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D5.1 Impact assessment tool to assess the resilience of farming systems and their delivery of private and public goods

Managed by Partner 7, System Dynamics Group, University of Bergen

Hugo HERRERA[1], Birgit KOPAINSKY[1], Franziska APPEL[2], Alfons BALMANN[2], Francesco ACCATINO[3], Muriel TICHIT[3], Federico ANTONIOLI[4], Simone SEVERINI[4], Wim PAAS[5,6], Pytrik REIDSMA[5]

(Contact: Birgit Kopainsky)

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[1] System Dynamics Group, University of Bergen, Norway
[2] Leibnitz Institute of Agricultural Development and Transition Economies (IAMO), Germany
[3] Agroecology, INRA, France
[4] Department of Agricultural and Forestry Sciences, Universita degli Studi della Tuscia, Italy
[5] Plant Production Systems, Wageningen University, the Netherlands
[6] Business Economics, Wageningen University, the Netherlands

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1 Introduction

Farming systems are sub-sets of food systems and thus coupled social-ecological systems (Ericksen, 2008; Liu et al., 2007). Food system outcomes arise from multiple interactions between the social and ecological subsystems (Folke, 2006) in response to internal or external pressures. A better understanding of these interactions is crucial for designing strategies that enhance social as well as ecological outcomes (Schlüter et al., 2014).

Understanding these interactions requires a comprehensive and holistic analysis of farming systems' behaviour, components and outcomes. The complexity of the connections between these underlying mechanisms makes it difficult to intuitively anticipate the consequence of a particular strategy on the ways farming systems behave, adapt and transform in case of shocks (Chu et al., 2003).

In SURE-Farm, we support our analysis by using computer models as an aid for understanding farming systems' resilience, for estimating and comparing resilience indicators and for exploring the role of different resilience attributes. Models act both as road maps that systematically represent our understanding of the system and as virtual laboratories where strategies can be tested, hypotheses can be explored and scenarios can be generated.

While models are identified as suitable tools for the complexity and multidimensionality of resilience (Carpenter et al., 2009, Walker et al., 2004), no single modelling approach or tool is likely to provide enough information to produce an integrated assessment of resilience. Hence, in SURE-Farm, we propose to use a multimethod interdisciplinary toolbox rather than a single one-size-fits-all model.

The objective of this report is to describe tools proposed within SURE-Farm Work Package 5 (WP5) to assess resilience and to articulate the rationale for using them. The report proceeds as follows. First the theoretical framework to analyse resilience is summarized. Then, we briefly describe each of the tools (models and modelling approaches) proposed to assess resilience in this project. Finally, we elaborate on how the different tools complement each other.

2 Theoretical framework

2.1 Resilience framework

The SURE Farm framework for analysing resilience (Meuwissen et al., 2018) is grounded in dynamic systems theory and aims at understanding the dynamics of a farming system's essential functions when facing changes or shocks from the environment. The proposed framework interprets the dynamics of adaptive cycles using three different types of resilience:

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- Robustness: the ability to maintain desired levels of outputs despite the occurrence of perturbations (Urruty et al., 2016).
- Adaptability: the capacity to adjust responses to changing external drivers and internal processes and thereby allow for development along the current trajectory while continuing important functionalities (stability domain) (Folke et al., 2010).
- Transformability: the capacity to create a fundamentally new system when environmental, economic, or social structures make the existing system untenable in order to provide important functionalities (Walker et al., 2004). Transformability is less about planning and controlling but more about preparing for opportunity or creating conditions of opportunity for navigating the transformations (Folke, et al., 2010, citing Chapin et al. 2010).

2.2 Essential functions: Private and Public goods

Farming systems provide a wide range of functions that differ considerably from each other depending on the system's location and purpose. The conceptual framework used to analyse these functions also plays a role in defining what functions are essential. For instance, there are different perspectives regarding what is understood with social well-being or sustainable development and which functions contribute to it.

While there is not an agreement about a single group of essential functions, in general, farming systems' functions can be subdivided into the provision of private goods and public goods. In simple terms, private goods can be understood as those that can generate enough profits to repay the expenses of individuals producing them (Kaul et al. 2003). Hence, there is an intrinsic motivation to produce them (Smith, 1994[1776]). Alternatively, those classified as public goods, while offering considerable service to society, are difficult to price in normal market mechanisms and hence, unlikely to be produced as a source of profits (Kaul et al., 1999; Adger, 2005). Multiple indicator frameworks exist to asses a system's performance regarding the essential functions. The SURE-Farm resilience framework (Meuwissen, et al., 2018; Figure 1) uses EC and SAFA guidelines as a basis, augmented with own elaborations. In order to select the indicators measuring the performance of farming systems, the first step is to identify and prioritise functions related to the provision of private and public goods and, as a second step, combine the functions with the relevant indicators, which are function and farming system specific.

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- Private goods:
    - Deliver healthy and affordable food products
    - Deliver other bio-based resources for the processing sector
    - Ensure economic viability
    - Improve quality of life in farming areas
- Public goods:
    - Maintain natural resources in good condition (water, soil, air)
    - Protect biodiversity of habitats, genes, and species
    - Ensure that rural areas are attractive places for residence and tourism (country side, social structures)
    - Ensure animal health & welfare

Trade-offs need to be expected between some essential functions. Although the interaction between the provision of various functions can provide significant synergies for farming systems, they are not always mutually supportive as there can be conflicts between e.g. social and economic dimensions. Thus, the level of interdependency can vary according to the farming system and its boundary. This means that each farming system has a level of sustainability which is relative to its own target functions and depending on system-specific interactions.

2.3 Impact assessment of resilience

The SURE-Farm resilience framework (Meuwissen, et al., 2018) distinguishes five phases: (1) characterising the farming system, (2) appraising key challenges affecting the system, (3) framing the essential functions of the system, (4) assessing resilience along a spectrum of robustness, adaptability and transformability, and (5) identifying resilience attributes and strategies which contribute to the robustness, adaptability and transformability of the farming system.

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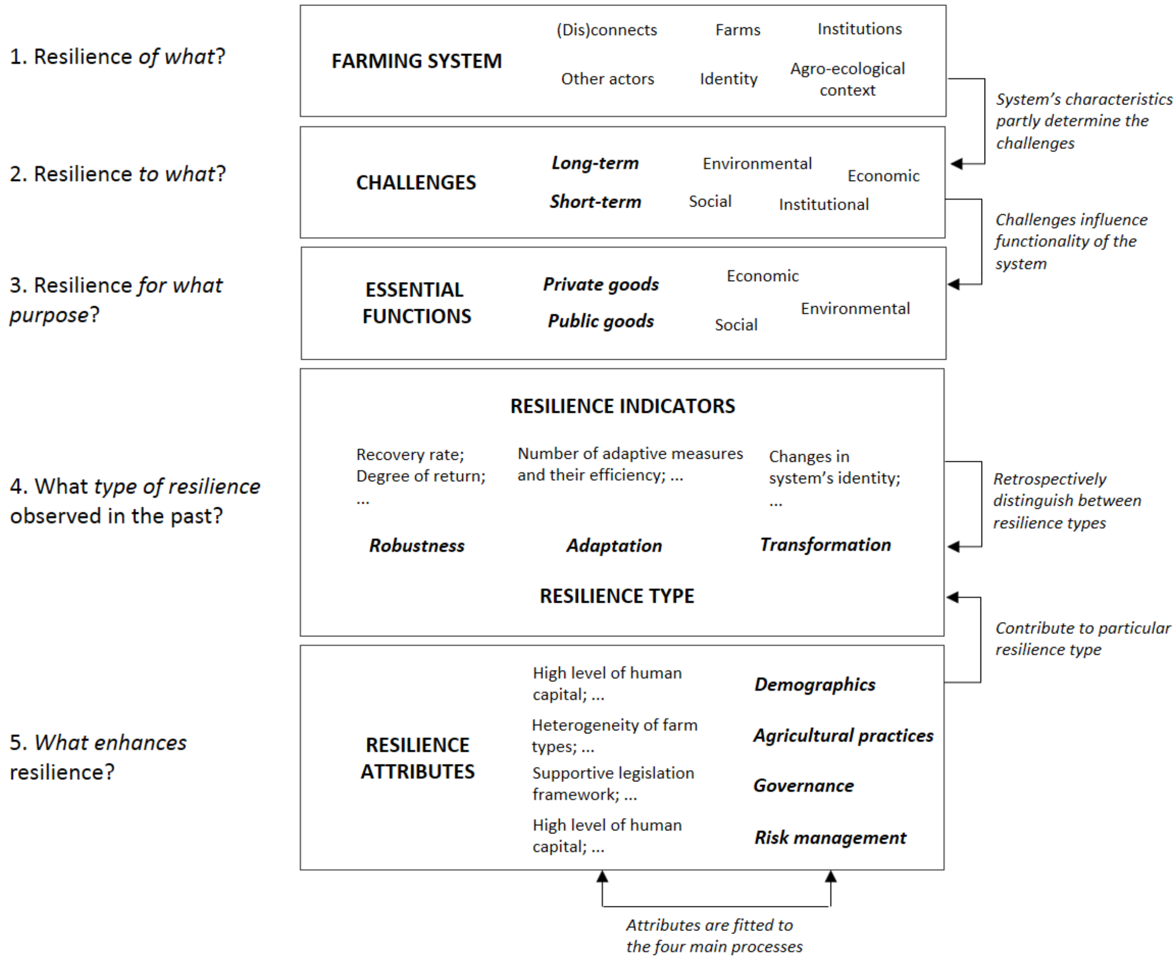

Figure 1. Framework to analyse the resilience of farming systems, including example resilience indicators and attributes (Meuwissen, et al., 2018).

2.4 Resilience indicators and attributes.

We define resilience indicators as means to describe the dynamics of the essential functions in terms of their resilience. Robustness refers to being resilient to a challenge without observing any significant effects and without adaptive measures undertaken after the challenge has been observed. Alternatively, adaptation refers to being resilient by being able to bounce back after the challenge (Walker et al., 2004). Walker et al. (2004) emphasise that this bounce back is not given but the results of the adaptive actions taken by the system's actors. Finally, transformability describes a system's ability to change its nature and getting a fundamentally new structure while still providing the same essential functions (Ludwing et al., 1997; Walker et al., 2004).

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Alternatively, the resilience attributes are characteristics of a farming system that contribute to improve resilience indicators and enhance systems resilience. Cabell and Oelofse (2012) identified 13 general attributes (see Table 1) contributing to the resilience of agroecosystems. The attributes are applicable to multiple scales and are based on the literature discussing resilience at farm level (Darnhofer, 2010) and socio-ecological systems level (Folke et al., 2010). Meuwissen, et al., 2018 incorporates these attributes in the SURE-Farm resilience framework as shown in Figure 1 and specify how the attributes contribute to resilience. Namely, the SURE-Farm resilience framework focuses on those attributes closely fitting to the four main process driving farming systems (see Table 1). While resilience attributes might be studied in isolation, we argue that the complexity of farming systems requires an integrated consideration in order to capture synergies and trade-offs between attributes.

Table 1: Resilience attributes considered in the SURE-Farm resilience framework

Process	Robustness	Adaptability	Transformability
Demographics	Flexibility with respect to labour resources, incl. access to labour resources	Diversity of labour, incl. new entrants	High level of social and human capital
Agricultural practices	Available buffer resources for production	Heterogeneity of farm types	Region diversification
Governance	Access to financial resources	Responsive regulation; investment subsidies	Flexible norms, legislation and regulatory framework
Risk management	Insurance	Diversification	Diversity and flexibility of risk management tools

3 SURE Farm impact assessment integrated toolbox

3.1 Models and modelling approaches

The overall task of WP5 is to analyse the integrated impact of resilience-enhancing strategies and actions on European farming systems using the SURE-Farm framework by assessing how their essential functions react to challenges from the environment in terms of robustness, adaptation and transformability. The analysis aims to explore farming systems at different time and conceptual scales, and will use static and dynamic perspectives for a) describing the current state of a system, b) outlining its potential developments and c) exploring relationships between resilience and broader system characteristics (resilience attributes).

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To this aim, WP5 will make complementary use of existing models (static and dynamic, quantitative and qualitative) by using them as part of an integrated toolbox for the assessment of resilience. In this report we use the term "toolbox" as a group of tools that can be used together or separately to explore different aspects of a farming system and to assess different aspects of resilience. The insights gained from the application of different models can be compared, discussed and integrated into qualitative narratives, scenarios or hypotheses for EU farming systems and their resilience. However, the model results are not quantitatively linked and the outputs of one model are not used as inputs or assumptions for any of the other models.

There are two reasons for deciding to use an integrated toolbox instead of a single model. First, the multi-scale and multi-level nature of resilience means that assessing different dimensions and levels of the systems' resilience with a single tool is complex and complicated (Cash et al., 2006). For example, to try to assess these multiple dimensions with the same model will require a representation of the many different aspects of the system (economic performance, social value, environmental services, etc.) that is extremely detailed. Moreover, this utopic model will also need to assess these aspects at different levels (national, local regional, etc.). When compounding the multiple layers and particularities of each system, such a model quickly becomes unbearable, difficult to understand and manage.

Second, there is a large variety of case studies in SURE-Farm and they differ in terms of farming systems, data availability and model expertise of the local partners (see Table 2). Building a model flexible enough to incorporate all these different types of systems and requirement will add an additional level of difficulty that does not guarantee that the results will be valid or meaningful.

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Table 2: Overview of SURE Farm case studies

Main farming system studied	Case Study	Geographical location
Livestock farms	Egg and broiler production in Sweden	Southern Sweden
	Intensifying dairy farming in Belgium	Flanders region (Vlaams Gewest),
	Extensive beef cattle systems in France	Bourbonnais region (more or less the department of Allier)
	Extensive beef and sheep farming systems in Spain	Aragon North Spain
Arable crops	Cereal and industrial crops in Bulgaria	North-East Bulgaria (Североизточна България)
	Large-scale corporate arable farming in East Germany	The Altmark is located in the German Federal State of Saxony-Anhalt (districts "Stendal" and "Altmarkkreis Salzwedel")
	Intensive arable farming in Netherlands	Veenkoloniën and Oldambt
	Large-scale corporate arable farming in East England	East of England (also known as East Anglia) located in Central-East part of England
Perennial crops	Small-scale farming of hazelnut farms in Italy	Viterbo, north of Lazio region, central-Italy
Horticulture farms	Private family fruit and vegetable farming in Poland	Mazovian region
Mixed farms	Mixed farming in Romania	North-East Region (targeted counties: Suceava, Iasi, Vaslui)

3.2 Overview of the models in the SURE Farm integrated toolbox

The models to be used include system dynamic models, the agent-based model of farm structural change AgriPoliS, the Farming System SIMulator (FSSIM), statistical modelling, a stochastic model, a spatially explicit model to assess ecosystem services, system dynamics models and a Framework for Participatory Impact Assessment (FoPIA). Table 3 contains an overall description of the different models. More details can be found in Appendix A.

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Table 3: General description of models in the integrated toolbox

Model	Main Purpose	Theoretical Background
AgriPolis	Simulation of **structural change of different agricultural regions,** particularly in response to different policies	***Economic concepts:*** profit or income maximization, sunk costs, path dependency, economies of size, myopic behaviour, shadow price, transport costs, and opportunity costs.
FSSIM	Assess **impacts of changes in policy, technology, climate and markets** on farm plans and associated economic, environmental and social impacts, for specific categories of farms	***Mathematical programming (MP)*** used, as an optimization approach. Positive and normative approaches are used. Normative approaches often consider profit maximization as the main objective but multiple objectives can be included.
Stochastic model	Measure **the impact of changes in the socioeconomic and ecological environments** on the economic sustainability of the considered farms. Uncertainty conditions in which actors operate are considered. This allows to analyse the extent of the overall risk farmers face and the relative importance of the elements that characterize it.	The socioeconomic sustainability of ***risk-averse economic agents*** operating in a risky/changing environment based on Monte Carlo simulations.
Ecosystem Service Model	Multi-criteria **optimization of ecosystem services**, or mono-criteria optimization of some ecosystem services with constraints of no-loss on other ecosystem services. Assessment of ecosystem services multifunctionality and classification in hotspots and coldspots of ecosystem services multifunctionality	***Ecological production functions*** (i.e., modelling the provision of ecosystem services starting from land cover, land use and climate variables). ***Multi-objective optimization*** theory and optimization techniques. ***Multi-functionality metrics***
Statistical modelling	To analyse **past and current farm robustness and adaptability** against climate, economic and policy variability, the contribution of resilience enhancing attributes, and adaptation measures	Empirical data and analyses are needed to assess relationships between challenges and essential functions, and between the resilience of essential functions and resilience enhancing attributes. The proposed method includes linear mixed models (calculating farm-specific resilience variables), principle component analysis (PCA; characterizing the diversity of farm resilience patterns) and partial least squared regression (understanding farm resilience from explanatory variables).
System Dynamics	To capture **high level dynamics** of a system by representing the key mechanisms driving behaviour of relevant outcomes.	***Systems thinking:*** models focus on the system, not the individual components. ***Causality:*** Models focus on (assumed) causal relations, not in correlations. ***Endogenous behaviour:*** models study how the observed behaviour is generated by the interactions between

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		the elements within the system rather than by external actions
FoPIA SURE Farm	To **assess current and future resilience and sustainability of farming systems** in participatory workshops. The participatory assessment aims to 1) define the farming system, 2) identify challenges, 3) identify essential functions, 4) identify resilience indicators, 5) identify resilience attributes, with the ultimate aim to assess the influence of challenges and strategies on 6) essential functions, 7) resilience of essential functions, 8) resilience attributes, using a semi-quantitative approach.	Using a broad, general framework, **stakeholders** are invited to **identify and assess indicators of sustainability and resilience** of farming systems. The framework builds on the Framework for Participatory Impact Assessment (FoPIA) and the Resilience Assessment (RA).

All the models operate using a wide range of inputs from the system's environment. These inputs are usually described by the initial and/or final state of the system in terms of economic, social and environmental parameters that are key drivers of farming systems (see Table 4). The inputs are fed, with the exception of FoPIA, into mathematical equations and the model uses different algorithmic methods to estimate optimal states of the system (e.g. FSSIM and the ecosystem services model), structural changes in the system (e.g. AgriPoliS and System Dynamics) or risk (stochastic model). More details about specific inputs required by each model are listed in Appendix B.

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Table 4. Summary of Model Inputs from Appendix B

Model inputs	AgriPoliS	FSSIM	Stochastic model	Ecosystem services model	Statistical models
Prices (crop prices, land prices, timber prices, etc.)	✓	✓	✓		✓
Operational costs (wages, technology, irrigation, etc.)	✓	✓	✓		✓
Access to credit					
Financial costs (interest rates)	✓				✓
Maps agriculture-related regional and structural characteristics	✓			✓	
Land cover (fodder land, cropland, non-permanent grassland, permanent grassland, or forest)	✓		✓	✓	✓
Soil type and/or quality	✓	✓			✓
Labour requirements		✓			✓
Labour force available		✓			✓
Yield, associated inputs (use of fertilizer, crop protection, labour, machinery)		✓	✓		✓
Management associated inputs (timing of operations))		✓			✓
Capital available		✓			✓
Pesticide expense in cropland and in fodder land		✓		✓	
Climatic characteristics (crop suitability, risk of crop pests, risk of environmental hazards)		✓	✓	✓	✓

Note: (✓) indicates the model uses this variable as an input. The inputs of FoPIA and System Dynamics are not included in the table since the specific inputs will be defined later during the project. FoPIA is a participatory approach, not a modelling technique per-se. Therefore, inputs are not explicitly needed, but boundaries and context of the system need to be clearly defined. In the case of System Dynamics, a new model will be built specifically for SURE-Farm, and hence, the inputs required are still not clearly defined.

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Since the models have been built separately and for different purposes, each of them produces different outputs and provides different insights about the essential functions of the farming system under study. Table 5 shows the extent to which each of the models assesses the essential functions of farming systems. For example, FoPIA provides an assessment of all the essential functions but not in depth and hence is ranked 2nd for all of them. Alternately, the Ecosystem services model provides only insights about five of the eight functions but does it in detail (see Table 5). Using the models provide a holistic assessment of the farming system under study by producing different economic, social and environmental indicators associated with the different essential functions. The detailed descriptions of the model outputs can be found in Appendix C.

Table 1. Models' assessment of farm systems' essential functions

Farming Systems Essential Functions		**AgriPoliS**	**FSSIM**	**Stochastic model**	**Ecosystem services model**	**Statistical models**	**FoPIA-SURE Farm**	**System Dynamics**
Private goods	Deliver healthy and affordable food products	2	3	1	3	3	2	3
	Deliver other bio-based resources for the processing sector	2	3	1	3	3	2	3
	Ensure economic viability	3	3	3		3	2	1
	Improve quality of life in farming areas		1			1	2	2
Public goods	Maintain natural resources in good condition (water, soil, air)	1	3		3	1	2	2
	Protect biodiversity of habitats, genes, and species		2		3	1	2	1
	Ensure that rural areas are attractive places for residence and tourism (country side, social structures)		1		3	1	2	1
	Ensure animal health & welfare						2	

***Note**: 3=model provides in depth analysis; core functionality of the model, 2=is part of the model functionality but not in depth, 1=the model can offer a high level perspective about this function.*

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This diversity among models, their calculation approaches and their outputs are the main strength of the SURE-Farm integrated toolbox because it enables the analysis of the farming systems and their resilience from different perspectives. In the integrated toolbox, each model uses different analytical lenses to assess each particular function (see Table 3 and 5). For instance, FSSIM and the Ecosystem Services Model use mathematical optimisation while System Dynamics focuses on the dynamics of systems over time. The aggregation used in each model is also different. For example, AgriPoliS assesses individual farms and their individual interactions while System Dynamics aggregates farms into big groups and focuses on the aggregated dynamics between the different groups and their environment.

It is important to highlight that models are means for enhancing understanding of a given system and often go beyond quantifying or estimating parameters. Whereas some outcome functions might not be quantitatively assessed using the model, the insights resulting from analysing the model results can be used for drawing hypotheses about how these outcomes might behave. This is particularly relevant if the results are discussed with a wide range of stakeholders, using FoPIA or participatory system dynamics for example, since a participatory assessment allows us to explore aspects of farming systems that are difficult to quantify (e.g. quality of life, biodiversity, or animal health and welfare). While there is no single model able to depict all the functions in detail, combining results and insights of all of them makes it possible to get an integrated perspective of the different outcomes of the farming system and how changes in the environment might affect them.

The differences among the models are also reflected in the extent to which each model can be used to assess the resilience indicators (see Table 6). As might be expected, there is a trade-off between depth and breadth in the assessment of the different types of resilience that each model and modelling tool can provide. Most flexible models and approaches such as FoPIA and System Dynamics are able to provide less details about each type of resilience but they have the advantage of being suitable for different indicators. Alternatively, other approaches might offer a more comprehensive picture of a given indicator but they are limited in their ability to address the rest.

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Table 6. Models' assessment of farming systems' resilience indicators

Resilience Indicator	AgriPoliS	FSSIM	Stochastic model	Ecosystem services model	Statistical models	FoPIA-SURE Farm	System Dynamics
Robustness	3	2	3	2	3	1	2
Adaptability	2	2	1	2	3	1	2
Transformability	1	1				1	1

***Note**: 3=model provides in depth analysis and/ or this attribute is a core functionality of the model, 2=is part of the model functionality but not in depth, 1=the model can offer a high-level perspective about this function.*

As shown in Table 6, since most of the models are static rather than dynamic, assessing transformability is probably the biggest challenge. As an alternative, we propose to use participatory discussions, for example using FoPIA or participatory System Dynamics, about alternative configurations of the farming system, transformation pathways and strategies. In particular, the models outputs and scenarios can be used to discuss: *what will happen if?,* and to build diagrams describing the chain of causal relationships that contribute to robustness, adaptation and transformability of farming systems.

The outputs of the models and assessment of the resilience indicators will be also used to study the relationships between resilience attributes and the resilience indicators. Causal relationships, statistic correlations and stakeholders inputs will be used to identify key attributes shaping the identity of a farming system and contributing specific resilience indicators. These relationships are likely to be different among case studies and the results will be bound to the data available in each case and the detail the integrated toolbox can provide about each attribute. Similarly to the resilience indicators, assessing all the proposed attributes in depth using a single model is not possible and the extent to which each attribute can be assessed by the models in the toolbox is summarised in Table 7.

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Table 7: Models' assessment of farm systems' resilience attributes

Resilience Indicators	Resilience Attributes	AgriPoliS	FSSIM	Stochastic model	Ecosystem services model	Statistical models	FoPIA-SURE Farm	System Dynamics
Robustness	Flexibility with respect to labour resources	1	3	-		3	1	2
	Available buffer resources for production	1	3		1	3	1	3
	Access to financial resources	3	2	3		2	1	3
	Insurance		1	2		2	1	1
Adaptability	Diversity of labour, incl. new entrants		1				1	
	Heterogeneity of farm types	3	2	1	2	2	1	1
	Responsive regulation; investment subsidies	2	1			1	1	1
	Diversification	2		1	2			
Transformability	High level of social and human capital	1	2				1	2
	Region diversification	1			2	1	1	
	Flexible norms, legislation and regulatory framework						1	1
	Diversity and flexibility of risk management tools	1		1		1	1	

***Note**: 3=model provides in depth analysis and/ or this attribute is a core functionality of the model, 2=is part of the model functionality but not in depth, 1=the model can offer a high-level perspective about this function.*

4 Application to SURE-Farm and deliverables

The aforementioned integrated toolkit will be applied in SURE-Farm to assess farming systems' resilience through the different deliverables of WP5. For simplicity purposes, the assessment conducted using the SURE-Farm toolkit is divided in three type of analysis: a) analysis for understanding farm systems' current and past resilience, b) analysis for exploring farm systems' future and expected resilience and c) analysis about strategies for improving resilience. The models to be used for each dimension are presented in Table 8.

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Table 8. WP5 deliverables and model results to be presented.

Assessment type	Models used	Associated Deliverables
Past and current resilience	Stochastic model Statistical model FoPIA SURE Farm Ecosystem Services	D5.2 and D5.3
Future resilience	AgriPoliS Ecosystem services FoPIA SURE Farm System Dynamics	D5.5
Strategies*	AgriPoliS Ecosystem services FoPIA SURE Farm System Dynamics FSSIM	D5.6

**The models to be used for strategy assessment are still to be confirm depending on the strategies proposed by other Work Packages.*

The specific case studies and scenarios used for each type of analysis and to be covered with each specific modelling approach are covered next.

4.1 Models to be used for the different case studies

As described in Section 3, there is a large variety of case studies in SURE-Farm and only some of the models will be applied in each case. Table 9 presents the case studies and the modelling approach currently planned in each case study. More applications may be possible for some tools, such as the statistical modelling. Note that system dynamics modelling will not be applied to any specific case but might instead be used to combine experiences and insights gained from different case studies about a particular farming system (e.g. arable land or livestock farms).

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Table 9. Models used in each case study

Case Study	AgriPoliS	FSSIM	Stochastic model	Ecosystem services	Statistical models	FoPIA-SURE Farm
Egg and broiler production in Sweden						✓
Intensifying dairy farming in Belgium	✓			✓		✓
Extensive beef cattle systems in France	✓			✓		✓
Extensive beef and sheep farming systems in Spain				✓		✓
Cereal and industrial crops in Bulgaria	✓			✓		✓
Large-scale corporate arable farming in East Germany	✓			✓		✓
Large-scale corporate arable farming in East England				✓		✓
Intensive arable farming in Netherlands	✓	✓		✓	✓	✓
Small-scale farming of hazelnut farms in Italy			✓	✓		✓
Private family fruit and vegetable farming in Poland				✓		✓
Mixed farming in Romania	✓			✓		✓

Note: (✓) indicates the model will be used for assessing the case study.

4.2 Potential scenarios to evaluate

Scenarios are a useful tool to cope with the future when uncertainties make it impossible to anticipate a single more likely development path. Scenarios can be used to explore—not predict—the future through the identification of potential opportunities and threats and as a way to adjust strategies to a wide range of conditions (Schoemaker, 1995; Fink et al., 2004).

For SURE-Farm, Work Package 1 (WP1) developed five scenarios based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), called Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014). These scenarios have been used and quantified in several projects (Bauer et al., 2017; Popp et al., 2017; Riahi et al., 2017) and have been expanded in WP1 from global level narratives for the economy into narratives describing relevant conditions for EU farming systems. These scenarios developed by WP1 are described in the report "D1.2 Scenarios for EU farming" (Mathijs et al., 2018). Table 10 presents a brief description of each of them.

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Table 10. Summary of scenarios for EU farming

Scenario Name	Summarised description
SSP1: Sustainability	Environmental awareness has led to environmental action in the form of strict environmental legislation, pro-environmental corporate strategies and sustainable food consumption. As a result, the cost of trade increased and the price of food as result of land scarcity, external costs of pollution. Consumer preferences are strongly influenced by considerations of health, sustainability and naturalness.
SSP2: Middle of the road	A mixture of all the scenarios without a clear distinctive pattern.
SSP3: Regional rivalry	Environmental awareness is low and international trade is strongly constrained by protective border measures. Consumption patterns have not changed a lot in terms of composition, but more attention is given to convenience and locally produced food.
SSP4: Inequality	Food prices are high, as productivity growth remains slow due to limited adoption of biotechnology based innovations. Consumers mainly care for the social status food relays, as showcased for instance by the image of slenderness.
SSP5: Fossil-fuelled development	Environmental awareness focuses mainly on local issues while ignoring global issues. International trade is very open, resulting in regional specialization in production. Diets are rich in meat which is both imported and produced in the EU using imported feedstuffs. The pressure to reduce food waste and losses is low. Food prices are low, mainly because of high productivity gains, but highly volatile.

The scenarios developed by WP1 will serve as a reference for running the models that will be used to assess how the resilience of farming systems in the EU might develop in the future. Since these scenarios are not specific for any case study they will only be used as reference framework for sketching the pathways that some key variables might follow in the future. Hence, the models will not predict the future but will explore what can be expected in terms of resilience for different farming systems and countries.

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Appendix A: Detailed model description

Table 11: Overall model description AgriPoliS

Purpose of the model	Simulation of structural change of different agricultural regions, particularly in response to different policies
Theoretical background	The following economic concepts are considered in the model: profit or income maximization, sunk costs, path dependency, economies of size, myopic behaviour, shadow price, transport costs, and opportunity costs.
Agents	Individual farms
Goals and values of agents	Profit or income maximization
Interaction	Land market; markets for selected products (only some regions)
Agricultural production	Farms are randomly distributed in the spatial grid of land plots and initialized with individual management skills (i.e. different variable production costs) and ages of the farmer and farm assets Length of rental contract is randomly drawn from a uniform distribution with a minimum and maximum contract length (regional specific) Amount of farm family labour is derived from accountancy data; opportunity cost for off-farm work; allocation based on mixed-integer programming Land market implemented as first-price auction
Model boundary	Homogenous region
Time frame	
Static/dynamic	Dynamic
Computational approach	Maximize profits or household income by use of a mixed-integer programming model that is linked to the selected farm agents' data on factor endowments (facilities, labour, capital, land, management quality, etc.), as well as the various production and investment alternatives from which the farms can choose to maximize their profit
Model language	C++
Calibration data	AgriPoliS is adapted to selected regions by specifying farm types that are typical for that region and which are weighted to match regional characteristics. In general two kinds of data are used: regional data (aggregated regional capacities) and farm level data (FADN and/ or expert knowledge)
Validated against…	In the beginning (base year or period) of each simulation, the derived farm agents should choose the same or similar production activities as the real farms they represent
Model described in…	Sahrbacher, C., Sahrbacher, A. and Balmann, A. (2014). Parameterisation of AgriPoliS: A Model of Agricultural Structural Change. In: Smajgl, A., Barreteau, O. (eds.), Empirical Agent-Based Modelling - Challenges and Solutions, Vol. 1: The Characterisation and Parameterisation of Empirical Agent-Based Models, Springer, 105-121. Sahrbacher, C., Sahrbacher, A., Kellermann, K., Happe, K., Balmann, A., Brady, M., Schnicke, H., Ostermeyer, A., Schönau, F. (2012): ODD-Protocol of AgriPoliS. IAMO, Available: http://projects.iamo.de/agripolis/documentation/ODD_AgriPoliS.pdf.

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Model applications	e.g.: Appel, F., Ostermeyer-Wiethaup, A., Balmann, A. (2016): Effects of the German Renewable Energy Act on structural change in Agriculture – The case of biogas, Utilities Policy 41, 172-182. Happe, K., Balmann, A., Kellermann, K., and Sahrbacher, C. (2008): Does structure matter? The impact of switching the agricultural policy regime on farm structures. Journal of Economic Behavior & Organization, 67:431–444. Uthes, S., Piorr, A., Zander, P., Bienkowski, J., Ungaro, F., Dalgaard, T., Stolze, M., Moschitz, H., Schader, C., Happe, K., Sahrbacher, A., Damgaard, M., Toussaint, V., Sattler, C., Reinhardt, F.J., Kjeldsen, C., Casini, L., and Müller, K. (2011): Regional impacts of abolishing direct payments: An integrated analysis in four European regions. Agricultural Systems, 104:110–121.

Table 12: Overall model description bio-economic farm model FSSIM

Purpose of the model	Assess impacts of changes in policy, technology, climate and markets on farm plans and associated economic, environmental and social impacts, for specific categories of farms
Theoretical background	Mathematical programming (MP) is used, which is an optimization approach.
Agents	Individual farms or farm types (depending on the data)
Goals and values of agents	Both a normative approach can be used, considering profit maximization as the main objective of farmers, or a positive approach, using positive mathematical programming (PMP). PMP implies that the model is calibrated, and implicit objectives are also considered. It is also possible to consider multiple objectives.
Interaction	In FSSIM itself there is no interaction between agents. FSSIM has however been coupled to an agent-based model for a specific study. The MP approach has also been used to assess interactions between individual arable and dairy farms in a province in the Netherlands.
Agricultural production	Farms can choose between different activities. A crop activity is hectare of a specific crop, with a yield (depending on climate and soil) and associated inputs (fertilizer use, crop protection use, labour, etc.). A livestock activity is a livestock unit with a yield (milk, meat, etc.) and associated inputs (feed, concentrates, etc.). Details depend on available data. FADN includes mainly economic data regarding inputs, and therefore often surveys on farm management are needed to define agricultural activities.
Model boundary	The model is run per farm or farm type, and results can be aggregated per region.

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Time frame	First the base year is simulated, and then one or more future situations. This can be the near future for policy scenarios (e.g. 5 years) and a long-term future for climate scenarios (e.g. 30 years).
Static/dynamic	Static
Computational approach	Mathematical programming. This can be linear programming (profit maximization) or positive mathematical programming (PMPP). PMP is less suitable for long-term scenarios, as calibrated objectives may not hold for the future.
Model language	The model is programmed in GAMS, and can be run via Access. A Graphical Use Interface (GUI) in Access is being developed, but this GUI can probably not be used for adapted cases.
Calibration data	Data on current farm plans are needed. The model simulates farm plans, and these need to be similar to observed farm plans. When using PMP, also past data on farm plans are needed, and exact calibration is ensured. When using a normative approach, data on farm plans are needed to evaluate whether included objectives and constraints are appropriate.
Validated against…	Observed farm plans.
Model described in…	The first version of FSSIM, as developed in the SEAMLESS project, is described in: Janssen, S., Louhichi, K., Kanellopoulos, A., Zander, P., Flichman, G., Hengsdijk, H., Meuter, E., Andersen, E., Belhouchette, H., Blanco, M., Borkowski, N., Heckelei, T., Hecker, M., Li, H., Oude Lansink, A., Stokstad, G., Thorne, P., van Keulen, H., van Ittersum, M., 2010. A generic bioeconomic farm model for environmental and economic assessment of agricultural systems. Environ. Manage. 46, 862-877. Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Oude Lansink, A., Van Ittersum, M.K., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agr. Syst. 103 585-597. The adapted FSSIM 2.0 version, linked to Access, is available on a model portal, and described in: http://models.pps.wur.nl/node/959 Kanellopoulos, A., Reidsma, P., Wolf, J., van Ittersum, M.K., 2014. Assessing climate change and associated socio-economic scenarios for arable farming in the Netherlands: An application of benchmarking and bio-economic farm modelling. Eur. J. Agron. 52, 69-80. Wolf, J., Kanellopoulos, A., Kros, J., Webber, H., Zhao, G., Britz, W., Reinds, G.J., Ewert, F., de Vries, W., 2015. Combined analysis of climate, technological and price changes on future arable farming systems in Europe. Agr. Syst. 140, 56-73. An example of how interaction can be included, is described in:

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	Nakasaka, K. 2016. Assessing the economic and environmental effects of land exchange on arable farms using a regional bio-economic model. MSc thesis, Plant Production Systems, Wageningen University. More general overviews can be found in: Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. Agr. Syst. 94, 622-636. Reidsma, P., S. Janssen, J. Jansen, M.K. van Ittersum, 2018. On the use of farm models for policy impact assessment in the European Union – A review and research agenda. Agr. Syst. 159, 111–125.
Model applications	e.g.: Paas, W., A. Kanellopoulos, G. Van de Ven, P. Reidsma. 2016. Integrated impact assessment of climate and socio-economic change on dairy farms in a watershed in the Netherlands. NJAS 78: 35-45. Reidsma, P., J. Wolf, A. Kanellopoulos, B. F. Schaap, M. Mandryk, J. Verhagen, M. K. van Ittersum, 2015. Climate change impact and adaptation research requires integrated assessment and farming systems analysis: a case study in the Netherlands. Environmental Research Letters 10, 045004. Reidsma, P., M. M. Bakker, A. Kanellopoulos, S. J. Alam, W. Paas, J. Kros, W. de Vries. 2015. Sustainable agricultural development in a rural area in the Netherlands? Assessing impacts of climate and socio-economic change at farm and landscape level. Agricultural Systems 141, 160-173. Reidsma, P., S. Feng, M. van Loon, X. Luo, M. Lubbers, A. Kanellopoulos, C. Kang, J. Wolf, M. van Ittersum, F. Qu. 2012. Integrated assessment of agricultural land use policies on nutrient pollution and sustainable development in Taihu Basin, China. Environmental Science & Policy 18, 66-76.

Table 13: Overall model description bio-economic farm models: Stochastic Model

Purpose of the model	Measuring how changes in the social and ecological environments affect the economic and social sustainability of the considered farming systems. Uncertainty conditions in which actors operate are considered. This allows to analyse the extent of the overall risk agents face and the relative importance of the elements that characterize it.
Theoretical background	The socioeconomic sustainability of averse-risk economic agents operating in a risky/changing environment.
Agents	Farmers and their households (i.e., farms managed by families relying also upon off-farm income sources).

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Goals and values of agents	Maximization of the net present value of income earned to the farmer (investor) and consumed over the planning horizon. Farmers operate in a risky environment and are expected to be risk adverse.
Interaction	Land market.
Agricultural production	The proposed modelling approach will be applied to the Viterbo's case study area. This refers to families that manage commercial farms cultivating hazelnut (> 2 ha) within the Viterbo's boundaries (i.e., county-level). The analysis will be developed on representative farming systems to be stratified according to some relevant dimensions such as: Size [small (up to 10 ha, 89% of the population), medium (11-50 ha, 10%), and large (>50 ha, 1%)]; Ecological zones (altitude, soil characteristics, irrigation requirements and traditional/new areas of production) Use of irrigation. The model does not provide an optimal production plan. Hence, it is suitable for farms where there is not a large room of manoeuvre in this regard (e.g. very specialized and not flexible production patterns).
Model boundary	Farm households in a given region.
Time frame	Annual Planning horizon for the considered tree crop (i.e. hazelnut) Life-cycle of the family.
Static/dynamic	Static
Computational approach	Monte Carlo Simulations on farm/household level simulation models.
Model language	NA. A Monte Carlo simulation add-on on spread-sheets software.
Calibration data	NA.
Validated against…	Model's ability to simulate a farm is validated against the current farmers behaviour and economic results (FADN). Furthermore, model results are discussed with stakeholders (especially farmers) to cement the hypothesis we retrieved from modelling (i.e., through interviews and focus groups).

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Model described in…	Hardaker, J. B., 2004. Coping with risk in agriculture. (J. B. Hardaker, R. B. M. Huirne, J. R. Anderson, and G. Lien, Eds.) (2nd ed.). Cambridge, MA: Cabi. Richardson J.W., Hennessy T., O'Donoghue C. (2014). "Farm level Models". Capther 17 in: O'Donoghue C. (2014) "Handbook of Microsimulation Modelling". Emerald, Bnley (UK).
Model applications	Similar models have been applied by: Richardson J.W. (2005). Simulation for applied risk management. College Station, Texas: Department of Agricultural Economics, Texas A&M University. Hardaker J.B., Richardson J.W., Lien G., Schumann K.D. (2004). Stochastic efficiency analysis with risk aversion bounds: A simplified approach. The Australian Journal of Agricultural and Resource Economics, 48(2): 253-270. Sterner, T., Troell, M., Vincent, J., Aniyar, S., Barrett, S., Brock, W., … Xepapadeas, A. (2006). Quick Fixes for the Environment : Part of the Solution or Part of the Problem ? *Environment: Science and Policy for Sustainable Development*, *48*(10), 20–27.

Table 14: Overall model description Ecosystem Services model

Purpose of the model	Multi-criteria optimization of ecosystem services, or mono-criteria optimization of some ecosystem services with constraints of no-loss on other ecosystem services
Theoretical background	Ecological production functions (i.e., modelling the provision of ecosystem services starting from land cover, land use and climate variables). Multi-objective optimization theory and optimization techniques.
Agents	Agents are not represented in the model. In its current formulation the agent is represented by a unique decision maker that wants to maximize one or some ecosystem services at the national scale without losing other ones.
Goals and values of agents	Ecosystem services to maximize according to the preferences of an exogenous unique agent
Interaction	Interactions between ecosystem services are given by land cover and land uses. They can be trade-offs or synergies. Trade-offs: expansion of a land cover causes decreasing of another land cover with consequent reduction in the provision of another ecosystem services. Synergies: some land covers provide multiple ecosystem services.

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Agricultural production	Agricultural production is represented as a provisioning ecosystem services. It is divided into crop production and livestock production (meat and milk).
Model boundary	National scale (first application done on France); within SURE FARM the boundary can be defined as the NUTS3 in which each case study is embedded
Time frame	Time dynamics is not included. The model is based on an optimization technique: it starts from an initial configuration and provides an optimized configuration. The time elapsed between the two configuration is not specified.
Static/dynamic	Static
Computational approach	Evolutionary techniques for the optimization.
Model language	Matlab, Python
Calibration data	Ecological production functions are calibrated with data. Data consists in layers of ecosystem services at the 1km² resolution
Validated against…	Possibility of applying cross-validation techniques for the Ecological Production Functions. By definition the result of the optimization procedure cannot be validated against data, as they are future scenarios.
Model described in…	Accatino, F., Tonda, A., Dross, C., Léger, F., Tichit, M., 2018. Trade-offs and synergies between livestock production and other ecosystem services. Under Review in Agricultural Systems. Teillard, F., Doyen, L., Dross, C., Jiguet, F., Tichit, M., 2016. Optimal allocations of agricultural intensity reveal win-no loss solutions for food production and biodiversity. Reg. Environ. Chang. 17, 1397–1408. https://doi.org/10.1007/s10113-016-0947-x Dross, C. 2016. Stratégies d'utilisation des sols agricoles pour conciliar production et oiseax specialists des milieu agricoles. Chapter 5: Optimizing agricultural land-use and intensity to maximize the farmland bird index while maintaining production: optimal win-no-loss solution is a mix of land sparing and land sharing. PhD thesis.
Model applications	The above-mentioned publications contain both model descriptions and application

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Table 15: Overall description statistical modelling

Purpose of the model	To analyse farm resilience against climate, economic and policy variability, the contribution of resilience enhancing attributes, and adaptation measures.
Theoretical background	Empirical data and analyses are needed to assess relationships between challenges and essential functions, and between the resilience of essential functions and resilience enhancing attributes. The proposed method includes linear mixed models (calculating farm-specific resilience variables), principle component analysis (PCA; characterizing the diversity of farm resilience patterns) and partial least squared regression (understanding farm resilience from explanatory variables).
Agents	Farms within farming systems
Goals and values of agents	Goals are not explicitly stated, but main resilience indicators to be analysed are means, trends and variability (i.e. resilience indicators) of farm productivity, gross margin and economic efficiency (i.e. essential functions).
Interaction	Interaction is not considered, but explanatory variables can relate to interaction.
Agricultural production	An aggregated indicator for production needs to be calculated, in order to compare different farms. For crop production, this could be total dry matter per ha, protein per ha, nitrogen per ha, or energy per ha. For meat production, similar measures can be used. Alternatively, production can be expressed in euros per ha, but then prices and costs also influence the indicator.
Model boundary	A NUTS2 region, similar to a province.
Time frame	Long-term historical data
Static/dynamic	Dynamics are analysed
Computational approach	Statistics: linear mixed models, principle component analysis (PCA) and partial least squared regression
Model language	R
Calibration data	In statistical analyses, no calibration takes place, but statistical tests are used to test hypotheses
Validated against…	Statistical analyses will be performed for multiple NUTS2 regions in multiple case studies, allowing some validation of relationships. In addition, relationships will also be discussed in the participatory impact assessment workshops.
Model described in…	The proposed method is directly based on: Martin G, Magne M-A, Cristobal MS. 2017. An Integrated Method to Analyze Farm Vulnerability to Climatic and Economic Variability According to Farm Configurations and Farmers' Adaptations. Front. Plant Sci. 8.

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	Earlier related studies include: Reidsma, P., Ewert, F., Oude Lansink, A., Leemans, R., 2010. Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses. Eur. J. Agron. 32, 91-102.

Table 16: Overall description framework for FoPIA SURE Farm

Purpose of the model	To assess the influence of scenarios and strategies on sustainability (essential functions) and resilience (dynamics of essential functions) of the farming systems in the case study. The participatory assessment aims to 1) define the farming system, 2) identify challenges, 3) identify essential functions, 4) identify resilience indicators, 5) identify resilience attributes, with the ultimate aim to assess the influence of challenges and strategies on 6) essential functions, 7) resilience of essential functions, 8) resilience attributes, using a semi-quantitative approach.
Theoretical background	Using a broad, general framework, stakeholders are invited to identify and assess indicators of sustainability and resilience. The framework builds on the Framework for Participatory Impact Assessment (FoPIA) and the Resilience Assessment (RA).
Agents	Farming systems (depends on application, but in SURE Farm will be the whole farming system)
Goals and values of agents	Not explicit, no simulations
Interaction	Not explicit, but indicators relating to interaction may be assessed by the stakeholders
Agricultural production	As one or more of the essential functions ('deliver healthy and affordable food production')
Model boundary	Farming system
Time frame	One or more future scenarios and strategies
Static/dynamic	FoPIA was static, but RA adds dynamic aspects
Computational approach	A simple scoring system. FoPIA scores the impact of scenarios on indicators between -3 and +3, where -3 is very negative and +3 is very positive. The importance of indicators is also ranked. Scores can be aggregated.
Model language	Word and Excel
Calibration data	Multiple stakeholder groups should be invited to avoid bias

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Validated against…	Quantitative models and literature (for ecological indicators, quantitative models may be more reliable, while for social indicators stakeholders provide the best indication)
Model described in…	Morris et al., 2011. A Framework for Participatory Impact Assessment' (FoPIA): involving stakeholders in European policymaking, a case study of land use change in Malta. Ecology and Society 16. König, H.J., Uthes, S., Schuler, J., Zhen, L., Purushothaman, S., Suarma, U., Sghaier, M., Makokha, S., Helming, K., Sieber, S., Chen, L., Brouwer, F., Morris, J., Wiggering, H., 2013. Regional impact assessment of land use scenarios in developing countries using the FoPIA approach: Findings from five case studies. J. Environ. Manage. 127, S56-S64. Resilience Alliance (2010): http://www.resalliance.org/3871.php
Model applications	König, H.J., Schuler, J., Suarma, U., McNeill, D., Imbernon, J., Damayanti, F., Dalimunthe, S.A., Uthes, S., Sartohadi, J., Helming, K., Morris, J., 2010. Assessing the Impact of Land Use Policy on Urban-Rural Sustainability Using the FoPIA Approach in Yogyakarta, Indonesia. Sustainability 2, 1991-2009. Purushothaman, S., Patil, S., Francis, I., König, H.J., Reidsma, P., Hegde, S., 2013. Participatory impact assessment of agricultural practices using the land use functions framework: Case study from India. International Journal of Biodiversity Science, Ecosystems Services and Management 9, 2-12. Selberg et al., 2017. Improving participatory resilience assessment by cross-fertilizing the Resilience Alliance and Transition Movement approaches. Ecology and Society 22(1): 28.

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Table 17: Overall description system dynamics modelling

Purpose of the model	To capture high level dynamics of a system by representing the key mechanisms driving behaviour of relevant outcomes.
Theoretical background	Systems thinking: models focus on the system, not the individual components. Causality: Models focus on (assumed) causal relations, not in correlations. Endogenous behaviour: models study how the observed behaviour is generated by the interactions between the elements within the system rather than by external actions.
Agents	Aggregated representation of agents
Goals and values of agents	Decision making process represented at an aggregated level.
Interaction	
Agricultural production	Aggregated representation of key inputs and outcomes.
Model boundary	Problem-driven, not geographical: A system dynamics analysis traces from the problem behaviour outward along chains of cause and effect, rather than from the system boundary inward.
Time frame	Depends on specific problem
Static/dynamic	dynamic
Computational approach	Difference equations
Model language	C++
Calibration data	NA
Validated against…	Two types of validation tests: Validation of model structure using literature, interviews, and laboratory experiments. Validation of model behaviour e.g. through extreme condition testing, sensitivity analysis and behaviour reproduction including error decomposition using Their statistics
Model described in…	NA

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Model applications	Applications in the context of resilience analysis in social-ecological systems: Herrera, H. (2017). From Metaphor to Practice: Operationalizing the Analysis of Resilience Using System Dynamics Modelling. Systems Research and Behavioral Science, 34(4), 444–462.

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Appendix B: Models Exogenous parameters

Table 18: Exogenous parameters AgriPoliS

Social and economic environment	***Prices, costs:*** Most product prices and costs are exogenously given. Some selected product prices in some model regions are endogenously calculated by a price function (Tâtonnement process) Including wages inside and outside agriculture, interest rates
	Policies: Implementation of EU CAP Various alternative policy scenarios Various price scenarios
Physical and natural environment	***Technology:*** Provided investment options are typical for the respective region. No technical progress but adoption of new technologies and economies of scale
	Soil/land-use: Synthetic landscape that maps agriculture-related regional and structural characteristics Land quality: no agricultural use, abandoned land, soil type, arable and grassland

Table 29: Exogenous parameters the bio-economic farm model FSSIM

Social and economic environment	***Prices, costs:*** current prices and costs are derived from data (FADN or local sources). Price and cost scenario are generally based on other models, such as CAPRI.
	Policies: implementation of EU CAP, various alternative policy scenarios. Subsidies and taxes relate to specific agricultural activities (in the technical coefficients). Regulations are included as constraints (e.g. sugar beet quota, minimum amount of Ecological Focus Area).
	Labour: each agricultural activity has certain labour requirements, and per farm (type) a certain amount of labour is available (in constraints)
Physical and natural environment	Each agricultural activity in a certain agro-climatic zone (climate and soil conditions) has a yield, associated inputs (use of fertilizer, crop protection, labour, machinery) and management (timing of operations), and additional outputs (crop

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	residues, management of crop residues, N losses, indicators related to crop protection use).
	Agricultural activities can change in the future due to technology and climate change (changes in yields and related inputs).
	A simulated farm (type) is located in a certain agro-climatic zone (where a sub-set of the agricultural activities can be selected), regulations may include constraints (e.g. maximum nitrate leaching) and has access to limited resources (land, labour, capital)

Table 20: Exogenous parameters bio-economic farm-models: Stochastic model

Social and economic environment	• Prices of farm products and inputs, including wages inside and outside agriculture • Financial farm and household economic indicators • Off-farm incomes and employment opportunities • Interest rates • For these parameters, it is needed to assess: current level, variability and trends. • Farm household characteristics • Farmers’ degree of risk aversion • On and off-farm investment opportunities
Physical and natural environment	Current and perspective technology parameters including technical parameters referring to environmental sensitive inputs (i.e. chemicals and irrigation water)
	Soil and land characteristics (crop suitability)
	Climatic characteristics (crop suitability, risk of crop pests, risk of environmental hazards)

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Table 213: Exogenous parameters ecosystem services model

Social and economic environment	• Pesticide expense in cropland and in fodder land • Land cover allocation decision
Physical and natural environment	• Land cover : fodder land, cropland, non-permanent grassland, permanent grassland, and forest • Compositions of different types of crops, different types of grasslands and different types of forests are assigned for each crop.
	Climatic variables : mean annual rainfall and mean annual temperature in the area

Table 22: Exogenous parameters statistical modelling

In the statistical modelling, the resilience (means, trends, variability) of essential functions (productivity, economic efficiency, ...) is explained by variables related to the "challenges" introduced in the system and the resilience attributes related to farm management. Specific indicators can be defined based on the data.

Social and economic environment	Challenges: input price, output price, ...
	Attributes: collaboration in networks, access to media, access to credit, flexibility with regard to markets, access to insurance
Physical and natural environment	Challenges: e.g. numbers of days with heat stress, earliness of the growing season, water deficit or excess in autumn/winter/spring/summer
	Attributes: local natural capital (soil organic carbon, agro-climatic zone), diversity (Shannon index of diversity of the farmland/herd) resources (amount of irrigation water used, mineral fertilizer rate, organic manure, crop protection use, ...)

Table 23: Exogenous parameters FoPIA SURE Farm

Social and economic environment	As it is a participatory approach, no model inputs are needed, but boundaries and context of the system need to be clearly defined.
Physical and natural environment	As it is a participatory approach, no model inputs are needed, but boundaries and context of the system need to be clearly defined.

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Appendix C: Delivery of private and public goods – sustainability indicators

Table 24: Delivery of private and public goods – sustainability indicators AgriPoliS

Economic	Structural change – farm structures. Farms leave the sector if they are illiquid or expect a lack of coverage of opportunity costs
	Production, farm profitability and incomes, regional value added,
	Land prices and Ricardian land rent
Social	Employment
	Labour income, land rental income
	Farm household income
Environmental	Structural change – land use
	Livestock figures
	Crop rotation

Table 25: Delivery of private and public goods – sustainability indicators bio-economic farm models FSSIM

Economic	Gross margin, total output, total input costs, output/input efficiency
	Crop production, meat production
	Shadow prices (have been used to assess tipping points: Groeneveld et al., 2016)
Social	Labour use
Environmental	Crop areas, crop diversification, livestock units
	N input, fertilizer costs, N losses (to air / water)
	Crop protection use, Biocide Residue Index
	GHG emissions (incl. change in soil organic carbon)
More information	The current version of FSSM is a structure including potential equations and indicators. Which indicators can be calculated depends on the data that are available. See Appendix 1 in Reidsma et al. (2018) for a long list of indicators used in bio-economic farm models: 'Reidsma, P., S. Janssen, J. Jansen, M.K. van Ittersum, 2018. On the use of farm models for policy impact assessment in the European Union – A review and research agenda. Agr. Syst. 159, 111–125.'

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Table 26: Delivery of private and public goods – sustainability indicators bio-economic farm models: Stochastic model

Economic	Farm income
	Farm household income
	Available net worth
Social	Labour use
	Use of inputs with potential negative impacts on human health
Environmental	Land use patterns (for the consequences on: biodiversity, soil coverage, landscape value and so on)
	Use of irrigation water (depletion of water stocks)
	Use of inputs with potential negative impacts on the environment

Table 47: Delivery of private and public goods – sustainability indicators ecosystem services model

Economic	Crop production Meat production Milk production Timber growth / Timber stock
Social	Cultural ecosystem service : recreation
Environmental	Regulating ecosystem service; pollutant retention; carbon storage; carbon sequestration; annual water flow; erosion control;
	Supporting ecosystem services: pollination

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Table 58: Delivery of private and public goods – sustainability indicators statistical modelling

The proposal is to assess the resilience of economic indicators (productivity, gross margin, economic efficiency) and the relations between environmental (e.g. nitrogen use efficiency, nitrogen losses) and social (e.g. labour use) indicators.

Economic	Productivity (aggregated, so based on dry matter / energy / protein / nitrogen), economic efficiency (output/input), gross margin
Social	Labour use
Environmental	Nitrogen input, nitrogen use efficiency, nitrogen balance, nitrogen losses (indicators related to nitrogen seem most appropriate if we also analyse environmental resilience; data need to be available in FADN); water input, water use efficiency, crop protection use and related environmental impacts.

Table 29: Delivery of private and public goods – sustainability indicators FoPIA SURE Farm

The original FoPIA, which provides the basis for this approach, uses the Land Use Functions approach to identify the main indicators (Konig et al., 2012). By identifying three main Land Use Functions per dimension (economic, environmental and social), a holistic approach is ensured, and indicators can be compared among case studies. Indicators related to the Land Use Functions can however differ per case study. In SURE Farm, our basis is not the Land Use Functions, but the principle private and public goods. Indicators related to these should be, as much as possible, similar in the different case studies. In a next version, we may propose some first general indicators.

Economic	Deliver healthy and affordable food products
	Deliver other bio-based resources for the processing sector
	Ensure economic viability (viable farms help to strengthen the economy and contribute to balanced territorial development).
Social	Improve quality of life in farming areas by providing employment and offering decent working conditions.
	Ensure that rural areas are attractive places for residence and tourism (countryside, social structures)
	Ensure animal health & welfare
Environmental	Maintain natural resources in good condition (water, soil, air)
	Protect biodiversity of habitats, genes, and species

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