2 FoPIA-SURE-Farm 2 ASSESSMENT

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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

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[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.

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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

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[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)

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?

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.

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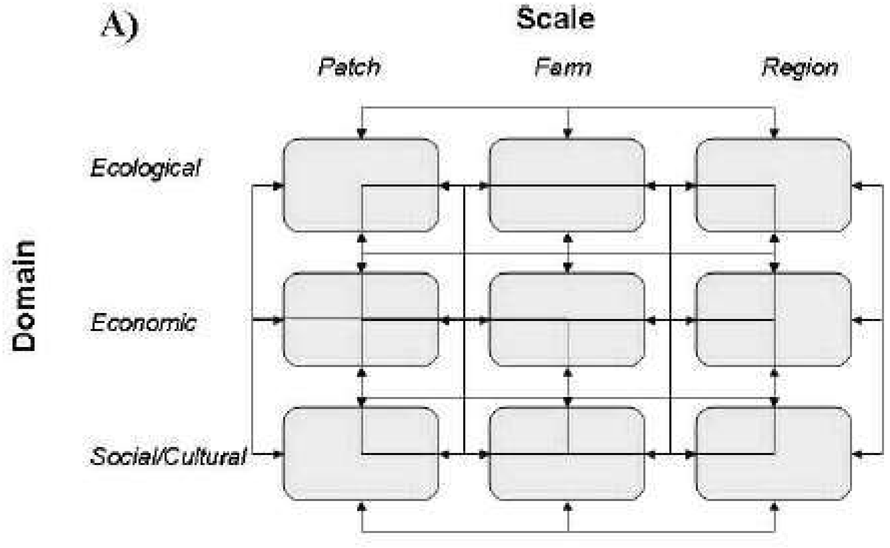

Figure 2.1. A visualization of possible threshold interactions between domains and scales leading to a system change. Source: Kinzig et al. (2006).

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.

Table 2.1. Stakeholder workshop timing and number of participants.

CS	Date	Total	Farmer	Government	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.

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.

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.

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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.

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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.

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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).

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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 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”.

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.

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

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.

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

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 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 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.

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-Horticulture	IT-Hazelnut	Total[1] (n)
Intensification				Intensification		Semi-intensive alternative system	Large farms			3
Specialization					Commercial specialization of family mixed farms			Horticulture farming		2
Diversification	Crop diversification	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	Technological innovation	6
Collaboration	Collaboration	Collaboration & water			Cooperation / multi-functionality					3

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.

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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.

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

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.

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.

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

	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

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 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,

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.

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 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

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.

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 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.

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.

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

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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 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 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 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 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.

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.

3 ECOSYSTEM SERVICE MODELLING ASSESSMENT

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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.

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).

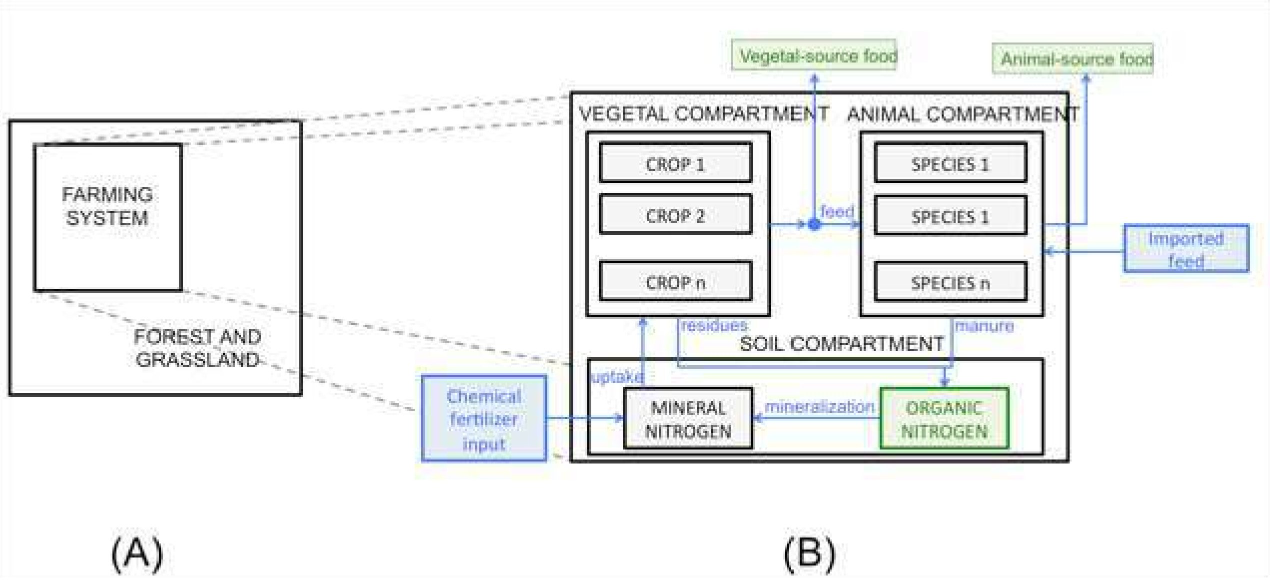

Figure 3.1.1 – Scheme depicting how system are conceived in the land use optimization model (Panel A) and in the nitrogen fluxes simulation model (Panel B). Panel A is referred to a whole region (NUTS3) containing a farming system among other land covers, Panel B is referred to the agricultural system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

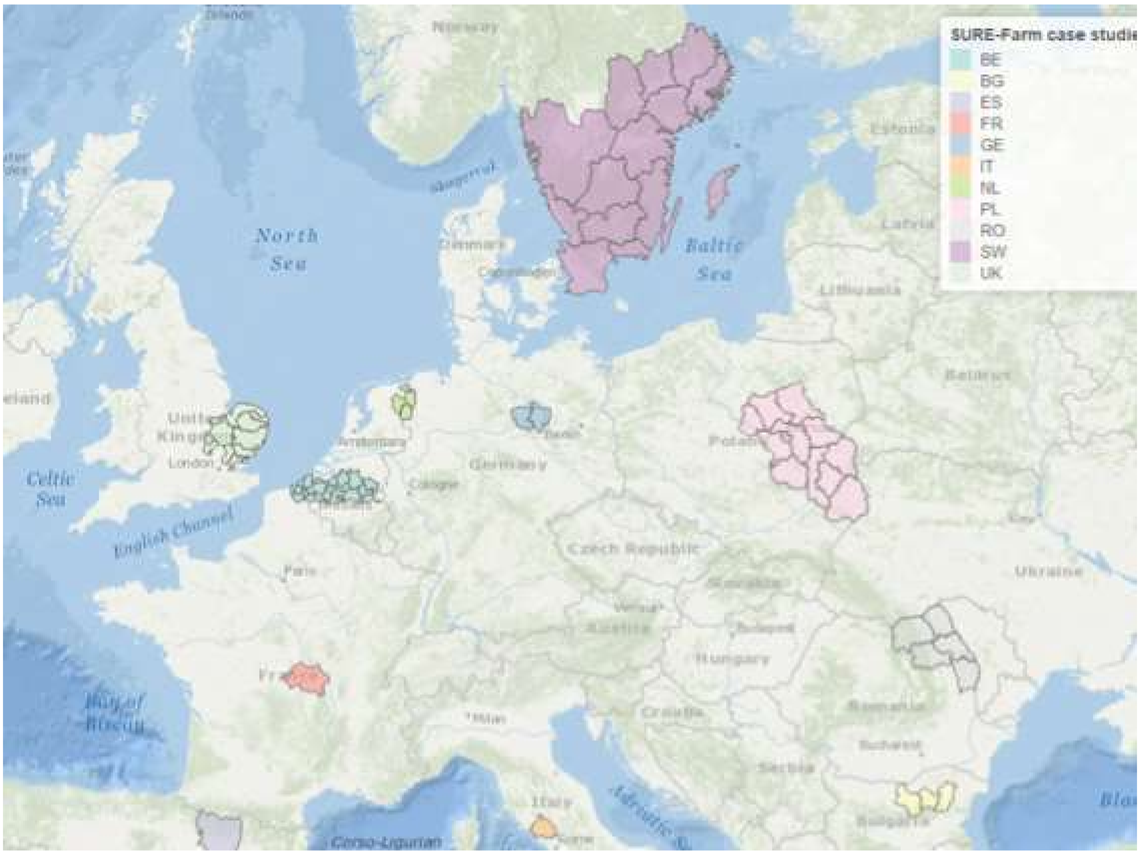

Figure 3.1.2 – Location of the NUTS3 regions considered for the different SURE-Farm case studies for the land use optimization model for ecosystem services.

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

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

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

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.

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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.

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

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

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		

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 (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 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.

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 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.

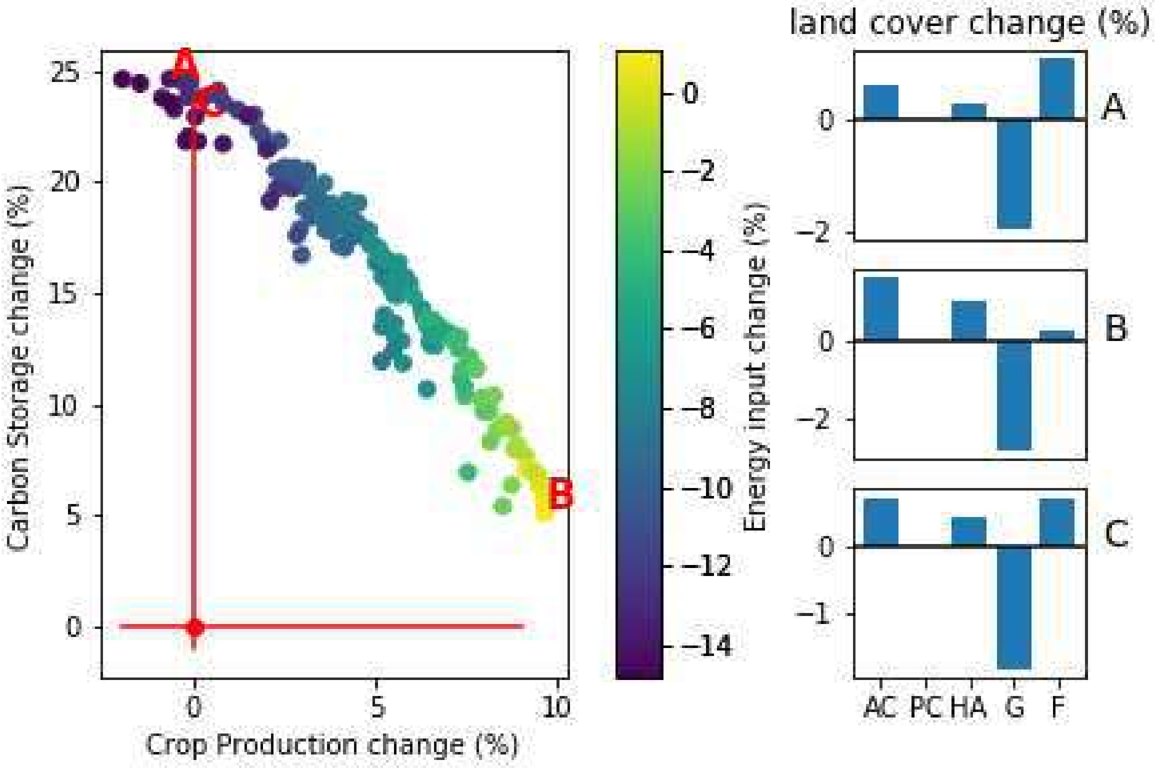

Figure 3.2.1 - Results of the land use optimization model for the French case study region. The left panel represents the Pareto frontier showing the tradeoff between carbon storage and crop production. Points on the Pareto frontier represent the variation as percentages of the initial state (identified 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”.

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.

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

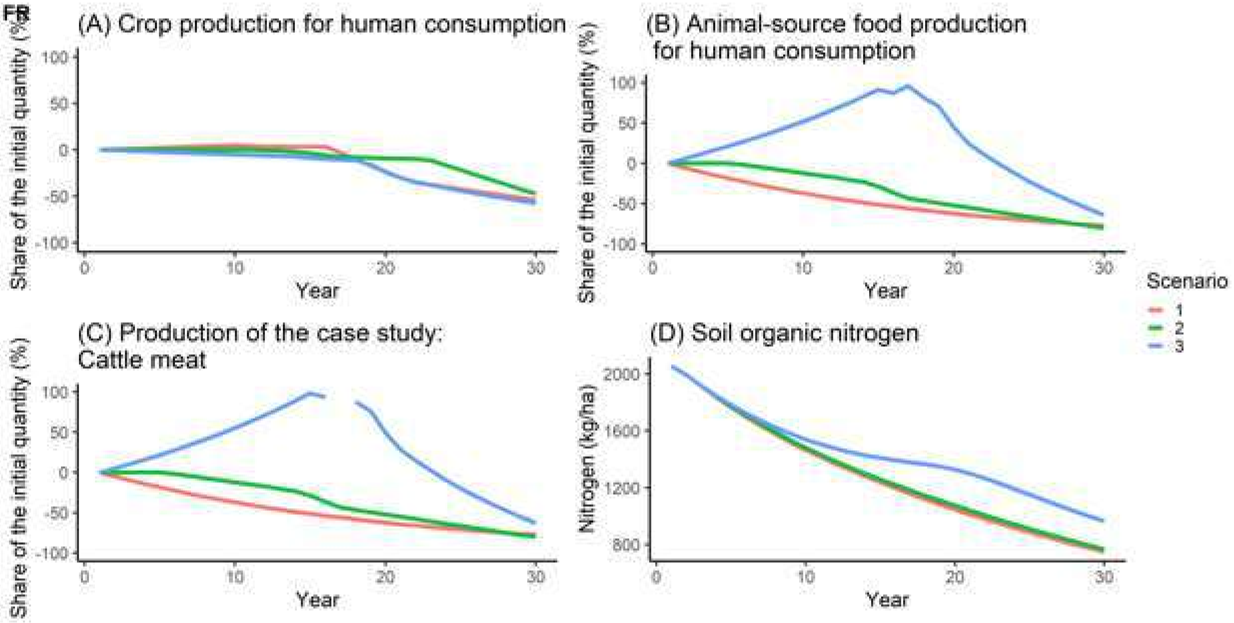

Figure 3.2.2. Simulation results of the nitrogen fluxes model for the French case study. Panels represent trajectories of the variation (in percentage of the initial state) in crop production for human consumption (Panel A), animal production for human consumption (Panel B), beef production (Panel C). 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).

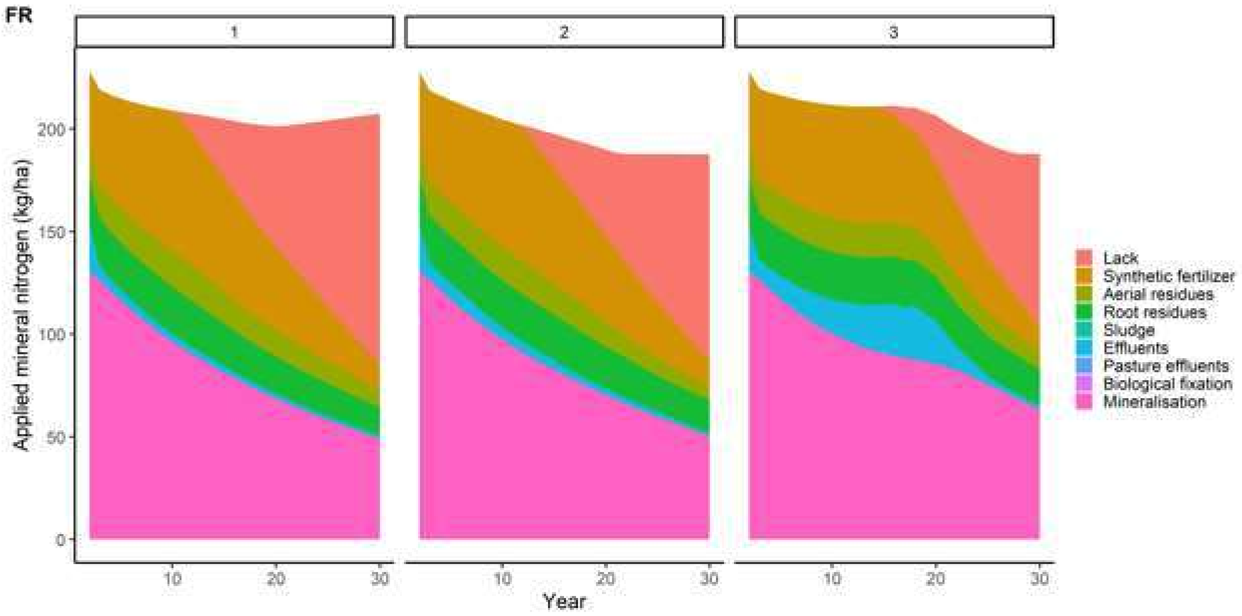

Figure 3.2.3. Repartition of the sources of mineral nitrogen available for plant uptake along the simulation of the nitrogen fluxes model for the French case study region. Fluxes are synthetic fertilizer, aerial plant residues left on field, root residues, sludge, animal effluent from animals in housings, 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 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.

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