduring	Economic	1					
PL-Horticulture	Diversification	Economic	1					
PL-Horticulture	Simplification of regulations	Institutional			1			
PL-Horticulture	Additional actions in the RDP targeting quality and profitability of agricultural production	Institutional				1		
PL-Horticulture	Preferential taxation system for shelter farming	Institutional				1		
PL-Horticulture	Creation and promotion of a locally recognized brand	Institutional				1		
PL-Horticulture	State support	Institutional	1					
PL-Horticulture	Education campaigns for consumers	Social			1			
PL-Horticulture	Increase in the number of ecological farms	Social					1	
PL-Horticulture	Intensification of vertical cooperation	Social	1		1		1	
PL-Horticulture	Horizontal cooperation	Social	1		1	1	1	
RO-Mixed	Information actions (technology, efficiency)	Agronomic	1	1	1	1	1	1
RO-Mixed	New technologies, new machinery and equipment adapted to the needs of small farms	Agronomic	1			1		
RO-Mixed	New crops / varieties to improve diversity	Agronomic	1			1	1	1
RO-Mixed	Land consolidation and technologization	Agronomic	1		1		1	
RO-Mixed	Organic production	Agronomic					1	
RO-Mixed	Improved quality of production, not only quantity	Agronomic					1	1
RO-Mixed	Creation of producers' associations / groups cooperatives	Economic	1	1	1	1	1	1
RO-Mixed	Diversification of activities (farm products processing, agro-tourism)	Economic	1		1	1		1

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

				Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
RO-Mixed	Technological and managerial improvement to cope with climate changes	Environmental	1	1	1	1	1	1
RO-Mixed	Insurance instruments adapted to small farms	Institutional	1	1		1		
RO-Mixed	Ensuring the correctness of paperwork	Institutional	1	1	1	1	1	1
RO-Mixed	Informing campaigns regarding the eco-conditionality rules	Institutional	1	1			1	
RO-Mixed	Implementation of rules by authorities (with sanctions and penalties for non-compliance)	Institutional	1	1	1	1	1	1
RO-Mixed	More stable policies and fiscal regulations	Institutional	1	1	1	1	1	1
RO-Mixed	Functional consultancy system	Institutional	1	1	1	1	1	1
RO-Mixed	Facilities and incentives for cooperation	Institutional	1	1	1	1	1	1
RO-Mixed	Funding / credit instruments adapted to small farms to enable their development and enlargement to medium-sized farms	Institutional	1		1		1	
RO-Mixed	Generational renewal facilitated by easier access to funding for young farmers and decent pensions for retiring farmers	Social	1	1		1		
RO-Mixed	For unskilled labor: continuous adult training and programs for exiting agriculture	Social	1	1	1			
RO-Mixed	For skilled labor: better adaptation of school / university training to the demand in the agricultural sector	Social	1	1	1		1	1
SE-Poultry	Knowledge Management	Agronomic	1	1	1	1	1	
SE-Poultry	Technology adaptation	Agronomic	1	1	1	1	1	
Case study	**Strategy**	**Domain**	**Current system**			**Future systems**		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

				Status quo	Alter-native 1	Alter-native 2	Alter-native 3	Alter-native 4
SE-Poultry	Farm size	Agronomic			1	1	1	
SE-Poultry	Knowledge Management	Economic	1	1	1	1	1	
SE-Poultry	Technology adaptation	Economic	1	1	1	1	1	
SE-Poultry	Farm size	Economic	1		1	1	1	
SE-Poultry	Knowledge Management	Institutional	1	1	1			
SE-Poultry	Farm size	Institutional	1		1	1	1	
UK-Arable	Land tenure arrangements	Agronomic		1	1			
UK-Arable	Reintroduction of livestock	Agronomic			1	1		
UK-Arable	Responsible management	Agronomic			1			
UK-Arable	Agricultural diversification	Economic		1		1		
UK-Arable	Increased area farmed	Economic	1	1				
UK-Arable	Non-agricultural diversification	Economic	1			1		
UK-Arable	Adoption of agri-environmental schemes	Environmental	1	1	1	1		
UK-Arable	Adoption of conservation farming	Environmental			1			
UK-Arable	Collaboration	Institutional		1	1	1		
UK-Arable	Knowledge Exchange	Institutional	1	1	1	1		
UK-Arable	Farmer led exchange	Social	1		1			
UK-Arable	Peer Learning	Social	1	1	1	1		

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table B11. Number of strategies mentioned per future system per case study per domain.

Future system per case study	Domains				
	Agronomic	Economic	Environmental	Institutional	Social
Status quo					
BG-Arable	1	1	1	0	1
NL-Arable	6	4	1	0	2
UK-Arable	1	2	1	2	1
DE-Arable&Mixed	2	0	1	1	0
RO-Mixed	1	1	1	7	3
ES-Sheep	2	10	1	1	4
SE-Poultry	2	2		1	
IT-Hazelnut	1	0	0	1	1
PL-Horticulture		0		0	0
Intensification					
DE-Arable&Mixed	4	2	1	7	2
ES-Sheep	5	7	1	6	4
SE-Poultry	3	3		2	
Specialization					
RO-Mixed	2	2	1	6	2
PL-Horticulture		1		1	3
Diversification					
BG-Arable	2	0	2	0	1
NL-Arable	7	5	1	1	3
UK-Arable	1	2	1	2	1
RO-Mixed	3	2	1	5	1
SE-Poultry	3	3		1	
IT-Hazelnut	1	1	0	1	1
Technology					
BG-Arable	2	1	2	2	2
NL-Arable	6	5	1	1	2
ES-Sheep	5	9	3	11	5
SE-Poultry	3	3		1	
IT-Hazelnut	1	0	0	2	2
PL-Horticulture		1		3	1
Collaboration					
BG-Arable	1	1	1	1	2
NL-Arable	5	1	5	3	3
RO-Mixed	3	2	1	6	1
Product valorization					
BG-Arable	1	1	2	2	3
IT-Hazelnut	0	0	0	1	1

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Future system per case study	Domains				
	Agronomic	Economic	Environmental	Institutional	Social
Organic / nature friendly					
NL-Arable	6	3	3	2	1
UK-Arable	3	0	2	2	2
DE-Arable&Mixed	3	2	2	8	2
RO-Mixed	5	1	1	7	1
IT-Hazelnut	1	0	1	3	1
PL-Horticulture		2		0	3
Attractive countryside					
DE-Arable&Mixed	1	0	1	6	2

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Appendix C: Parameters for ecosystem service models

The purpose of this appendix is to provide the parameters for the ecosystem service models.

Parameters of the land use optimization model

The formulation of the statistical model for ecosystem services provision (described in session 3.1) is given by the following equation:

$$ES = \sum_i \alpha_i LC_i \cdot \prod_j \theta_j{}^{\gamma_{i,j}} \quad \text{Eq. (C1.1)}$$

Where LC_i refers to a land use fraction in a spatial unit, and the θ_j refers to a land use or climate variable; the land use variable is energy input and the climate variables are mean annual precipitation an mean annual temperature. The coefficients to calibrate are the land cover coefficients α_i and the exponents $\gamma_{i,j}$ of energy input, precipitation, and temperature. Note that the exponents are specific to the land use and climate variables, but also to the land cover (i.e., the exponent of energy input is different if the energy is on annual crops or on forest).

We calibrated the parameters using Corine Land Cover data and the layers of ecosystem services provided by the Joint Research Center (Maes et al., 2012). The calibration is done separately for each case study region, therefore parameters are different for each case study region. The parameters do not have a physical meaning, as the model is statistics. The procedure implemented for calibration is based on an evolutionary algorithm where the fitness function to minimize corresponds to the sum of the square errors. We calibrated the parameters for crop production (Table C.1) and carbon storage (Table C.2).

Table C.1 – Parameters of the land use optimization model for the ecosystem service "Crop production". The land covers considered are: annual crops (AC), permanent crops (PC), and heterogeneous agricultural land (HA).

		Land cover coefficient	Exponent of energy input	Exponent of precipitation	Exponent of temperature
BE	AC	0.0002	0.4001	1.5082	0
	PC	0.0001	0.5299	1.8749	0
	HA	0.0001	0.4383	0.9664	0.3569
BG	AC	0.0002	0.3879	0	0.0062
	PC	0.0001	0	0	0
	HA	0.0001	0	0.003	1.8508
DE	AC	0.0002	0.4004	0.2842	0.4158

	PC	0.0001	0.7458	1.4348	0.4284
	HA	0.0001	0.173	0	1.9969
ES	AC	0.0002	0.4021	0.4359	0.0142
	PC	0.0001	0.016	0	1.9885
	HA	0.0001	0	0	1.8425
FR	AC	0.0002	0.4001	0.283	0.3018
	PC	0.0001	0.0551	1.9853	1.9753
	HA	0.0001	0	1.9482	1.581
IT	AC	0.0002	0.3992	0.1321	0
	PC	0.0001	0.00379	1.9823	1.32599
	HA	0.0001	0	2.001	1.4244
NL	AC	0.0002	0.3829	0.853	0.342
	PC	0.0001	1.5929	07781	0.6468
	HA	0.0001	0.0684	1.4215	1.9834
PL	AC	0.0002	0.3899	0	0.0977
	PC	0.0001	0	0.6937	1.9999
	HA	0.0001	0.0457	0.1182	1.9842
RO	AC	0.0002	0.4003	0	0.1937
	PC	0.0001	0	1.2198	1.6152
	HA	0.0001	0.389	1.9545	0.0226
SE	AC	0.0002	0.4000	0.4169	0.0178
	PC	0.0001	1.1894	0	1.9999
	HA	0.0001	0.0798	0	2.021
UK	AC	0.0002	0.4021	1.2066	0.4547
	PC	0.0001	2.0000	2.0024	1.4917
	HA	0.0001	0	0	1.9911

Table C.2 – Parameters of the land use optimization model for the ecosystem service "Carbon storage". The land covers considered are: annual crops (AC), permanent crops (PC), and heterogeneous agricultural land (HA), grassland (G), and forest (F).

		Land use coefficient	Exponent of energy input	Exponent of precipitation	Exponent of temperature
BE	AC	0.1	-0.4516	0	0
	PC	0.26898	-1.1514	0	2.0123
	HA	0.105	-0.5955	0	0.5741
	G	1.2355	-0.5354	0	0.5630
	F	3.001	-1.1188	0.5044	1.9842

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

BG	AC	0.1	-2.091	0	0
	PC	0.10865	-1.9831	0	0
	HA	0.1008	-0.3799	0.8163	0
	G	0.1058	-0.4555	0	0
	F	3.0131	-0.8840	0.6716	0.5961
DE	AC	0.1	-1.9923	0	0
	PC	1.6488	-1.9711	0	0
	HA	0.105	-0.1413	0	0
	G	1.6438	-0.7599	0	0
	F	3.0912	-1.1103	1.0161	1.8646
ES	AC	0.1	0.30709	2.4215	-2.2471
	PC	1.634	0.08039	-6.021	-2.4667
	HA	1.5395	0.59671	-0.54078	-5.5531
	G	2.1918	-0.0899	-2.4395	-1.8829
	F	2.972	-0.6020	-0.6099	-0.2095
FR	AC	0.1	-0.67493	0	0.7967
	PC	0.091	-1.2365	2.0012	2.000
	HA	0.105	-1.9942	0	0
	G	1.11	-0.6063	0	0
	F	2.9942	-1.1996	2.0042	1.5125
IT	AC	0.1	-2.001	0	0
	PC	2.031	-0.7794	2.003	0.5306
	HA	0.105	-0.5685	1.0279	0
	G	1.6235	-2.001	0	0
	F	2.045	-1.2075	2.001	2.001
NL	AC	0.1	-0.7948	0.3221	1.3709
	PC	0.6862	-0.3788	1.4895	-1.0116
	HA	0.105	-0.1112	-1.2106	-1.2105
	G	2.9173	-0.6652	-2.001	-0.0369
	F	3.0532	-0.2060	0.0775	-2.001
PL	AC	0.1269	-1.0907	0	2.0012
	PC	0.5791	-1.0596	0	2.0049
	HA	0.1282	-0.8864	0	1.4725
	G	0.1368	-0.6263	2.001	0.0214
	F	2.9983	-0.6830	0.3977	0.03315
RO	AC	0.1	-2.000	0	0
	PC	1.2141	-1.942	0	0
	HA	0.105	-2.0592	0	0
	G	1.2091	-0.6843	2.092	0
	F	3.011	-1.033	1.9853	1.2865
SE	AC	0.01	0.0206	2.5541	-6.0012

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	PC	0.01	0.7933	1.2807	-6.0021
	HA	0.01	-6.0139	-3.822	-3.6561
	G	0.11	1.0105	0.6051	-4.6016
	F	2.8334	-0.4544	0.2201	-1.0637
UK	AC	0.1	-0.8458	1.2997	1.1818
	PC	0.1118	-0.3252	0	0
	HA	0.1018	-2.021	0	0
	G	0.10681	-0.6104	0	0.0735
	F	2.605	-0.7221	0	0.3122

Parameters of the nitrogen fluxes model

This section of the Appendix provide data used for the simulations done with the nitrogen fluxes model: nitrogen production per livestock unit (Table C.3), animal diet composition (Table C.4), humification coefficients of animals' effluents for different species (Table C.5), and the sources for the other data used for the model (crop compositions, yields, and livestock composition for each case study) (Table C.6).

Table C.3 Nitrogen production per animal product, and species class in kg/livestock unit for each case study

animalProduct	Species	SpeciesClass	BE	BG	DE	ES	FR	IT	NL	PL	RO	SE	UK
egg	**poultry**	laying hens	21.50	19.31	28.80	24.50	20.78	14.94	22.01	17.53	11.35	25.34	19.26
meat	**cattle**	other cattle	14.83	6.21	15.38	12.98	14.92	14.05	9.65	14.15	7.92	15.36	15.90
	goatSheep	goats		3.89		2.89	3.88				3.94		
		sheeps		3.89	10.79	4.32	6.85	4.34		8.15	3.97	7.41	7.44
	pigs	pigs	10.93	7.72	10.82	9.82	10.53	14.99	10.93	10.57	9.65	10.67	9.65
	poultry	broilers	7.77	8.88	8.25	9.56	7.04	9.50	8.67	9.52	8.60	7.79	7.94
		ducks		3.47									
		geese		4.57									
		turkeys		6.24									
milk	**cattle**	dairy cows	39.75	18.78	40.96		37.00	33.38	41.21	32.40	17.24	45.85	41.98
	goatSheep	goats		10.56		22.45	39.31				0.00		
		sheeps		6.45	0.00	20.85	21.93	7.64		1.12	7.66	0.00	0.00

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table C.4 Animal diet composition- Nitrogen consumption per species class, feed product in kg/livestock unit for each case study

			BE	BG	DE	ES	FR	IT	NL	PL	RO	SE	UK
cattle	dairy cows	animal-fish	0.0	0.0	0.0		0.0	0.0	12.0	0.0	0.0	0.0	0.0
		cereals	69.0	26.0	11.8		123.3	33.8	45.0	18.2	28.0	44.0	34.5
		coproducts	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
		fodder	77.0	24.7	115.0		0.0	59.7	0.0	96.3	74.3	1.7	134.0
		grass	0.0	38.8	0.0		87.3	49.3	125.0	1.2	23.3	138.3	0.0
		meals	0.0	11.5	13.2		3.6	0.2	0.0	2.3	0.0	0.0	4.5
		oil-protein	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
		other	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0
	other cattle	animal-fish	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0
		cereals	16.5	0.0	1.8	8.7	1.6	18.6	19.4	15.3	8.1	11.3	7.0
		coproducts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		fodder	48.1	14.9	54.4	0.0	0.0	30.2	0.0	39.7	9.9	0.0	62.5
		grass	0.0	40.8	0.0	81.2	65.7	57.3	43.1	2.1	62.0	83.8	0.0
		meals	0.0	0.0	6.3	0.1	1.0	0.2	0.0	0.0	0.0	0.0	3.0
		oil-protein	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
goatSheep	goats	animal-fish		0.0		2.0	0.0				0.0		
		cereals		0.0		21.9	18.9				5.0		
		coproducts		0.0		0.0	0.0				0.0		
		fodder		99.9		0.0	0.0				25.0		
		grass		46.6		53.0	85.0				75.0		
		meals		0.0		0.1	1.1				0.0		
		oil-protein		55.4		0.0	0.0				0.0		
		other		0.0		0.0	0.0				0.0		
	sheeps	animal-fish		0.0	0.0	2.0	0.0	10.0		4.3	0.0	0.0	0.0
		cereals		0.0	0.0	21.9	18.9	19.9		0.0	5.0	0.0	0.0
		coproducts		0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
		fodder		6.9	65.0	0.0	0.0	29.5		63.9	25.0	0.0	90.0
		grass		46.6	0.0	53.0	85.0	40.5		3.6	75.0	63.8	0.0
		meals		0.0	7.8	0.1	1.1	0.1		0.0	0.0	0.0	0.0
		oil-protein		20.7	17.2	0.0	0.0	0.0		18.2	0.0	26.2	0.0
		other		0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
pigs	pigs	animal-fish	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		cereals	52.4	40.5	42.5	45.5	50.3	50.9	48.3	42.9	41.4	56.0	49.2
		coproducts	1.9	0.0	0.0	0.0	0.0	0.3	0.0	0.8	2.0	0.0	0.0
		fodder	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		grass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		meals	0.0	4.5	14.2	0.2	6.3	0.2	0.0	1.2	1.6	0.0	6.8

This Project has received funds from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 727520

		oil-protein	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		other	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poultry	broilers	animal-fish	14.3	0.0	7.1	21.4	14.3	14.3	7.1	21.4	0.0	21.4	7.1
		cereals	124.9	71.3	88.6	170.8	139.5	169.7	100.0	166.3	72.3	0.0	127.2
		coproducts	0.0	0.0	14.8	0.0	0.0	1.1	71.4	2.0	0.0	64.3	16.5
		fodder	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		grass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		meals	0.0	85.7	60.9	0.6	17.6	0.7	0.0	16.7	20.6	0.0	27.7
		oil-protein	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.9	0.0
		other	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
	laying hens	animal-fish	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	0.0	0.0
		cereals	67.9	46.4	56.1	81.8	65.0	67.1	78.6	62.9	32.9	85.7	61.8
		coproducts	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
		fodder	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		grass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		meals	0.0	32.1	33.2	0.3	6.4	0.3	0.0	5.0	5.2	0.0	9.6
		oil-protein	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Table C.5 - Humification coefficient and C to N ratios of effluent per species

species	effluentType	coefHum	C:N
cattle	manure	0.46	19
goatSheep	slurry	0.26	7.7
	manure	0.46	11.7
pigs	slurry	0.26	10.8
	manure	0.46	22.8
poultry	slurry	0.26	4.5
	guano	0.26	5.8
	manure	0.46	9.2

Table C.6 – Data sources for the calibration of the nitrogen fluxes model for the different case studies

BE	Data elaborated from the following sources: http://www.lcvvzw.be/wp-content/uploads/2019/01/Kostprijsraming-voedergewassen-gangbare-teelten-2019-v5.pdf https://www.vlm.be/nl/SiteCollectionDocuments/Publicaties/mestbank/Mestrapport_2018.pdf https://lv.vlaanderen.be/nl/voorlichting-info/publicaties-cijfers/landbouwcijfers#overzichtsrapporten https://statbel.fgov.be/nl/themas/landbouw-visserij/land-en-tuinbouwbedrijven#figures
BG	Ministry of Agriculture, Food and Forestry. 2018. Annual Report on the Situation and Development of Agriculture (Agrarian Report 2017) Ministry of Agriculture, Food and Forestry. 2017. Farm structure survey in 2016 Ministry of Agriculture, Food and Forestry. 2017/2018. Situation-perspective analysis of wheat, barley and rape 2016, 2017 Ministry of Agriculture, Food and Forestry. 2017/2018. Situation-perspective analysis of corn and sunflower 2016, 2017 National Statistical Institute. 2019. Statistical Yearbook 2018 National Statistical Institute. 2018/2019. Regions, Districts and Municipalities in the Republic of Bulgaria 2016, 2017
DE	**Feed consumption:** https://www.dvtiernahrung.de/aktuell/futterfakten/futtermittel-fuer-nutztiere.html?referer=www.dvtiernahrung.de%2Faktuell%2Fnachrichten%2Fdetail%2Farticle%2Fmischfutterherstellung-in-der-eu-fefac-erwartet-stabile-entwicklung.html%3Freferer%3Dwww.dvtiernahrung.de%252F195.html

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	Crop composition: https://statistik.sachsen-anhalt.de/themen/wirtschaftsbereiche/land-und-forstwirtschaft-fischerei/tabellen-wachstumsstand-und-ernte/ Livestock: https://statistik.sachsen-anhalt.de/themen/wirtschaftsbereiche/land-und-forstwirtschaft-fischerei/tabellen-viehwirtschaft-und-tierische-erzeugnisse/
ES	Gobierno de Aragón database: https://www.aragon.es/-/estadisticas-ganaderas. Last Access 30.10.2019. Gobierno de Aragón (2018). Estiércoles. Caracterización, analítica e implicaciones sobre su aprovechamiento fertilizante. Informaciones Técnicas, 268. Dirección General de Desarrollo Rural. Centro de Transferencia Agroalimentaria. MAPA (2018) Balance del nitrógeno en la agricultura española. Metodología y resultados. Secretaría General de Agricultura y alimentación. Dirección General de producciones y mercados agrarios. MAPA (2017) Definición y caracterización de extensividad en las explotaciones ganaderas en España Nevado A. (2019) Caracterización espacial de los flujos de Nitrógeno reactivo en el sistema agroalimentario español a escala provincial. Trabajo de Fin de Master. Universidad Politécnica de Madrid. Sebek, L.B et al. (2014) Nitrogen and phosphorous excretion factors of livestock. In-depth analyses of selected country reports. Veltholf, G.L (2014) Alterra Report. Task 1. Methodological studies in the field of Agro-Environmental Indicators. Lot 1. Excretion factors.
FR	Data elaborated from the following sources: AGRESTE (2016,2017,2018 & 2010 for poultry) Registre Parcellaire Graphique 2016
IT	Data elaborated from the following sources: Anagrafe nazionale zootecnica (2018) CLAL Agea (2019) Liso et al. (2017) Ribaudo et al. (2000) ISTAT
NL	Tabellenboek (CBS: NUTS111, 131, 132) Agrovision (North-East) For grass and maize Agrimatie (zandregio 230; https://www.agrimatie.nl/PublicatiePage.aspx?subpubID=7352&sectorID=3550&themaID=2754&indicatorID%20=%202773)
PL	https://lublin.stat.gov.pl/files/gfx/lublin/pl/defaultaktualnosci/759/1/14/1/2019_rolnictwo_woj.lub_za_2018.pdf https://warszawa.stat.gov.pl/publikacje-i-foldery/rolnictwo-lesnictwo/rolnictwo-wojewodztwa-mazowieckiego-na-tle-kraju-i-pozostalych-wojewodztw-w-2018-r-

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

	,2,12.html https://swiatrolnika.info/uprawy/4075-najwiecej-chmielu-w-wojewodztwie-lubelskim **https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5509/6/15/1/wyniki_produkcji_roslinnej_w_2017.pdf** **https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rolnictwo/srodki-produkcji-w-rolnictwie-w-roku-gospodarczym-20162017,6,14.html** https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/uprawy-rolne-i-ogrodnicze/produkcja-upraw-rolnych-i-ogrodniczych-w-2018-roku,9,17.html https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/produkcja-zwierzeca-zwierzeta-gospodarskie/fizyczne-rozmiary-produkcji-zwierzecej-w-2018-roku,3,14.html https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/produkcja-zwierzeca-zwierzeta-gospodarskie/zwierzeta-gospodarskie-w-2018-roku,6,19.html https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rolnictwo/srodki-produkcji-w-rolnictwie-w-roku-gospodarczym-20172018,6,15.html
RO	http://statistici.insse.ro:8077/tempo-online/#/pages/tables/insse-table https://insse.ro/cms/sites/default/files/field/publicatii/bilanturi_de_aprovizionare_pentru_principalele_produse_agroalimentare_in_anul_2017.pdf https://insse.ro/cms/sites/default/files/field/publicatii/bilanturi_alimentare_in_anul_2017.pdf https://insse.ro/cms/sites/default/files/field/publicatii/bilanturi_de_aprovizionare_pentru_principalele_produse_agroalimentare_in_anul_2018_0.pdf https://insse.ro/cms/sites/default/files/field/publicatii/bilanturi_alimentare_in_anul_2018.pdf https://insse.ro/cms/ro/content/ancheta-structurală-în-agricultură-2016-date-pe-macroregiuni-regiuni-de-dezvoltare-şi-judeţe http://www.rga2010.djsct.ro/inceput_j.php?codj=22&den=IAŞI&pgj=3&jd=0&new=0
SE	Elaborated from Eurostat – year 2017 and 2018
UK	Data elaborated from Land Cover plus (2018) dataset from the Center of Ecology and hydrology DEFRA (2015, 2016) FAOSTAT (average UK yields 2012-2017) Eurostat (2018)

This Project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 727520

Appendix D: System dynamics representation for a farming system

Figure D.1 provides the complete causal loop diagram of a farming system for the quantitative analysis

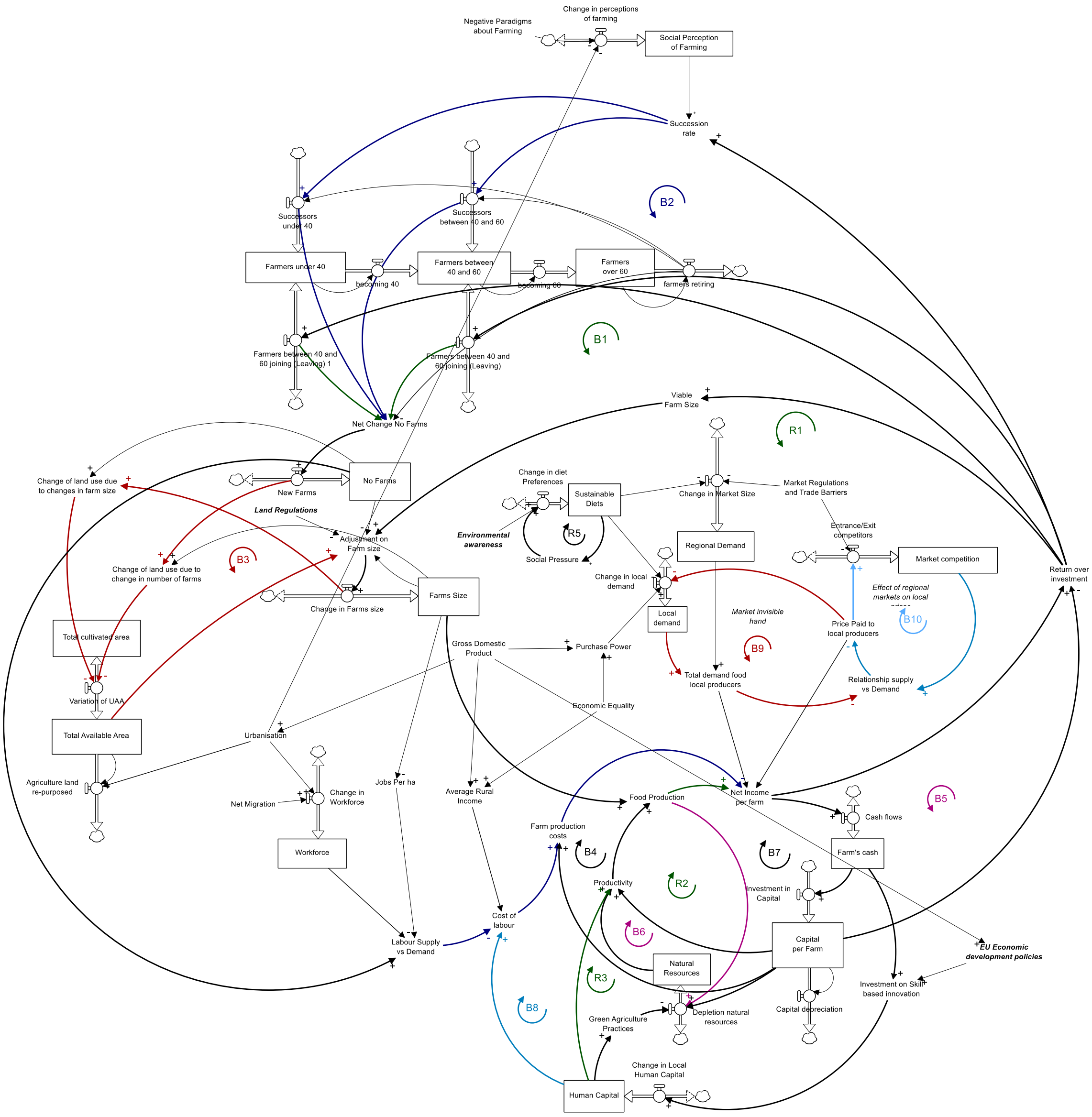


Figure D.1 – Complete causal loop diagram of a farming system