Sustainability and resilience of European farming systems

An integrated assessment

Wim Paas

Propositions

1. European farming systems operate closely to at least one critical threshold. (this thesis)
2. A focus on the economic domain undermines farming system sustainability and resilience. (this thesis)
3. Transparent and negotiable trade-offs between quality and workload yield healthy doctors.
4. Financialization of agriculture is a risk for global food security.
5. Providers of public goods, such as farms, need to "borrow" from society for their resilience.
6. Strong governments are necessary for thriving societies.

Propositions belonging to the thesis, entitled

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Thesis committee

Promotors
Prof. Dr M.K. van Ittersum
Personal Chair at the Plant Production Systems Group
Wageningen University & Research

Prof. Dr M.P.M. Meuwissen
Personal Chair at the Business Economics Group
Wageningen University & Research

Co-promotor
Dr P. Reidsma
Associate professor at the Plant Production Systems Group
Wageningen University & Research

Other members
Prof. Dr M. Bakker, Wageningen University & Research
Dr J.C.J. Groot, Wageningen University & Research
Prof. Dr K Helming, Leibniz Centre for Agricultural Landscape Research (ZALF), Germany
Dr O. Therond, Université de Lorraine, France

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Wim Paas

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Abstract

An increasing variety of stresses and shocks provides challenges for European farming systems. As a consequence, the sustainability and resilience of Europe's diverse farming systems is at stake. In particular the possible presence of economic, social or environmental thresholds in farming systems is worrying, as beyond those thresholds permanent and undesired system change may happen.

The aim of this thesis is to operationalize a resilience framework and to assess the sustainability and resilience of current and future European farming systems. Sustainability of a system is in this thesis defined as an adequate performance of all system functions across the environmental, economic and social domains. Sustainability of agricultural systems has been studied extensively, but existing frameworks and tools are not designed to study resilience which is much more about the different capacities of systems to deal with disturbances, i.e. robustness, adaptability and transformability.

The following research questions are central in this thesis: 1) Is there a balance between social, economic and environmental functions in European farming systems in terms of importance and performance? 2) Are European farming systems approaching critical thresholds? 3) What resilience capacities do and should European farming systems have? 4) What strategies enhance sustainability and resilience of European farming systems?

Based on the application of new and (semi-)quantitative methods developed in this thesis, the following conclusions on the sustainability and resilience of European farming systems – and the methods to assess these - can be drawn:

European farming systems are perceived to have low to moderate sustainability and resilience, and operate close to critical thresholds. In the studied farming systems there is an overemphasis on (short-term) economic viability and a lack of attention for (long-term) social variables, while robustness was perceived to prevail over adaptability and transformability. According to stakeholders, main building blocks for current resilience in most case studies were the resilience attributes related to having production coupled with local and natural resources, heterogeneity of farm types, social self-organization, reasonable profitability, and infrastructure for innovation. The latter two were perceived as particularly important for transformability. Past strategies of farming systems were often geared towards making the system more profitable, and to a lesser extent towards the other important building blocks for current resilience. For improving sustainability and resilience, future farming systems need a more balanced attention for economic, social and environmental domains, and an enabling institutional and socio-economic environment. In terms of strategies, technological innovation is often required, provided it is implemented simultaneously with social, agro-ecological and institutional strategies that consider the long-term. To implement such strategies, all involved actors inside and outside the farming system need to collaborate.

Sustainability and resilience of farming systems remains a challenging subject due to its complexity in terms of detail (different domains, many concepts and variables) and dynamics (non-linearity, thresholds, interactions). The research presented in this thesis confirmed the usefulness of the resilience framework in reducing this complexity through a step-wise approach tailored to farming systems. The participatory approaches presented in this thesis contributed mainly to describing and explaining sustainability and resilience of current farming systems. These methods provide, therefore, a good basis for exploring future farming systems. The quantitative approach (presented in Chapter 4) confirmed the impact of weather extremes on economic and environmental farm performance, but was limited in explaining resilience, and raised awareness about the influence researchers have on the results through the selection of response variables. Based on the work and reflections presented in this thesis I see scope for better understanding and assessing farming system sustainability and resilience through system thinking theory and the use of participatory integrated assessments.

Contents

Chapter 1

General introduction

1.1 Contemporary agriculture in a global context

In its attempt to produce food and improve the quality of life for an increasing population, humanity is approaching and exceeding the limits of the earth's carrying capacity, i.e. exceeding planetary boundaries (Rockström et al., 2009b, 2009a; Steffen et al., 2015). Beyond those planetary boundaries, there is a high risk of non-linear and drastic changes that have a lasting impact on life on earth. In the context of an increasing demand for food, feed, fibre and fuel, agriculture is a major contributor to the exceedance of two planetary boundaries: biosphere integrity, in particular regarding the loss of genetic diversity, and biogeochemical flows regarding phosphorus and nitrogen (Campbell et al., 2017). For two other planetary boundaries, land-system change and freshwater use, agriculture alone brings humanity in a danger zone, i.e. in a zone with increasing risk of exceeding the earth's limits (Campbell et al., 2017). Without interventions, agricultural activity is expected to contribute to the exceedance of the planetary boundaries for climate change and land-use change in 2050 (Springmann et al., 2018).

The global agricultural system is characterized by specialization, intensification, land expansion and a strong connection to global markets that drive these developments (Giller et al., 2021; Nyström et al., 2019). Globally, expanding and intensive agriculture is a major driver of environmental degradation (Tilman et al., 2002) and collapse of ecosystems (Rocha et al., 2015). Expansion directly contributes to further approaching the land-system change boundary, i.e. nature area is replaced by farmland area. Intensification coerces agricultural systems to high food production levels (Rist et al., 2014), but simultaneously decouples them to a certain extent from the underlying ecosystem and its natural regulating and supporting processes (Nyström et al., 2019; Rist et al., 2014; Therond et al., 2017). This reduces the capability of actors in agricultural systems to notice feedback signals and develop abilities to adapt to changing conditions (Nyström et al., 2019). Continued intensification and expansion is expected in particular in the developing world (Giller et al., 2021; Koning and van Ittersum, 2009), implying, with current production practices, a greater pressure on the environment, thus reducing the ecological base. This reduces the resilience of agricultural systems (Cabell and Oelofse, 2012). At the same time, the main resources that currently make agricultural intensification possible, i.e. fossil fuel and rock phosphate, are finite.

Although a wide variety of farms exists in terms of area, degree of technology use and management structure (family farm/corporate structure), almost all farms are susceptible to low and declining market prices determined by global markets (Giller et al., 2021; Koning and van Ittersum, 2009). The globalized setting for agriculture further reduces the feedback signals, or signals are simply ignored as production and consumption are spatially distanced (Nyström et al., 2019; Sundkvist et al., 2005). One quarter of all production is traded internationally (Nyström et al., 2019). Producing more locally could improve feedback signals (Ericksen, 2008; Sundkvist et al., 2005) and thus improve resilience (Biggs et al., 2012; Cabell and Oelofse, 2012). However, a large proportion of the human population is dependent on importing food (Fader et al., 2013; Kinnunen et al., 2020). In the, by now, seemingly necessary, global markets, overexploitation of natural resources can go unnoticed and support regions to displace pressure on the environment to somewhere else in the world (Nyström et al., 2019).

While humanity is approaching global environmental limits, the most important feedback signals that are received by agricultural systems are the increased occurrence of mostly climate-change induced shocks in food production (Cottrell et al., 2019). Towards the future, the risk of co-occurring yield failures in bread basket regions is expected to increase, which will affect global food security (Gaupp et al., 2019). An important feedback signal from society to agriculture and the broader food system (including production and consumption) is the large proportion of the global population that is either obese or undernourished. This signal suggests that the current food system is also approaching or exceeding socio-economic limits related to human health and affordability of food. An important feedback signal in the economic domain is the low income of farmers around the world. Small-holder farmers, in particular in developing countries, often have an income below the poverty line (van de Ven et al., 2021; van Vliet et al., 2021). In western countries, farmers have (partly subsidized) incomes that are substantially lower than the national average (Giller et al., 2021; van Vliet et al., 2015). The social and economic feedback signals from agriculture to society are important and therefore need to be considered in local and global projects or frameworks for improved sustainability, i.e. the Sustainable Development Goals (sdgs.un.org).

1.2 European agriculture

1.2.1 Structure and diversity

In this thesis the focus is on European agriculture. The structure of the agricultural system in Europe resembles largely the global agricultural system with regard to intensification, specialization and being connected to global markets (Giller et al., 2021). In Europe, the bulk of the food is produced by medium to highly intensive, specialized farms (DG-Agri, 2017), which are often run by families (European Commission, 2018; Eurostat, 2018) and, to a lesser, but increasing extent, by large-scale agricultural corporations (Giller et al., 2021). Medium to highly intensive, specialized farms occupy roughly two-thirds of Europe's agricultural land (Andersen et al., 2007; European Commission, 2018). The other third of the agricultural land is mostly under extensive farming and often located in mountainous and/or remote areas with natural production constraints, e.g. low soil fertility (European Commission, 2018). Europe is self-sufficient regarding cereals and vegetables, depends on imports for tropical products (e.g. coffee, cane sugar, palm oil) and animal feed, and mainly exports dairy products, processed foods (European Environment Agency, 2020) and meat (Chatellier, 2021).

Through its regional diversity in climate, environment and cultures, European agriculture comprises many different types of farms regarding specialization, size, intensity and land use (Andersen, 2017; Andersen et al., 2007). Within a farm type, further variation can be found (e.g. small-scale farms; Guarín et al., 2020). In addition, within a relative homogeneous farm type regarding specialization, size and intensity, different farm types can be distinguished regarding their orientation (e.g. Mandryk et al., 2012). Apart from the farmers in one particular region, there is a wide diversity of actors that influence farmers (Meuwissen et al., 2019; Urquhart et al., 2019), for instance national and regional governments, social and environmental NGOs and value chain actors. The combination of actors across agricultural systems can vary widely, which is most likely related to the diversity of agricultural products in Europe: the degree of technology required for cultivation, whether the produce is fresh or can be stored, the degree to which produce needs to be processed and whether it is intended for export or national/local consumption. The high degrees of technology use and long value chains in most European food systems increase the risk for low added values for farmers, power concentration of supplying and processing actors and a lock-in of interest of all system actors (see e.g. Balmann et al., 1996; Plumecocq et al., 2018 on this topic). This limits the capacity of European agricultural systems to make necessary adaptations in case of low sustainability and resilience.

1.2.2. Performance

In Europe, agricultural food production has increased substantially since 1945. Cereal yields per hectare, for instance, have increased with over 150% since 1961 (Giller et al., 2021). From an economic perspective, however, contemporary European agriculture is associated with low labour productivity and low income compared to other economic sectors (DG-AGRI, 2017; European Commission, 2018), and decreasing numbers of farms and job opportunities (European Commission, 2013). Even with direct-income support from the European Union, around 70% of farmers in Europe earn less than an average wage (DG-AGRI, 2017). Across years, farmers experience a large variation in income (DG-AGRI, 2017). With continued exposure to global markets in combination with increased weather variability due to climate change, the prices of agricultural commodities are expected to become more volatile (European Environment Agency, 2020) and thus farmers' incomes as well.

Farmers in Europe are (to a certain extent) acknowledged for their important role in maintaining rural landscapes through which they provide public goods to society. However, farm practices may also result in trade-offs with the environment. In Europe, different agro-environmental sustainability indicators show distinct dynamics. For instance, the populations of farmland birds and grassland butterflies have declined by 30% in the EU-28 since 1990 and continue to decline, even with the current measures in place (European Court of Auditors, 2020), while pressure on the environment through nitrogen and phosphorus surpluses remains at more or less stable levels after roughly 2010. The environmental cost (water pollution, loss of diversity, climate change) of nitrogen surplus in Europe has been estimated to be between 70 and 320 billion Euro per year (Sutton et al., 2011). For a comparison: the total budget of the current Common Agricultural Policy is 365 billion Euro for seven years (2021-2027). Greenhouse gas emissions of EU-28 agriculture, accounting for roughly 10% of emissions in these countries, have declined over the period 2000-2016, but the decline has slowed down and has reversed in some countries (European Commission, 2018).

From a social perspective, rural areas in Europe are associated with an aging population and lower (self-reported) well-being and education levels compared to urban regions (Eurofound, 2019). These social aspects are reflected in agriculture. For instance, more than half of the farmers in the EU is over 55 years old (European Commission, 2018); agriculture knows long working hours and increased health risks compared to other sectors in the economy (Eurofound, 2017); and, except for a few countries, over half of the farmers in EU member states have not received any formal education related to their profession (European Commission, 2018). Farm numbers in the EU have declined by about 25% from 2005 till 2016, while the utilized agricultural area has remained stable. The remaining farms have become larger in terms of area (Eurostat, 2018) and economic production (European Commission, 2013), requiring a higher investment for potential farm successors. Generational renewal of Europe's (family) farms is needed, but increasingly problematic due to the low financial and social perspectives for potential farm workers and successors (Coopmans et al., 2021; Suess-Reyes and Fuetsch, 2016).

A diverse set of policies are put in place to improve the performance of Europe's agricultural systems. However, their success varies and often negative externalities occur. Income or production subsidies, for instance, are known to primarily support farms with relatively high environmental foot prints (FAO UNDP and UNEP, 2021). Another example is the observation that current EU policies for stimulating efficient water resource management in agriculture actually seem to stimulate increased water usage (European Court of Auditors, 2021). Also the European Commission's new Farm to Fork strategy may result in negative externalities as it may imply a greater dependence on import, resulting in environmental pressure elsewhere (Fuchs et al., 2020). In addition, this makes food supply in the Europe more vulnerable as at least 40% of imports is vulnerable to drought (Ercin et al., 2021). It should be noted however that new public policies also have the potential to avoid supply risks by reducing the demand and import of vulnerable products regarding their availability and supply. This potential of public policies is actually seen as an opportunity for reducing products with a large environmental footprint (European Environment Agency, 2020). It should also be noted that any policy change to address the above mentioned issues regarding agricultural performance may be experienced as a severe challenge by actors in farming systems (Spiegel et al., 2020), even when it actually could lead to a win-win situation. This applies in particular to environmental sustainability as policies aimed at this often limit the current basket of options of farmers, while benefits may only be experienced in the long-term. The creation, implementation, monitoring and evaluation of new policies should therefore be well-considered.

1.3 Sustainability and resilience

What becomes clear from the previous sections is that the sustainability of agricultural systems is generally at stake and their resilience is decreasing while their environmental, social and economic context is becoming more instable. Sustainability and resilience needs, therefore, to be assessed, monitored and improved.

Sustainability of a system is in this thesis defined as an adequate performance of all system functions across the environmental, economic and social domains (see e.g. Morris et al. 2011, König et al. 2013). In line with the Brundtland report (United Nations, 1987), an adequate performance is realized when functionality can be preserved for future generations. Sustainability of agricultural systems has been studied extensively (Godfray, 2015; Pretty, 2008), but existing frameworks and tools are not designed to study resilience, i.e. dealing with disturbance. Moreover, in agricultural sustainability assessments, the social aspects are often least integrated, compared to the economic and environmental aspects (Helfenstein et al., 2022). Of particular importance for improving environmental, social and economic sustainability and resilience are participatory assessments that are designed to come up with adaptation options and action-oriented approaches together with relevant stakeholders (Ridder and Pahl-Wostl, 2005; Toth, 2001).

Resilience has been defined in different ways, dependent on the discipline and context in which it was studied (Brand and Jax, 2007). Ecological resilience can be defined as the capacity to resist change without changing its feedback system and functionality, i.e. robustness, while acknowledging the possibility of alternative stable states (Gunderson and Holling, 2002). The acknowledgement of possible stable alternative states of a system has led scholars to argue that ecological resilience thinking should encompass, besides robustness, the system's capacity to adapt or organize structural and functional change, too (Anderies et al., 2013; Folke et al., 2010). The notion of ecological resilience finds its origin in extensive studies on socio-ecological systems with a strong natural component and relatively clearly delineated system boundaries, e.g. a regional ecosystem, such as a lake. However, agricultural systems also have a strong technological component (Blomkvist and Larsson, 2013) and their boundaries are difficult to delineate (see e.g. Giller, 2013). A definition of resilience geared towards technology, i.e. engineering resilience, is the capacity to return to its stable state after a perturbation, i.e. robustness without considering the possibility of an alternative state (Pimm, 1984). For agricultural systems, the choice for applying an ecological or technological definition of resilience is likely to be influenced by disciplinary background (Brand and Jax, 2007) and the degree of control over a system that is assumed (Hoekstra et al., 2018).

In this thesis, the ecological resilience thinking is taken as point of departure. This allows for evaluating the seemingly much-needed change of European agricultural systems to improve their sustainability and resilience simultaneously. In fact, sustainability and resilience should be considered as complementary concepts (Marchese et al., 2018; Meuwissen et al., 2020, 2019; Westley et al., 2011), as sustainability is aimed at preserving system functioning in the long-term, while resilience realizes a continued functioning in the meantime while being faced with disturbances (Tendall et al., 2015). As agriculture, by definition, supposes some form of control over the natural environment, notions of engineering resilience are also included in this thesis.

Resilience of agricultural systems has been studied at a conceptual level (e.g. Callo-Concha and Ewert, 2014; Ge et al., 2016; Prosperi et al., 2016; Tendall et al., 2015) and resilience indicators have been proposed (e.g. Peterson et al., 2018; Prosperi et al., 2016). The actual operationalization has taken place only to a limited extent. In particular, quantitative assessments of agricultural system and farm resilience are lacking in literature (Dardonville et al., 2021; Thomas Slijper et al., 2021). Lack of good data may be one of the reasons for this. Much resilience work on agricultural systems is therefore qualitative in nature, for instance involving assessments based on system parameters that supposedly bring resilience to the system (Cabell and Oelofse, 2012). The examples in which the resilience concept of agricultural systems is operationalized (e.g. Ashkenazy et al., 2018; Kinzig et al., 2006; van Apeldoorn et al., 2011) are not guided by an integrated resilience framework that was applied to many different agricultural systems. It can be concluded that, in order to address resilience of agricultural systems, approaches and methods need to be borrowed from different research fields. Agricultural systems can be defined as socio-ecological systems in which large technological systems interact with common pool resources, such as water reserves (Blomkvist and Larsson, 2013). Such a definition implies that, besides resilience thinking, notions from different disciplines need to be considered: 1) as in most agricultural systems multiple farm(er)s and other actors have different kinds of agency (Mathijs and Wauters, 2020), collaboration with all actors is needed to collectively manage the common pool of resources (Ostrom, 1990). This implies that individual and collective decision making processes need to be understood, e.g. in relation to risk management and adaptive capacity (Slijper et al., 2020), learning (Slijper et al., 2022; Urquhart et al., 2019) and farm succession (Bertolozzi-Caredio et al., 2020; Coopmans et al., 2021); 2) the technological aspect of agricultural systems makes that the boundaries of the system are diffuse regarding the influence of socio-technical regimes and the introduction of innovations (Geels, 2011). This implies that understanding of the potential (technological) transition process of the system needs to be understood as well (e.g. Geels, 2011; Termeer and Dewulf, 2019) ; 3) combining the first two points, a notion of agency (capacity to decide) and structure (that what determines/limits decision making) is necessary in terms of identifying the boundary of the system and in terms of which actors inside and outside the farming system can and need to take action.

Finally, it should be noted that the notion of planetary boundaries is firmly grounded in common pool resource management research and resilience theory (Biermann and Kim, 2020), i.e. through the perception of a sustainable safe operating space for the global commons and simultaneously considering environmental limits after which non-linear changes are expected. However, to be useful for the diverse set of multi-dimensional agricultural systems, socio-economic boundaries need to be included and boundaries should be assessed more locally (Biermann and Kim, 2020). Dearing et al., (2014) argue more specifically that the planetary boundaries concept is best discussed at regional level because governance systems are more developed at that level, compared to the planetary level. Although global orchestration is needed to deal with, for instance, climate change, some other environmental problems are much more local or regional than global, e.g. nitrogen pollution (Schulte-Uebbing and de Vries, 2021). Finally, critical boundaries, whether global or more regional, should be assessed by a diversity of (local) actors, rather than a selected group of scientists (Biermann and Kim, 2020).

1.4 Framework to assess resilience and sustainability of farming systems

The work presented in this thesis was part of the EU Horizon 2020 project SURE-Farm to assess the sustainability and resilience of European farming systems. SURE-Farm focused in particular on risk management, farm demographics, policies, public & private goods and an enabling environment in 11 case studies (see below). The work presented in this thesis was part of SURE-Farm's work package 5 on the integrated impact assessment of resilience-enhancing strategies on the provisioning of public and private goods. Within SURE-Farm, a framework was developed that considers the need for combining approaches, having a local focus and stimulating participation of relevant (local) actors when assessing the sustainability and resilience of farming systems.

The SURE-Farm framework proposes five steps to assess farming system sustainability and resilience (Meuwissen et al., 2019; Figure 1.1). From step 1 till 5 specific resilience is addressed, i.e. resilience in case the type of shock is known (Walker and Salt, 2012). Steps 1 to 3 relate to the questions "of what?", "to what?" and "for what purpose?". Step 4 addresses the farming system specific resilience capacities that need to be developed. Based on the previous steps, system characteristics are identified that convey general resilience to the system, regardless the type or shock (resilience attributes; Step 5).

1.4.1 Step 1. Resilience of what? (Farming system)

Combining the reflections on sustainability and resilience approaches in the previous section 1.3., it can be concluded that a system delineation is needed that includes interacting stakeholders, the potential for including local knowledge and solutions and interactions with an enabling environment.

In this study we take the farming system as the focus level. In the context of resilience, the farming system relates to the question "Resilience of what?" (Meuwissen et al., 2019). The social delineation of farming systems includes farms producing the main products of interest in a regional context with relatively homogeneous conditions with regard to soils, climate, demographics and institutions. Farming system actors included in the farming systems are the producers of main products and other actors that mutually influence one another (Meuwissen et al., 2019). The geographical delineation of the system follows more or less the common pool resource of interest, e.g. an ecosystem, watershed, or the highest governance level that encompasses the common pool resource. This definition provides flexibility with regard to determining the geographical size of the farming system. In more abstract terms, this implies that a farming system should be delineated at a level where emergent properties are expected anywhere above farm level (K. E. Giller, 2013) and below the governance level that encompasses the common pool resource of interest.

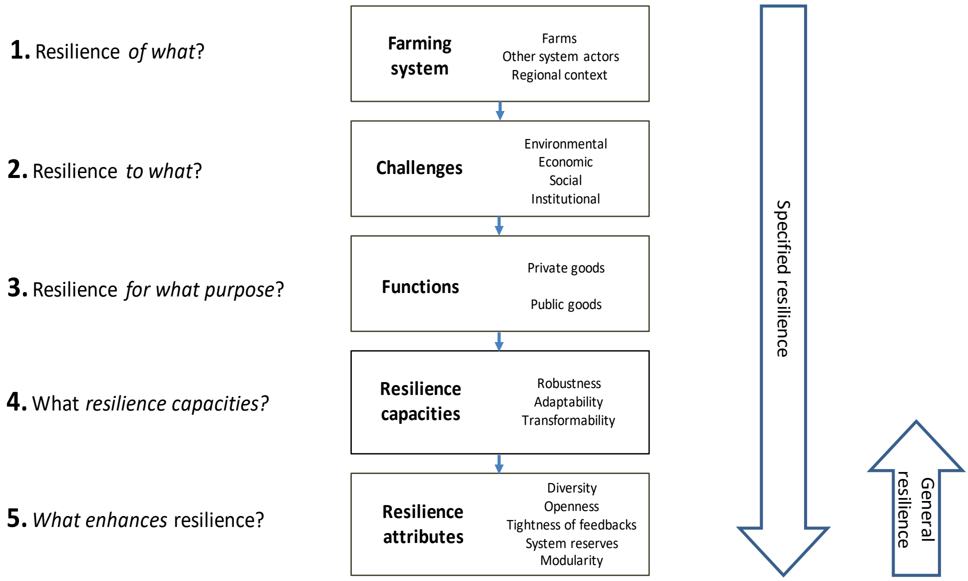

Figure 1.1. Resilience framework used in this thesis. Source: Meuwissen et al. (2019)

1.4.2 Step 2. Resilience to what? (Challenges)

The agricultural production process of farming systems is faced with environmental challenges such as weather extremes and disease pressure. Because of their open boundaries, most European farming systems are also facing challenges in the institutional, economic and social domain. Institutional challenges may be the result of social or environmental challenges that are primarily observed by actors outside the farming system. For instance institutional challenges arising from regulations on crop protection products in the context of safeguarding public health and reducing environmental pollution.

In case of low sustainability, for instance in the social domain, challenges may be experienced as stemming from within the farming system, i.e. dynamics in systems caused by low sustainability may push the system further towards critical thresholds. For instance, rural depopulation may lead to lack of farm labour, causing farm exit, which contributes to further rural depopulation.

1.4.3 Step 3. Resilience for what purpose? (Functions)

The output is an important element of a system. The output of a system can be seen as the reason for the system to be maintained, which, in the case of this thesis, is to provide goods to society. In the resilience framework, four private and four public goods (or 'functions') across the economic, social and environmental domains are considered (Table 1.1). Farming systems can provide multiple of these functions simultaneously. Farming systems will differ in the emphasis put on different functions. For instance, intensive agricultural systems are generally emphasizing food production rather than maintaining (local) biodiversity & habitat. In this thesis, the focus is mostly on the categorization of functions according to domains: for society, being the ultimate benefiter of the provided goods, all functions are important.

Table 1.1. System functions considered in the resilience framework of Meuwissen et al. (2019).

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

1.4.4 Step 4. Which resilience capacities?

Withstanding shocks, adapting to global change and improving sustainability at the same time requires at least two, and probably three resilience capacities: robustness, adaptability and transformability (Anderies et al., 2013; Folke et al., 2010; Meuwissen et al., 2019; Walker et al., 2004). For farming systems, Meuwissen et al. (2019) define robustness as the capacity to resist to and endure shocks and stresses; adaptability as the capacity to actively respond to shock and stresses without changing farming system structures and feedback mechanisms; and transformability as the capacity of a system to reorganize its structure and feedback mechanisms in response to shocks and stresses (Figure 1.2).

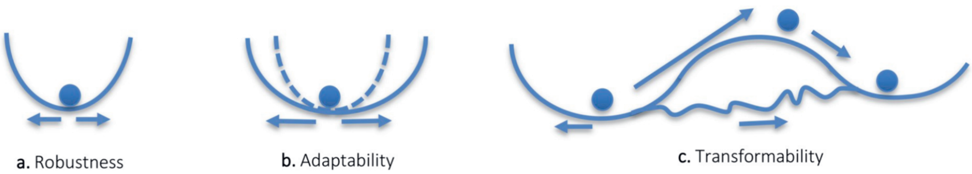

Figure 1.2. Illustration of robustness, adaptability and transformability. Source: Meuwissen et al. (2019)

Adaptability may be employed to make a system more robust, while reducing its transformability. For instance, investment in irrigation infrastructure may increase the robustness of a farming system with regard to drought, but reduces the (economic) resources to keep other adaptation options viable that could lead to a transformation. Robustness and transformability are each other's inverse with regard to approaching critical thresholds: being closer to a critical threshold implies a higher likelihood that a system cannot resist to and endure shocks and stresses, i.e. lower robustness, which leads to a forced reorganization of its structure and feedback mechanism, i.e. a transformation. Transformability can also be expressed more gradually, where transformation is the result of small incremental changes (Meuwissen et al., 2019; Termeer et al., 2017; Figure 1.2). These incremental changes may be the result of deliberately planned adaptations in anticipation of transformations (Enfors-Kautsky et al., 2018). Hence, the distinction between adaptability and transformability is in some cases a result of the time-horizon that is used.

1.4.5 Step 5. What enhances resilience? (Resilience attributes)

After addressing resilience in Steps 1 to 4, it is useful to identify the system characteristics that have realized robustness, adaptability and/or transformability. Based on these characteristics, a system's general resilience can be assessed, even in case an unknown shock or stress would occur (Meuwissen et al., 2021). General resilience helps a system in 1) responding quickly, 2) having (access to) reserves in times of need, and 3) keeping options open (Walker and Salt, 2012). From a methodological point of view, resilience attributes can be used as a time-efficient way to assess general resilience (Allen et al., 2018).

The initial and basic idea behind general resilience is that the underlying structure of a system, i.e. the slow variables/processes in the system, should allow for resilience. This idea is derived from early resilience work on slow and fast variables in lakes where phosphorus levels in lake sediment (slow variable) are more determinant for resilience than fast variables such as nutrient fluxes. These studies and others (e.g. Bennett and Peterson 2005), while focusing on ecological resilience, propose a system modelling approach to identify quantifiable proxies for general resilience. However, not all important variables in socio-ecological systems (SES) can be quantified and modelled. Biggs et al. (2012) consulted resilience literature and experienced resilience researchers. Their study yields seven principles of which three relate to the actual socio-ecological system and four to the governance system in place to guide the SES. Walker and Salt (2012) propose six resilience principles that convey resilience, regardless the type of shock or stress: modularity, openness, diversity, tightness of feedbacks, system reserves and high levels of all sorts of capital. Meuwissen et al. (2019) include the resilience principles of (Walker and Salt (2012) and propose that "system reserves" include the different levels of capital. Considering the importance of governance for system resilience (Biggs et al., 2012), these capitals include, for instance, learning capacities (e.g. Spiegel et al., 2020; Urquhart et al., 2019) and policy arrangements to enable farming system's resilience (e.g. Buitenhuis et al., 2020).

The resilience principles enable to compare different socio-ecological systems, but are generally too abstract to be used for specific systems. More concrete characteristics, specified for a farming system, are needed. These concrete characteristics are called "resilience attributes" in this thesis. Nemec et al. (2014), for instance, propose a list of nine resilience attributes for studying watersheds. Cabell and Oelofse (2012) developed resilience attributes for agricultural systems that are widely used (e.g. Tittonell, 2020). These resilience attributes consider agro-ecological aspects such as ecological self-regulation, socio-economic aspects such as being reasonable profitable, and social self-organization, but lack attention for the role of innovation as was put forward by Gunderson and Holling (2002), the role of policies (e.g. Biesbroek et al., 2017; Buitenhuis et al., 2020) and connections with actors outside the farming system (e.g. Mathijs and Wauters, 2020). Hence, adaptations need to be made to tailor the resilience assessment for contemporary European farming systems. Moreover, so far, the resilience attributes have not been formally (and quantitatively) evaluated/tested by researchers and local farming system stakeholders. Because of their origin in ecological research, it is questionable whether the resilience attributes are actually contributing to building resilience of a farming system. Dardonville et al. (2020), for instance, show that conclusions based on quantitative empirical research on the role of diversity of resilience are diverse and context dependent. Finally, in case resilience attributes do contribute to resilience, their specific contribution to robustness, adaptability and/or transformability needs to be considered and evaluated.

1.5 Objectives/Aim

The aim of this thesis is to operationalize the above introduced resilience framework with new and (semi-)quantitative methods and to assess the sustainability and resilience of current and future EU farming systems (Figure 1.3). The following research questions are central in this thesis:

- Is there a balance between social, economic and environmental functions in European farming systems in terms of importance and performance? (Chapters 2 & 3)
- Are European farming systems approaching critical thresholds? (Chapters 5 & 6)
- What resilience capacities do and should European farming systems have? (All chapters)
- What strategies enhance sustainability and resilience of European farming systems? (All chapters)

The methods applied in this thesis follow the steps of the resilience framework as much as possible. Specific attention is given to current (Chapters 2, 3 & 4) and future (Chapters 5 & 6) resilience (Figure 1.3). From a methodological point of view, the methods aim to operationalise the framework by using locally adapted indicators and different sources and types of data. An overview of the concepts used in this thesis is presented in Table A1.1 in the Appendix of this Chapter.

1.6 Case studies

Eleven European farming systems are studied in this thesis: large-scale arable farming in Northeast Bulgaria (BG-Arable), intensive arable farming in the Veenkoloniën, the Netherlands (NL-Arable), arable farming in East of England, United Kingdom (UK-Arable), large-scale corporate arable farming with additional livestock activities in Altmark, Germany (DE-Arable&Mixed), small-scale mixed farming in Nord-Est Romania (RO-Mixed), intensive dairy farming in Flanders, Belgium (BE-Dairy), extensive beef cattle systems in the Massif Central, France (FR-Beef), extensive sheep farming in Huesca, Spain (ES-Sheep), high-value egg and broiler systems in southern Sweden (SE-Poultry), small-scale hazelnut production in Lazio, Italy (IT-Hazelnut), and fruit and vegetable farming in the Mazovian region, Poland (PL-Horticulture). These case studies were selected based on the difference in produce and the challenges that they are facing, and the presence of participants in the consortium of SURE-Farm. These case studies are, obviously, not exhaustive for the diversity of farming systems across Europe. Nevertheless, using the resilience framework as a reference, and having a relatively large number of case studies, allow for comparison between the farming systems regarding challenges, functions, resilience capacities and resilience attributes and strategies.

1.7 Outline

This thesis includes an introductory chapter (Chapter 1), three research chapters on past and/or current sustainability and resilience (Chapters 2, 3 & 4), two chapters on future sustainability and resilience (Chapters 4 & 5) and a general discussion chapter (Chapter 7) (Figure 1.3).

Chapter 2 presents a participatory approach for an integrated assessment of current sustainability and resilience of European farming systems. As the approach has been developed in tandem with the resilience framework of Meuwissen et al. (2019), all steps of the resilience framework are included. The approach in Chapter 2 is illustrated with an application to three specialized farming systems: BE-Dairy, IT-Hazelnut and NL-Arable. Chapter 3 is based on the same participatory approach (Chapter 2) and presents a synthesis of perceived current sustainability and resilience in all 11 European farming systems of the project.

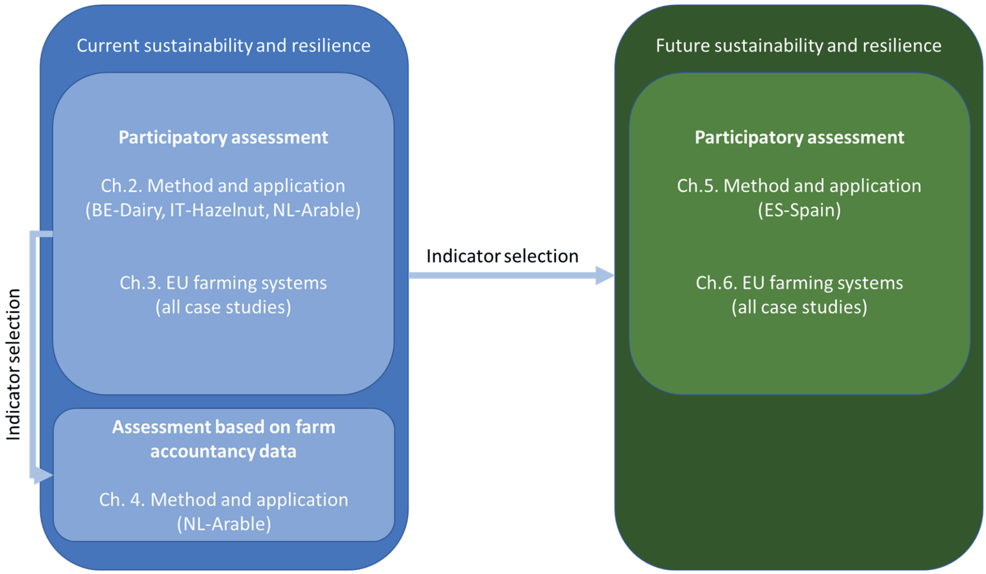

Figure 1.3. Outline of the thesis. Arrows indicate information flows among chapters.

Chapter 4 presents a multi-variate statistical approach in which longitudinal data on weather, economic and farm-level conditions are studied in relation to economic and environmental farm performance. The aim in this work is to detect farm level indicators that may help to improve economic and environmental sustainability and resilience at farm level. We apply the approach to three potato producing regions in the Netherlands: ware potato production in the Dutch provinces Flevoland and Zeeland and starch potato production in the Dutch agricultural region Veenkoloniën (part of NL-Arable). Weather and market conditions are considered as challenges (Step 2 RF). Economic and environmental performance are considered as representative indicators of functions (Step 3 RF). The farm level indicators selected for the analysis are linked to resilience attributes (Step 5). The resilience capacities robustness and adaptability (Step 4 RF) are deduced based on results from the statistical analyses.

Chapter 5 presents a participatory approach for assessing future sustainability and resilience. The chapter commences with an elaboration on the importance of critical thresholds in ecological and agricultural systems. The first half of the approach in Chapter 5 concerns the assessment of critical thresholds of important farming system variables. The second half of the approach concerns the identification of alternative systems and strategies to improve future sustainability and resilience. The approach in Chapter 5 addresses Steps 2-5 of the RF and is illustrated with an application to ES-Sheep. Chapter 6 is based on the same participatory approach as presented in Chapter 5 and makes a synthesis of the outcomes of 11 European farming systems regarding the assessment of critical thresholds.

Chapter 7 provides a synthesis of the research presented in this thesis. Based on the synthesis, policy recommendations are made. Subsequently, I evaluate the framework and methods used in this thesis. After that, I further reflect on the relevance of my work and on ways to evaluate and monitor sustainability and resilience of farming systems in Europe.

Appendix

Table A1.1. Overview of concepts with their explanations and main references as used in this thesis. The table continues on the next page.

Concept	Explanation	References
Sustainability	An adequate performance of all system functions across the environmental, economic and social domain. Obviously adequate is normative and depends on environmental thresholds and societal constraints and objectives.	See e.g. König et al. (2013); Morris et al. (2011)
Resilience capacities	Robustness, adaptability and transformability potential of systems in the face of shocks and stresses. The explanation of the resilience capacities follows below and is influenced by the mentioned sources.	Anderies et al. (2013); Folke et al. (2010); Meuwissen et al. (2019); Walker et al. (2004)
Robustness	Robustness is the capacity to resist to and endure shocks and stresses.	
Adaptability	Adaptability is the capacity to actively respond to shock and stresses without changing farming system structures and feedback mechanisms	
Transformability	Transformability is the capacity of a system to reorganize its structure and feedback mechanisms in response to shocks and stresses.	
Specific resilience	Resilience specified with regard to answering the questions "resilience of what, to what and for what purpose?"	Carpenter et al. (2001); Quinlan et al. (2016)
General resilience	General resilience is related to a system's robustness, adaptability and transformability, regardless the type of challenge or shock, including the unknown, uncertainty and surprise.	Resilience Alliance (2010), Walker and Salt (2012), Meuwissen et al. (2019)
Farming system	The basis of a farming systems consists of farms producing the main products of interest in a regional context. Farming system actors included in the farming systems are the producers of main products and other actors that mutually influence one another. In the context of resilience, the farming system relates to the question "Resilience of what?"	Meuwissen et al. (2019)
Challenges	Shocks or stresses that constrain farming system functioning. In the context of resilience, challenges relate to the question "Resilience to what?".	Meuwissen et al. (2019)
Functions	Delivery of public and private goods from the farming system to society (categorized according to the domain they belong to): production of food (economic), bio-based resources (economic), economic viability (economic), quality of life (social), maintenance of natural resources (environmental), biodiversity & habitat (environmental), attractiveness of the area (social), and animal health & welfare (environmental).	Meuwissen et al. (2019)
Function indicators	Indicators that represent farming system functions in the absence of a unique metric for these functions. Indicators with high allocated importance are assumed to represent the identity of the farming system.	Meuwissen et al. (2019)

Concept	Explanation	References
Resilience attributes	Specific system characteristics that are supposedly contributing to general resilience of farming systems. For the *resilience attributes* that are treated in this study, see also Table 2.5.	Cabell & Oelofse (2012), Meuwissen et al. (2019)
Resilience principles	Generic system characteristics that are associated with general resilience: diversity, modularity, openness, tightness of feedbacks, system reserves. The explanation of the principles follows below and is, apart from the mentioned sources, influenced by the work of Biggs et al. (2012).	Resilience Alliance (2010), Walker and Salt (2012), Meuwissen et al. (2019)
Diversity	Diversity in the system with regard to functioning of sub-components and their response to shocks and stresses.	
Modularity	The degree of independence of connected sub-components in the system.	
Openness	Connectivity within the farming system and with systems beyond the farming system.	
Tightness of feedbacks	The degree into which the farming system and its sub-components and processes can create signals and interact in reaction to these internal signals as well as external signals from other (overarching) systems. Included are signals from slow variables and feedbacks.	
System reserves	Natural, economic and social capital that the farming system can access to use as a buffer to compensate for losses or changes in the system during and after a disturbance.	
Critical thresholds	Levels at which *function indicators*, *resilience attributes* or *challenges* are expected to cause large and permanent system change.	Adapted from Kinzig et al. (2006) and Biggs et al. (2018).
Enabling conditions	Conditions around the farming system that enable the maintenance of the current system or the realization of alternative systems in the future.	This study
Interacting thresholds	Critical thresholds, when exceeded, leading to the exceedance of another critical threshold.	Kinzig et al. (2006)
Current strategies	Strategies implemented to counteract impact of current shocks and stresses on the farming system (indicators).	Meuwissen et al. (2019)
Future strategies	Strategies to maintain the current system in the future or to realize alternative systems in the future.	

Participatory assessment of sustainability and resilience of three specialized farming systems

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Abstract

There is a need for participatory methods that simultaneously assess agricultural sustainability and resilience at farming system level, as resilience is needed to deal with shocks and stresses on the pathways to more sustainable systems. We present the Framework of Participatory Impact Assessment for Sustainable and Resilient FARMing systems (FoPIA-SURE-Farm). FoPIA-SURE-Farm investigates farming system functioning, dynamics of main indicators, and specifies resilience for different resilience capacities, i.e., robustness, adaptability, and transformability. Three case studies with specialized farming systems serve as an example for the used methodology: starch potato production in Veenkoloniën, The Netherlands; dairy production in Flanders, Belgium; and hazelnut production in Lazio, Italy. In all three farming systems, functions that related to food production, economic viability, and maintaining natural resources were perceived as most important. Perceived overall performance of system functions suggest moderate sustainability of the studied farming systems. In the studied systems, robustness was perceived to be stronger than adaptability and transformability. This indicates that finding pathways to higher sustainability, which requires adaptability and transformability, will be a challenging process. General characteristics of farming systems that supposedly convey general resilience, the so-called resilience attributes, were indeed perceived to contribute positively to resilience. Profitability, having production coupled with local and natural resources, heterogeneity of farm types, social self-organization, and infrastructure for innovation were assessed as being important resilience attributes. The relative importance of some resilience attributes in the studied systems differed from case to case, e.g., heterogeneity of farm types. This indicates that the local context in general, and stakeholder perspectives in particular, are important when evaluating general resilience and policy options based on resilience attributes. Overall, FoPIA-SURE-Farm results seem a good starting point for raising awareness, further assessments, and eventually for developing a shared vision and action plan for improving sustainability and resilience of farming systems.

2.1 Introduction

2.1.1 Assessing sustainability and resilience of farming systems

Sustainability and sustainable intensification of agriculture is well studied (Pretty 2008, Godfray 2015) and multiple frameworks and tools for sustainability assessments are available (Alkan Olsson et al., 2009; Arodudu et al., 2017; Sieber et al., 2018). Several approaches are specifically designed for assessing multi-dimensional sustainability and sustainable development with participatory approaches (Delmotte et al., 2013; König et al., 2013; Morris et al., 2011; Vaidya and Mayer, 2014). Yet, these have not been designed to study resilience of agriculture, i.e. the robustness, adaptability and transformability of agricultural systems in the context of shocks and challenges (Meuwissen et al., 2020). Many studies have contributed to the search for operationalization of resilience research in agricultural and food systems (e.g. Callo-Concha and Ewert, 2014; Ge et al., 2016; Peterson et al., 2018; Prosperi et al., 2016). Only few have reflected on addressing agricultural sustainability and resilience simultaneously (e.g. Meuwissen et al., 2019; Tendall et al., 2015). We see sustainability and resilience as two separate, but often complementary concepts that may, or may not influence each other, depending on the situation (Marchese et al., 2018). Assessing both sustainability and resilience is necessary to move beyond static sustainability assessments and to explain dynamics. Addressing both is also needed to identify unsustainable, but resilient systems or vice versa. Resilience is needed to deal with known and novel shocks and stresses, in order to keep track of pathways to more sustainable systems. Other researchers have studied resilience and sustainability of farms (e.g. Darnhofer, 2014, 2010), but did not address the farming system as a whole in which multiple actors beyond the farm also play a prominent role. Ashkenazy et al. (2018) address resilience at farm and regional level, but lack the perspective of a well-defined resilience assessment framework and the attention for the role of different actors. The latter can be evaluated with a participatory assessment which is necessary to adequately address perspectives and issues of multiple actors and issues. Currently, multiple resilience assessment frameworks are available (Douxchamps et al., 2017; Quinlan et al., 2016). The "wayfinder guide" of the Stockholm Resilience Centre (https://wayfinder.earth/) provides an extensive framework for the integration of multiple, iterative sustainability and resilience assessments for social-ecological systems, including notions on persistence, adaptability and transformability. However, to the best of our knowledge, there is no single framework, designed for a one-day workshop, that combined the assessment of multi-dimensional sustainability and resilience (specified and general) of farming systems which include notions of all three resilience capacities, i.e. robustness, adaptability and transformability.

This paper aims to present and test a framework for using a participatory integrated assessment (PIA; Toth 2001, Ridder and Pahl-Wostl 2005) to address perceived sustainability and resilience of farming systems. PIA, in combination with other methods, can contribute to a project cycle where the following steps can be distinguished: data gathering and analysis, planning, implementation, and monitoring and evaluation (Ridder and Pahl-Wostl, 2005). In the PIA presented in this paper, the emphasis is on data gathering and analysis at the start of a project cycle. Participatory input allows to identify the most important indicators of the system from the stakeholders' point of view. The identification of these indicators is a first step towards determining the identity of the system, i.e. mapping its most important structure and feedback mechanisms (Cumming and Peterson, 2017). Participatory input also allows to assess variables that are not readily measurable, e.g. social variables such as satisfaction or pride of being a farmer. Variables from the social domain are potentially important for system functioning, but often neglected in studies for instance related to land use (Gliessman, 2015; Winkler et al., 2018). Participatory research also reveals differences in perceptions of goals and functioning of a system, which is important to take into account when assessing sustainability and resilience (Robards et al., 2011).

2.1.2 Intensive specialized agriculture in Europe

The framework was applied to three intensive, specialized farming systems in the EU through three workshops. Having three farming systems as case studies in different regions allows to demonstrate how the framework works in different conditions. A common denominator, which in our case studies is the intensive and specialized nature of the farming systems, also allows for evaluating the usage of the framework for comparison between farming systems. Applying the proposed framework to intensive, specialized systems in this study is relevant and interesting from different perspectives. Regarding representativeness, the bulk of the food produced within the European Union is provided by medium to highly intensive, specialized farming systems (Andersen et al., 2007). Regarding sustainability, more intensive agricultural systems are associated with higher yields and revenues through economy of scales (Peterson et al., 2018), but also with higher pressure on the environment, certainly per unit of area (Pretty and Bharucha, 2014; Tilman et al., 2002). As to resilience, specialized and intensive agricultural systems are often optimized for production under stable socio-economic and biophysical environments (Urruty et al., 2016). However, many external influences, such as increased occurrence of weather extremes and volatile markets, create a more variable production environment than most specialized agricultural systems are designed for. Farms in such systems often have a relatively high share of financial capital invested in production equipment that cannot be reinvested without making substantial losses (sunk costs). Sunk costs create path-dependency and lock-in of individual farmers, which makes it difficult for the whole agricultural system to adapt and transform if new challenges arrive (Balmann et al., 2006). In addition, the professional network required for providing inputs to and processing outputs from intensive, specialized systems can create a lock-in of stakeholders' interests inside and outside the agricultural system. Examples may refer to businesses that need to fulfil shareholder expectations regarding economic profit (Westley et al., 2011), or intellectual property rights in technology intensive agriculture (Plumecocq et al., 2018).

2.1.3 Concepts used in this study

In this study we define a farming system as a geographical region with relatively homogenous agro-ecological and social conditions. In the farming system, we start with one farming sector and its farms as the focal point of attention and then include all actors in the farming system who influence the focal farmers and who are themselves influenced by focal farmers (Meuwissen et al., 2019). Our working definition for sustainability of farming systems is an adequate performance of all system functions across the environmental, economic and social domain (see e.g. Morris et al. 2011, König et al. 2013). Obviously 'adequate' is normative and depends on environmental thresholds and economic and societal constraints and objectives. For resilience, we distinguish three resilience capacities: robustness, adaptability and transformability. Robustness is the capacity to resist to and endure shocks and stresses; adaptability is the capacity to actively respond to shocks and stresses without changing farming system structures and feedback mechanisms; and transformability is the capacity of a system to reorganize its structure and feedback mechanisms (Meuwissen et al., 2019). We consider along with Walker and Salt (2012) that to assess resilience, we need to distinguish between specified and general resilience. Assessing specified resilience relates to the questions of resilience "of what?", "to what?" and "for what purpose?" (Carpenter et al., 2001; Quinlan et al., 2016). General resilience relates to system's robustness, adaptability and transformability, regardless the type of challenge or shock. General resilience is mainly assessed by looking at system principles that are presumably conveying resilience. The five principles for general resilience that we use in this paper are tightness of feedbacks, modularity, diversity, openness, and system reserves (Resilience Alliance, 2010). Based on these principles, more concrete resilience attributes or indicators are needed in order to assess the general resilience of a specific system. Cabell and Oelofse, (2012), for instance, present 13 resilience indicators for agro-ecosystems that are considered as conveying resilience to the system. Some of these indicators are somewhat linked to either robustness, adaptability or transformability, although not in a consistent manner, as we will elaborate further in this study by addressing potential contributions of resilience attributes to the three defined resilience capacities. Table A1.1 in the Appendix of Chapter 1 provides an overview of all important concepts used in this study.

2.2 Methods

To study the perceptions of farming systems' current sustainability and resilience, we designed the Framework of Participatory Impact Assessment for Sustainable and Resilient EU Farming systems (FoPIA-SURE-Farm; Paas et al., 2019; Reidsma et al., 2019). FoPIA-SURE-Farm includes elements from five different existing sources. First, for assessing perceived sustainability, it is inspired by the semi-quantitative approach of the Framework for Participatory Impact Assessment (FoPIA; Morris et al. 2011, König et al. 2013). Second, for assessing perceived resilience, elements from the Resilience Assessment Framework are implemented (RAF; Resilience Alliance, 2010). Third, for analyzing dynamics of sustainability indicators, we included participatory techniques used for system dynamics modelling by Herrera (2017). Fourth, general resilience was assessed based on a list of resilience attributes as proposed by Cabell and Oelofse (2012), which was tailored and complemented for the assessment of farming systems. Last, FoPIA-SURE-Farm builds on the framework developed by Meuwissen et al. (2019) in the context of the SURE-Farm project (https://surefarmproject.eu). Meuwissen et al. (2019) propose to investigate farming system resilience by answering the questions a) Resilience of what? (defining the farming system), b) Resilience to what? (identifying challenges), c) Resilience for what purpose? (identifying main goods and services delivered by farming systems to society), d) What resilience capacities? (assessing robustness, adaptability as well as transformability), e) What resilience attributes? (identifying system characteristics that convey resilience to the system). These questions facilitate the framing of general and specific research topics related to resilience for which qualitative as well as quantitative research methods can be applied.

2.2.1 Farming systems

Compared to studies at farm level, a study at the farming system level allows to take into account challenges that operate at similar levels of integration (Peterson et al., 2018), such as the decrease of farm numbers and specific climate changes in a region. Also, at the farming system level, processes and actors that can influence system dynamics in the face of challenges, such as stakeholder interaction with the environment (Urruty et al., 2016) and self-organization (Cabell and Oelofse, 2012), can be included. Consequently, at this level the system dynamics are not entirely due to external challenges, but include strategies by different actors to adapt and transform (Cumming et al., 2017). At the same time, the farming system is a level above the farm (K. E. Giller, 2013) at which individual stakeholders can still be heard (Cabell and Oelofse, 2012), allowing for multiple stakeholder input in participatory settings.

2.2.2 Case studies

Workshops were held in three specialized farming system case studies (CS): starch potato production in Veenkoloniën, the Netherlands (NL-Starch potato), dairy production in Flanders, Belgium (BE-Dairy) and hazelnut production in Lazio, Italy (IT-Hazelnut).

NL-Starch potato is a capital and input-intensive system with relatively low economic productivity per unit of input (Table 2.1). Predominant soils are sandy with a high amount of inactive organic matter. The most economically productive crop, starch potato, is typically grown with cereals and sugar beets in a narrow 1:2 or 1:3 rotation. On some farms also onions, carrots or tulips are cultivated. Relative to cereals and sugar beets, most crop protection products are applied to starch potatoes. Farmers are organized in a cooperative that processes the starch potatoes, which are often grown on a contract basis. Sugar beets are also grown on contract and sold to a cooperative. Main challenges in NL-Starch potato are low economic productivity, plant parasitic nematodes in the soil, and changing policies and legislation. In NL-Starch potato, the number of farmers is decreasing and the prices of agricultural land are increasing.

BE-Dairy is also a capital intensive system (Table 2.1). Livestock diets contain mainly grass (silage), supplemented with maize silage and feed concentrates. Farmers are organized in cooperatives that collect, process, and market the milk and its derived products. Important challenges are competition on export markets and fluctuating prices of milk and feed. Nitrogen surpluses put pressure on the environment. Other debated subjects in this system are the production of greenhouse gasses and the use of antibiotics. Future farm succession is a concern in this farming system due to the capital intensity (Table 2.1), a decreased interest into farming of the younger generation (relating to a competition with other occupations) and the challenge of administrative and legislative demands.

IT-Hazelnut is the least capital intensive system (Table 2.1). Use of crop protection products and abstraction of ground-water for irrigation have been claimed to put a pressure on the environment, especially on surface waters causing public concern (Liberti, 2019). Most of the production is sold to processing facilities outside the farming system. In the region some cooperatives collect the raw product and perform only the first processing step (i.e. shelling) and provide storage services. Main challenges for this system are price instability and competition on the world market, mainly with Turkey. Recent modernization of harvesting through auto-propelled machines has increased labour productivity and instigated a demand for more land for hazelnut cultivation. As a result, land that is less suitable for hazelnut cultivation will be taken into production in the coming years. Results from FoPIA-SURE-Farm in IT-Hazelnut are presented in detail in Nera et al. (2020). Compared to Nera et al. (2020), this study puts more emphasis on presenting and evaluating the methodology when applied to three different farming systems. Nera et al. (2020) evaluate sustainability and resilience in the case study in more detail.

Table 2.1. Average farming system characteristics related to size, economic performance, specialization and intensity.

Indicator	Unit	BE-Dairy	IT-Hazelnut	NL-Starch potato
NUTS-areas CS		BE02	ITI41	parts of NL111,NL112, NL131, NL132[†]
Number of farms of interest in sector of CS	#	2756[1]	5,640[2]	727[3]
People working in agriculture in CS[‡]	AWU[§]	4841	11,226.5[2]	1209
Total area CS	1000 ha	1,352	361	140
Total agricultural area CS	1000 ha	623	242	84
NUTS-areas harmonized public FADN-dataset[ǀ4]		BE02	ITI4[¶]	NL01[#]
Area per farm	ha	46.6	10.0	61.9
Labour input per farm	AWU	1.76	1.13	1.66
Economic size of farms	European Size Unit (1,200 gross margin)	256	55	203
Intensity (Input per area)	€ / ha	4097	2419	4669
Intensity (Output per area)	€ / ha	4858	5298	5184
Crop output	€ output from crops / € total output *100	6.5	97.4	79.8
Livestock output	€ output from livestock / € total output *100	91.3	0.2	0.3
Other output	€ other output / € total output *100	2.2	2.4	19.8
Rentability	€ output / € input	1.19	2.17	1.11
Total subsidies per farm-excluding subsidies on investments	1,000 €	21	3	28
Family farm income	1000 € / family work unit	33.8	33.9	46.5
Leverage ratio per farm	€ total liabilities / € total assets	0.20	0.00	0.22
Fraction of sunk costs per farm	€ fixed assets / € total assets	0.83	0.65	0.89
Cost of crop protection	€ / ha	83	138	445
Cost for chemical fertilizer	€ / ha	158	269	223

*[†]The CS area does not follow the contours of administrative boundaries, as a result, data at the scale of this CS is based on data from two encompassing, and hence larger, nationally defined areas: "Westerwolde and Groninger Veenkoloniën" and "Drentse Veenkoloniën en Hondsrug", [‡]People working in agriculture is calculated as "number of farms of interest of sector in CS" * "Labour input per farm", [§]AWU: Annual Work Unit, equaling 1800 working hours, [ǀ]Below this point in the table, data is derived from the public data base of the Farm Accountancy Data Network of the European Commission, [¶]ITI4: Lazio region, encompassing the CS, [#]NL01: The Netherlands, encompassing the CS.*

[1]Departement Landbouw en Visserij (2019), [2]Italian National Institute of Statistics (2020),[3] Centraal Bureau voor de Statistiek (2019), [4]Farm Accountancy Data Network of the European Commission (2019).

2

2.2.3 Stakeholder participation

Multiple actors influence the dynamics of a farming system. The heterogeneity of actors included in the systems has hence been accounted for in the workshops. Participants were invited via existing stakeholder networks in the case study areas. Attendance to the workshop was based on participants' own initiative and therefore not necessarily balanced across stakeholder groups. Participants mainly consisted of farmers and representatives from the government, NGOs, research institutes and the processing industry (Table 2.2). Participant numbers varied across case studies (from one to eight per stakeholder group, and 12 to 21 in total).

Table 2.2. Overview workshop dates and number of participants.

Country	Workshop dates	Partici-pants	Farmers	Industry	Govern-ment	NGO	Research /consultancy	Miscellaneous
BE-Dairy	27-11-2018	16	5	5	2	1	1	2
IT-Hazelnut	21-01-2019	21	8	3	3	3	4	-
NL-Starch potato	11-12-2018	12	4	1	3	1	3	-

To bring all participants to the same level of analysis, the research team, which differed in each case study, started the workshop by presenting the social delineation of the farming system (Table 2.3), showing farming system actors and (in)direct influencers of the farming system. Participants were given the opportunity to react to the farming system representation. Updates were made if necessary.

2.2.4 Assessing sustainability of farming system functions

Eight functions of the farming system, along with their representative indicators, all identified by the research team, were presented to the participants and discussed in a plenary session (Table 2.3). If necessary, changes were made to the list of representative indicators (Table 2.4). In BE-Dairy, the function "Bio-based resources" was interpreted broadly as all edible products from the system other than milk. In IT-Hazelnut, "Animal health and welfare" was not assessed because animals are not part of this farming system. Participants were invited to individually assess the importance of the different functions (see Table 2.3 for details). Similarly, they were asked to assess all indicators regarding their degree of representativeness for the function they were to represent. The outcomes for the degree of representativeness were transformed to relative importance in order to compare importance of indicators across functions (see also SM2.1). Furthermore, the performance of each indicator was assessed by each participant. Function performance was calculated per participant as the sum of scores of indicators per function times the average indicator representativeness according to the stakeholder group to which the participant belonged to (see also SM2.1). Importance and performance of functions and indicators was directly fed back and discussed with the participants during the workshop. Perceived indicator and function performance was interpreted as being indicative for perceived sustainability levels of the system (see e.g. Morris et al. 2011, König et al. 2013 who applied this method for assessing policy impact on sustainable development). Perceived importance and performance levels of functions between farmers and non-farmers were tested for significant differences, using a Kruskal Wallis test in R (R Core Team, 2015). Perceived function importance and performance across functions were tested for significant differences using a Kruskal Wallis test and a post-hoc Conover Iman test with Bonferroni correction using the R-package "conover.test" (Dinno, 2017).

Table 2.3. FoPIA-SURE-Farm workshop design. For details see Reidsma et al. (2019).

Assessment of:	Activity	Format	Scoring
Farming system delineation	Identifying the actors and boundaries of the farming system	Plenary discussion	-
System sustainability	Feedback on list with representative indicators for system functions	Plenary discussion	-
	Assessing function importance	Filling in a form individually	Divide 100 points over the eight functions
	Assessing indicator representativeness per function	Filling in a form individually	Divide 100 points over the indicators per function
	Assessing indicator importance	Calculation	Equation A2.1
	Assessing indicator performance	Filling in a form individually	Score from 1-5; where 1: very poor performance, 2: poor performance, 3: moderate performance, 4: good performance, 5: perfect performance.
	Assessing function performance	Calculation	Equation A2.2
	Discussion indicator and function importance and performance	Plenary discussion	-
	Selecting indicators for further analysis	Plenary discussion	-
System resilience	Explanation of robustness, adaptability and transformability	Presentation	-
	Sketching dynamics of selected indicators	Discussion in small groups	-
	Identifying major challenges and strategies	Discussion in small groups	-
	Assessing strategy implementation	Filling in a form individually	Score from 1-5 for implementation; where 1: not to very poor, 2: poor, 3: moderate, 4: good, 5: perfect implementation.
	Assessing the contribution of strategies to robustness, adaptability and transformability	Filling in a form individually	Score from -3 to +3 for contribution; where 0: no, 1: weak, 2: moderate, 3: strong contribution, and -: negative, +: positive contribution
	Assessing presence of resilience attributes	Filling in a form individually	Score from 1-5 for presence; where 1: not to very poor, 2: poor, 3: moderate, 4: good , 5: perfect presence.
	Assessing the contribution of resilience attributes to robustness, adaptability and transformability	Filling in a form individually	Score from -3 to +3 for contribution; where 0: no, 1: weak, 2: moderate, 3: strong contribution, and -: negative, +: positive contribution

Table 2.4. Overview of farming system functions and case study specific indicators representing those functions. The first four functions are private goods, and the last four are public goods.

Farming system function	Indicators NL-Starch potato	Indicators BE-Dairy	Indicators IT-Hazelnut
Deliver healthy and affordable food products (Food production)	Starch potato production (t/ha)	Total milk production Flanders	Hazelnut production
	Sugar beet production (t/ha)	Real milk price for consumers†	Hazelnut quality
	Cereal production (t/ha)	-	-
Deliver other bio-based resources for the processing sector (Bio-based resources)	Diversity of industrial potato products	Tons of meat produced	Shell production for heating
	Straw production (t/ha)	Tons of crops produced	Production of pruning waste for energy generation
	-	Total number of farms with bio-gas systems	-
Ensure economic viability (viable farms help to strengthen the economy and contribute to balanced territorial development) (Economic viability)	Profit (Euro/ha)	Share of total farm income from milk	Gross Margin per hectare
	Income from agricultural activities (%)	Labour income	Public support to agriculture (CAP and RDP)
	Land prices	Gross margin per liter of milk	Margin from in situ processing activities
Improve quality of life in farming areas by providing employment and offering decent working conditions. (Quality of life)	Working hours per year per farmer	Average amount of working hours per farmer per day	Number of people in the area employed in the farming system
	Employment related to agriculture	Number of fully employed workers per farm	Percentage of women among the people employed in the system
	Satisfaction of being a farmer	Pride of profession	Health of agricultural workers
	Women working in agriculture (%)	-	-
Maintain natural resources in good condition (water, soil, air) (Natural resources)	Greenhouse gas emissions	Soil quality	Groundwater availability
	Soil quality	Water quality	Water quality in the area
	Regional water availability	Total carbon footprint	-
	Responsible use of nutrients	-	-
Protect biodiversity of habitats, genes, and species (Biodiversity & habitat)	Responsible use of crop protection products	Genetic diversity of livestock	Diversification in land use
	Number of bird species	Share of ecologically valuable grassland	Number of organic farms
	Surface of land with nature friendly management	Responsible use of crop protection	-
Ensure that rural areas are attractive places for residence and tourism (countryside, social structures) (Attractiveness of the area)	Unhealthy stress under farmers	Extent to which farms are involved in public activities such as; education, tourism, healthcare.	Touristic flow
	Farms with broadened activities	Share of farms with outside grazing	Retention of young people in the area
	Villages with a minimum of one school and supermarket	Income from farm tourism	-
Ensure animal health & welfare (Animal health & welfare)	Farms with certificates for animal welfare	Longevity	-
	Responsible use of antibiotics	Amount of antibiotics per cow	-

† Participants in the Belgian case study insisted on "Real price for consumers", because in their point of view it relates to affordability from the perspective of consumers. This pronounced preference was not ignored because of the participatory setting and to stimulate participants to keep giving input.

2.2.5 Assessing resilience

Based on indicator importance and performance, participants decided in a plenary session which 3 to 4 indicators were most interesting to assess in further detail with regard to farming system resilience. Participants were invited to sketch the yearly dynamics of the selected indicators over the timespan 2000-2018, and to identify challenges that induced the sketched dynamics. Also they were invited to identify strategies that have been applied by farmers and other farming system actors to deal with the identified challenges. Identified strategies were assessed for their level of implementation and for their contribution to resilience capacities. Results were directly fed back to participants in a plenary setting. In the evaluation phase, strategies were linked to resilience attributes in order to visualize the connection between specified and general resilience and to allow for comparability of strategies between case studies.

To assess general resilience, a list with resilience attributes was constructed (Table 2.5) based on Cabell and Oelofse (2012) and Meuwissen et al. (2019) to serve the purpose of this study within the context of the SURE-Farm project. This implied that details on the farming system were added in the resilience attribute description. We also split up certain attributes as provided by Cabell and Oelofse (2012). Finally, we arrived at a list with 22 resilience attributes from which we selected 13 to study in the workshop to not overtask the participants. This selection was based on the 1) SURE-Farm research focus, 2) paying equal attention to the different resilience principles, and 3) avoiding overlap between attributes. For instance, "Reflective and shared learning" is partly dependent on "Social self-organization", which is why we selected the latter as the overarching attribute. We use the term "resilience attribute", which refers to a higher hierarchical level compared to the term "resilience indicator" as was originally used in Cabell and Oelofse (2012). This distinction also helps to avoid confusion with the concept of 'function indicators' as used in this study. Resilience attributes were assessed for their level of presence and for their contribution to resilience capacities. Due to time limitations, results could only be fed back into a limited extent during the workshop. Perceived contribution of resilience attributes to resilience capacities across attributes was tested for significant differences using a Kruskal Wallis test and a post-hoc Conover Iman test with Bonferroni correction in R using the "conover.test" package (Dinno, 2017).

Table 2.5. Resilience attributes used in FoPIA-SURE-Farm based on Cabell & Oelofse (2012) and Meuwissen et al. (2019). The resilience attribute name and the explanation statement were presented to stakeholders to assess presence and contribution to resilience capacities. The table continues on the next page.

Resilience attribute	Definition	Implications	Explanation statement	Link with resilience principle†
Reasonably profitable	Persons and organizations in the farming system are able to make a livelihood and save money without relying on subsidies or secondary employment	Being reasonably profitable allows participants in the system to invest in the future; this adds buffering capacity, flexibility, and builds wealth that can be tapped into following release	Farmers and farm workers earn a livable wage while not depending heavily on subsidies	Systems reserves (economic capital)
Production‡ coupled with local and natural capital	The system functions as much as possible within the means of the bio-regionally available natural resource base and ecosystem services	Responsible use of local resources encourages a system to live within its means; this creates an agroecosystem that recycles waste, relies on healthy soil, and conserves water	Soil fertility, water resources and existing nature are maintained well	Systems reserves (natural capital), tightness of feedbacks
Functional diversity§	Functional diversity is the variety of (ecosystem) services that components provide to the system	Diversity buffers against perturbations (insurance) and provides seeds of renewal following disturbance	There is a high variety of inputs, outputs, income sources and markets	Diversity
Response diversity§	Response diversity is the range of responses of these components to environmental change	Diversity buffers against perturbations (insurance) and provides seeds of renewal following disturbance	There is a high diversity of risk management strategies, e.g. different pest controls, weather insurance, flexible payment arrangements‡	Diversity
Exposed to disturbance	The system is exposed to discrete, low-level events that cause disruptions without pushing the system beyond a critical threshold	Such frequent, small-scale disturbances can increase system resilience and adaptability in the long term by promoting natural selection and novel configurations during the phase of renewal; described as "creative destruction"	The amount of year to year economic, environmental, social or institutional disturbance is small (well dosed) in order to timely adapt to a changing environment	Openness
Spatial and temporal heterogeneity of farm types‡	Patchiness across the landscape and changes through time	Like diversity, spatial heterogeneity provides seeds of renewal following disturbance	There is a high diversity of farm types with regard to economic size, intensity, orientation and degree of specialization‡	Modularity, diversity
Optimally redundant§ farms‡	Critical components and relationships within the system are duplicated in case of failure§	Redundancy may decrease a system's efficiency, but it gives the system multiple back-ups, increases buffering capacity, and provides seeds of renewal following disturbance§	Farmers can stop without endangering continuation of the farming system and new farmers can enter the farming system easily‡	Modularity

Resilience attribute	Definition	Implications	Explanation statement	Link with resilience principle[†]
Supports rural life[ǀ]	The activities in the farming system attract and maintain a healthy and adequate workforce, including young, intermediate and older people.	A healthy workforce that includes multiple generations will ensure continuation of activities and facilities in the area, and the timely transfer of knowledge.	Rural life is supported by the presence of people from all generations, and also supported by enough facilities in the nearby area (e.g. supermarkets, hospital, shops)	Systems reserves (social capital)
Socially self-organized	The social components of the agroecosystem are able to form their own configuration based on their needs and desires	Systems that exhibit greater level of self-organization need fewer feedbacks introduced by managers and have greater intrinsic adaptive capacity	Farmers are able to organize themselves into networks and institutions such as co-ops, community associations, advisory networks and clusters with the processing industry[‡]	Tightness of feedbacks, system reserves (social capital)
Appropriately connected with actors outside the farming system[‡]	The social components of the agroecosystem are able to form ties with actors outside their farming system[‡]	In case self-organization fails, signals can be send to actors that indirectly influence the farming system[‡]	Farmers and other actors in the farming system are able to reach out to policy makers, suppliers and markets that operate at the national and EU level[‡]	Tightness of feedbacks
Legislation[‡] coupled with local and natural capital	Regulations are developed to let[‡] the system function as much as possible within the means of the bio-regionally available natural resource base and ecosystem services	Responsible use of local resources encourages a system to live within its means; this creates an agroecosystem that recycles waste, relies on healthy soil, and conserves water	Norms, legislation and regulatory frameworks are well adapted to the local conditions[‡]	Systems reserves (social capital)
Infrastructure for innovation[ǀ]	Existing infrastructure facilitates diffusion of knowledge and adoption of cutting-edge technologies (e.g. digital)	Through timely adoption of new knowledge and technologies, a farming system can better navigate in a changing environment	Existing infrastructure facilitates knowledge and adoption of cutting-edge technologies (e.g. digital)	Openness, system reserves
Diverse policies[ǀ]	Various policy instruments stimulate different mechanisms that improve different resilience capacities.	Policies addressing all three resilience capacities avoid situations in which farming systems are permanently locked in a robust but unsustainable situation. Or situations in which adapting and transforming systems are increasingly vulnerable	Policies stimulate all three capacities of resilience, i.e. robustness, adaptability, transformability	Diversity

[†]Link of resilience attributes with resilience principles, as perceived by the authors, [‡]Deviating from Cabell and Oelofse (2012) for the purpose of this study, [§]Only part of the original resilience attribute of Cabell & Oelofse is presented, [ǀ]New resilience attributes for the purpose of this study.

2.3 Results

2.3.1 Farming system actors

Participants provided feedback on the social delineation of all three farming systems. For BE-Dairy and NL-Starch potato, many farming system actors and influencers were identified, while these were much fewer in IT-Hazelnut (Figure 2.1). In NL-Starch potato, the cooperative for processing starch potatoes was seen as part of the farming system. In BE-Dairy, the cooperative for processing and distributing milk was moved inside the farming system, after feedback from participants. In IT-Hazelnut, cooperatives exist within the farming system, but main processors of hazelnut were considered to be outside the farming system, because they operate on the international market and are not directly affected by changes within the considered farming system. Local NGOs were mentioned in BE-Dairy and NL-Starch potato, but not in IT-Hazelnut.

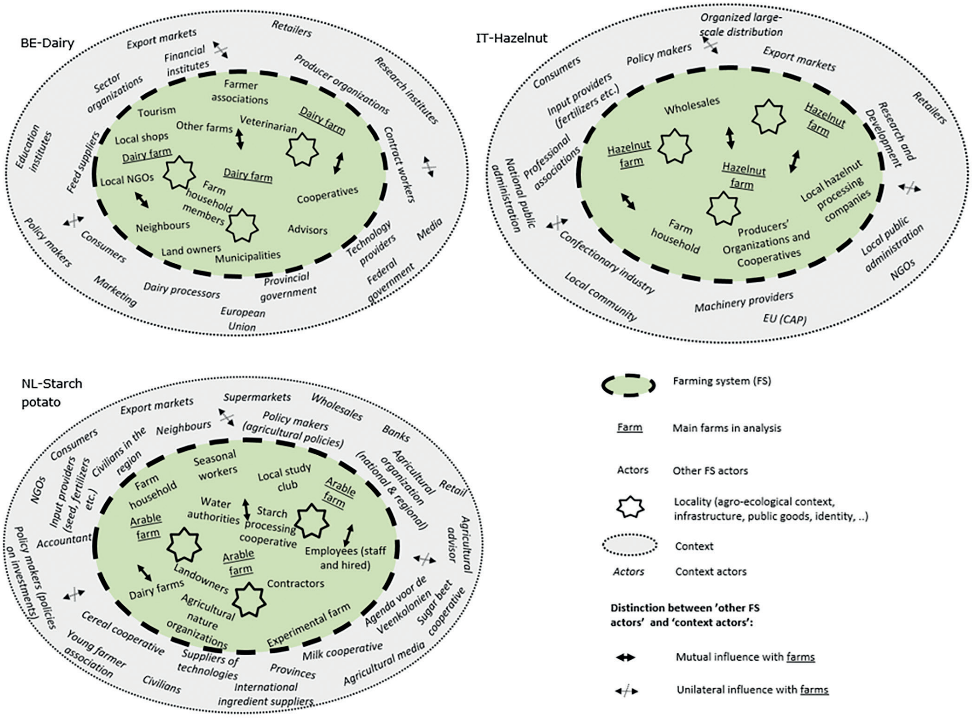

Figure 2.1. Farming system visualization after feedback from participants.

2.3.2 System sustainability

In all three case studies, "Food production" and "Economic viability" were considered to be among the most important functions (Figure 2.2). In NL-Starch potato and BE-Dairy, "Maintaining natural resources" was also considered as important. In NL-Starch potato, the function "Food production" was evenly represented by the three main crops: starch potato, sugar beet and wheat (Table 2.4). In IT-Hazelnut, this function was represented by hazelnut quantity and quality. In BE-Dairy, this function was represented by milk production and the price consumers pay for milk in the supermarket. Representative indicators for "Economic viability" related to farm income and profit per hectare. Representative indicators for "Maintaining natural resources" related to soil and water quality.

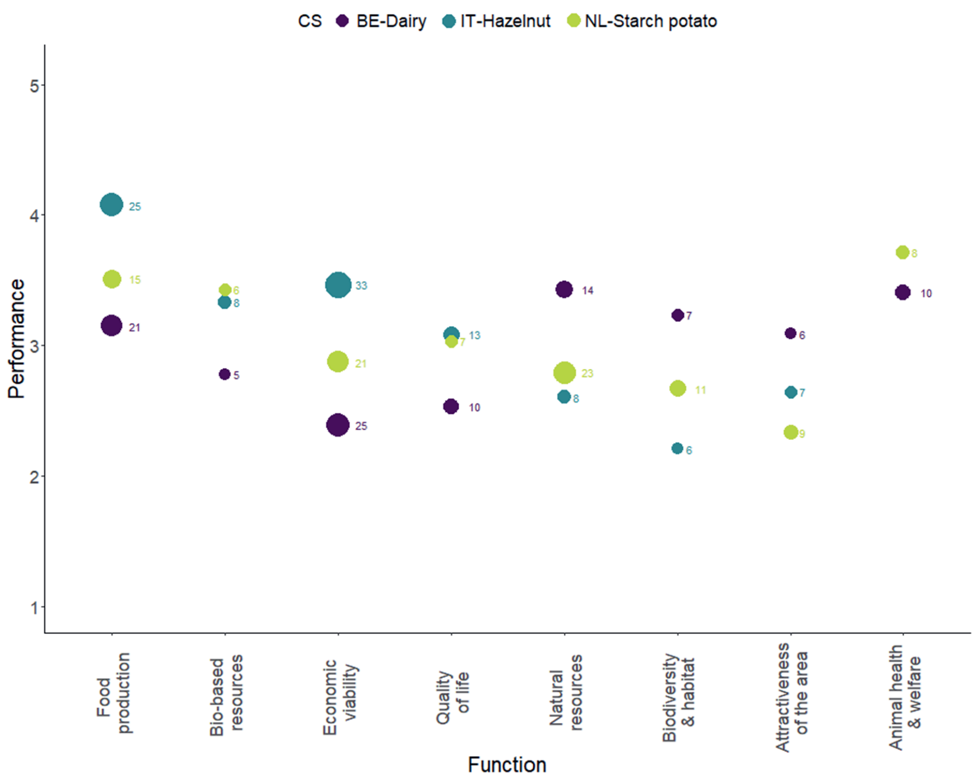

Figure 2.2. Relative importance (size of symbols and accompanying number) and performance (y-axis) of farming system functions. Relative importance was assessed individually by dividing 100 points over the eight functions (Table 2.4). Performance was assessed on a scale from 1 to 5 (Table 2.3). "Animal health & welfare" was not assessed in IT-Hazelnut.

Performance of "Food production" and "Economic viability" was considered high in IT-Hazelnut and moderate in BE-Dairy (Figure 2.2). For "Natural resources", participants in BE-Dairy perceived a moderate to high performance, while participants in IT-Hazelnut and NL-Starch potato perceived a moderate performance. Participants in NL starch potato indicated that they found it challenging to assess individual functions, because they perceived functions as interacting with each other. Participants in IT-Hazelnut indicated that they perceived that the recent modernization and enlargement of the sector increased pressure on the environment, while neglecting the importance of the function of "Natural resources".

In all case studies, it seemed that farmers perceived "Economic viability" more important and "Natural resources" less important compared to other stakeholders. However, only for "Natural resources" in BE-Dairy, a significant difference was detected. Farmers generally allocated less importance to functions that deliver public goods. At the same time, in BE-Dairy and NL-Starch potato, farmers tended to assess performance of "Natural resources" on average higher than other stakeholders. In BE-Dairy, participants indicated that these results would have been different if more people from nature organizations had participated in the workshop. In NL-Starch potato, farmers also assessed the performance of "Biodiversity & habitat" higher than other stakeholders (SM2.2).

2.3.3 Dynamics of sustainability indicators

In all case studies, participants indicated that they had little knowledge on year-to-year fluctuations of selected indicators. However, they were able to indicate trends and important years with regard to changes in trends, lows and peaks. For each selected indicator, participants identified main challenges and strategies applied to maintain or improve the indicator performance (Table 2.6). According to participants, important underlying causes for dynamics in NL-Starch potato were nematode pressure and increased costs per hectare that were amongst others counterbalanced by improved potato varieties that resist nematodes, reducing costs and increasing efficiency. The change from production-based to area-based subsidies in 2013 was seen as a big challenge in NL-Starch potato. As strategy to deal with this challenge, the cooperative decided to abandon less lucrative lower quality starch markets and invest in product innovation. In BE-Dairy, participants indicated that main indicators were particularly affected by the abolishment of the milk quota and events that affected the international market. Identified strategies to cope with these challenges were mainly related to improved efficiency, but also included strategies related to risk management and diversification at farm and farming system level. In IT-Hazelnut, dynamics of indicators were perceived to be mainly influenced by the development of new machinery that enhanced labour productivity. Apart from competition at the international market with Turkey, no major challenges were reported. Strategies to maintain or improve main indicators in IT-Hazelnut were related to mechanization, cooperatives, producer groups and using funds of the Rural Development Program of the European Commission (RDP funds).

In all three case studies, indicators related to food production and economic viability were assessed to have improved over time, except in BE-Dairy, where farm income was perceived to be on average stable, but with increased yearly variation. The perspective in all three case studies is more negative for indicators representing the environmental domain. In NL-Starch potato, soil quality was perceived to decline, in BE-Dairy, emissions of carbon were perceived to go up again. In IT-Hazelnut, the indicator "Area of organic hazelnut production" was seen as positively related to the function "Biodiversity & habitat" and was perceived to be increasing. However, participants indicated that they perceived that biodiversity in the farming system was generally decreasing because of the limited habitat provision in the expanding area with hazelnut monocultures. In the expansion areas, hazelnut cultivation also requires more ground water extraction compared to the cultivations of chestnut and olives that it usually replaces

Table 2.6. Stakeholder perceptions of main dynamics, underlying causes and applied strategies to maintain or enhance performance of selected indicators in the three case studies.

Case study	Function	Indicator	Main trend in last 20 years	Main causes of dynamics	Strategies
NL-Starch potato	Food production	Starch potato production	Remained stable	Cultivated area decreased and production per hectare increased; decoupled payments reducing subsidies	Exchanging land with dairy farmers, reduce costs
	Economic viability	Profit per hectare	Increased, but a plateau seems to be reached	Increased but also variable prices; higher yields; increased input prices; extreme events; decoupled payments reducing subsidies; more alternative crops	Extending knowledge on soils and varieties, scale enlargement, increase value of starch potato products, better varieties, reduce costs, have land available outside contract farming, precision agriculture
	Natural resources	Soil quality	Decreased	Nematode pressure, nutrients not being replenished, lack of awareness	Improved varieties against nematodes, raising awareness, replenish soil minerals, avoid artificial fertilizer
BE-Dairy	Food production	Total milk production	Increased	Increased efficiency, abolishment of quota	Increase efficiency, expansion of business (own rearing), expansion of business (buying cattle), broaden business, futures exchange
	Food production	Real milk price for consumers	Decreased, currently stable	Banking crises, Arabic spring, stop on export to Russia	Open up to international markets, exceptional financial support from sectoral federation, creating milk powder stocks
	Economic viability	Farm income	Average is stable, but more fluctuations in the last decade	Financial crises, globalization, decreasing demand from China, export ban to Russia	Intensification and scale enlargement, cyclic investing, investments of cooperatives, maintain diversity of dairy farms
	Natural resources	Total carbon foot print	Gradual decrease in 00's, increase in 10's	Increased efficiency, abolishment of quota	More efficient feeding, manure recycling/circular agriculture, production of green energy, increase longevity of cows, genetic improvement
IT-Hazelnut	Food production	Gross saleable production	Increase, with a peak in 2012-2014	Machinery development, frost in Turkey	Mechanization, cooperatives
	Economic viability	Gross margin per hectare	Increase, with a peak in 2012-2014	Machinery development, frost in Turkey	Mechanization, producer organizations
	Biodiversity & habitat	Organic cultivated area	Increase	Launch of tenders for organic production	Applying for rural development program funds
	Attractiveness of the area	Retention of young people in the area	Stable	Hazelnut value chain generating job opportunities, attracting young people that would have out-migrated otherwise	Mechanization, value chain activities

2.3.4 Resilience strategies for the farming system

Overall, perceptions on implementation levels of strategies was scored most positive in IT-Hazelnut (Figure 2.3A-C). In IT-Hazelnut, the strategies of establishing cooperatives and starting new value chain activities were perceived to be least well implemented. In BE-Dairy and NL-Starch potato implementation levels of different strategies were scored poor to good. In BE-Dairy, strategies related to the carbon footprint were less well implemented than for the indicators 'real milk price' and 'labour income'. In NL-Starch potato, strategies related to soil quality were less well implemented than for profit per hectare. (Figure 2.3A-C)

Strategies (Table 2.6) could mostly be related to the resilience attributes "Reasonably profitable", "Infrastructure for innovation", "Production coupled with local and natural capital", "Socially self-organized" and "Functional diversity". Strategies linked to "Socially self-organized" were perceived to be well implemented in all case studies. Strategies related to innovation were perceived to be very well implemented in IT-Hazelnut, and moderately in the other case studies. Only in BE-Dairy and NL-Starch potato several strategies could be evaluated as contributing to functional diversity and the coupling of production with local and natural capital. In the case studies there were no strategies identified that could be linked to redundancy of farms or to policies (SM2.3).

In general, perceived contribution of strategies to robustness was moderate. Contribution to adaptability was generally equal or lower, with a few exceptions. Contribution to transformability was considered positive as well as negative. When positive, contribution was equal or lower than moderate, with a few exceptions. When negative, contribution was considered weak and sometimes moderate. (Figure 2.3D-F)

In IT-Hazelnut, the perceived contribution of RDP funds was controversial, where participants scored negative as well as positive. Participants indicated that the RDP funds were de facto used as subsidies by farmers, without changing farming practices in the long-term. Dependent on the indicator that was considered, mechanization was sometimes seen as being negative for transformability, but overall positive. Cooperatives, producer organizations and value chain activities were all perceived to contribute to farming system resilience. In BE-Dairy, all strategies were perceived to contribute positively to robustness, and to a lesser extent to adaptability and transformability. Moreover, interventions from outside this farming system, such as exceptional financial support from the sectoral federation (Fedis-support), genetic improvement and creation of milk powder stocks, as well as strategies that require on-farm investments, were perceived to negatively affect transformability. In NL-Starch potato, many strategies were perceived to contribute positively to robustness and adaptability. There were four strategies that were evaluated to weakly affect transformability in a negative way: scaling (of area and hence the production), increase value of starch products, have land available outside contract farming, apply precision agriculture. In NL-Starch potato, strategies related to soil quality and potato production were perceived to be good for transformability. With regard to strategies related to profit per hectare, only cost reduction, better varieties and improved knowledge on soil and varieties were perceived to be good for transformability. However, strategies that require investments from mainly within the farming system, such as scaling, increased value of starch products and adopting precision agriculture were regarded as negatively affecting transformability.

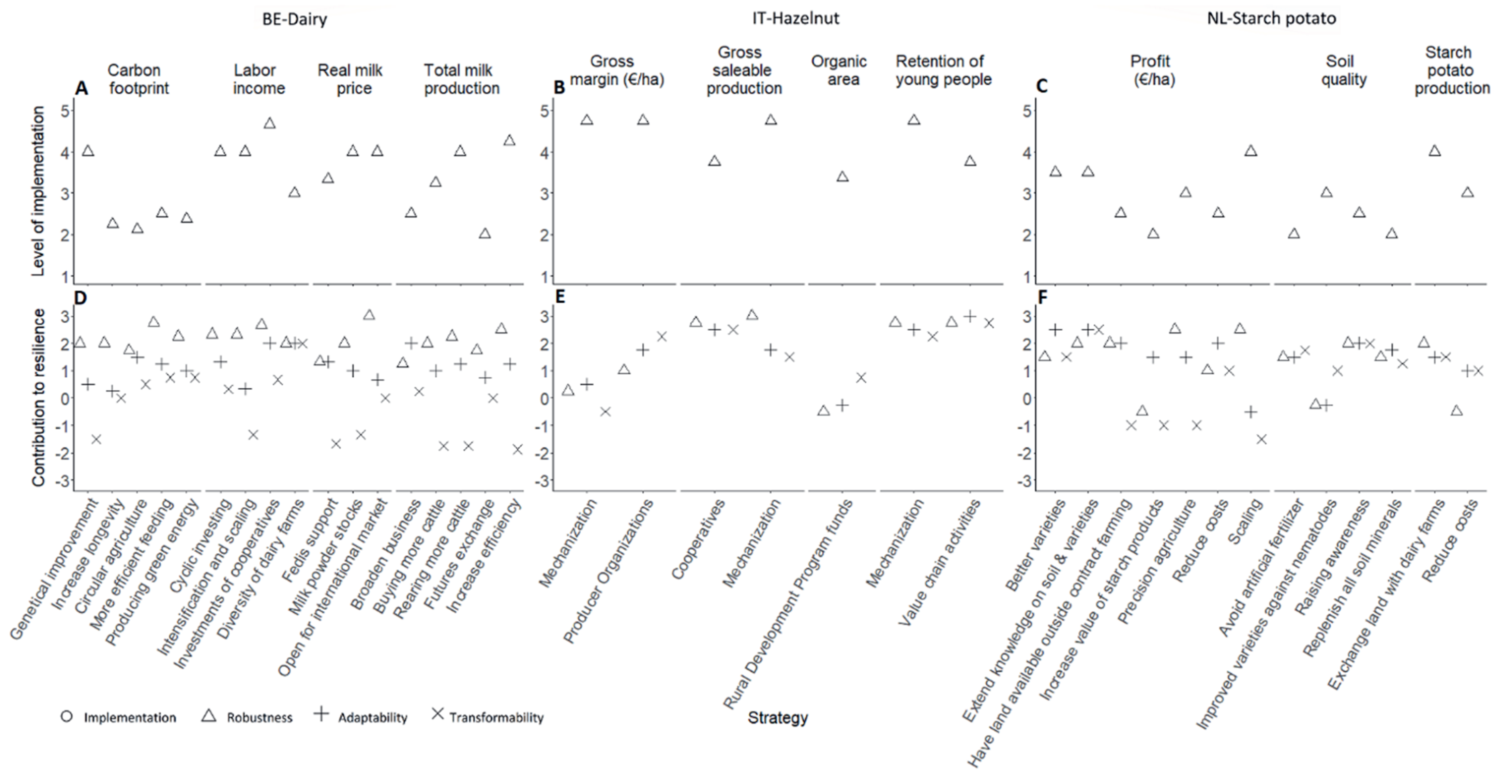

Figure 2.3. Perceived level of implementation of resilience enhancing strategies (A-C) and their contribution to the resilience capacities (D-F) per CS per studied indicator. Level of implementation was assessed on a scale from 1 to 5 and contribution to the resilience capacities was assessed on scale from -3 to 3 (Table 2.3).

2.3.5 Resilience attributes

As shown in Figure 2.4A, perceptions about presence of most resilience attributes followed similar patterns in the three case studies. Presence of resilience attributes was perceived to be low to moderate, with some exceptions, especially in IT-Hazelnut. For example, BE-Dairy and NL-Starch potato scored "Reasonably profitable" as low, while this attribute scored high in IT-Hazelnut, providing it with financial capital reserves. "Socially self-organized" scored high in IT-Hazelnut and moderate in other case studies, which has an effect on the social capital reserves. In IT-Hazelnut, the coupling of production to local and natural capital was perceived low, while it was perceived to score moderately in the two other case studies. Perceptions on legislation being coupled to local and natural capital were low in all three case studies, especially in NL-Starch potato. The studied farming systems were perceived to have a poor to moderate degree of openness. Especially "Exposed to disturbance" was evaluated lower, as participants perceived that disturbances are threatening system functioning instead of making a system more resilient. Diversity was evaluated to be poorly present in all case studies, with the exception of "Spatial and temporal heterogeneity of farm types", which was assessed to be moderately present. Modularity in the farming system was perceived to be moderately present in IT-Hazelnut and weakly present in BE-Dairy and NL-Starch potato.

Figure 2.4B reveals that the potential contribution of resilience attributes to robustness was perceived to be very weakly to moderately positive in all three case studies. High scoring attributes in all three case studies related to the profitability of the system and its production being coupled with local and natural resources. Being exposed to disturbance was evaluated negatively as well as positively by stakeholders in BE-Dairy and NL-Starch potato, respectively, explaining the low overall score. Scores for robustness were specifically low for some resilience attributes in NL-Starch potato, namely "Exposed to disturbance", "Optimally redundant (farms)", "Supports rural life" and "Legislation coupled with local and natural capital".

Scores for contribution of resilience attributes to adaptability were similar or lower compared to contributions to robustness (Figures 2.4B and 2.4C). An exception was "Infrastructure for innovation", which received similar scores for adaptability and for robustness in all three case studies. Other resilience attributes scoring relatively high in all three case studies related to the profitability, production being coupled with local and natural capital, response diversity and diverse policies.

Finally, contribution of resilience attributes to transformability was assessed to be very weak to moderate (Figure 2.4D). Scoring patterns for transformability deviated from the patterns as observed for robustness and adaptability. In BE-Dairy, expectations were lower for resilience attributes contributing to transformability than to adaptability. In all three case studies, "Infrastructure for innovation" got relative high scores for contributing to transformability compared to other resilience attributes.

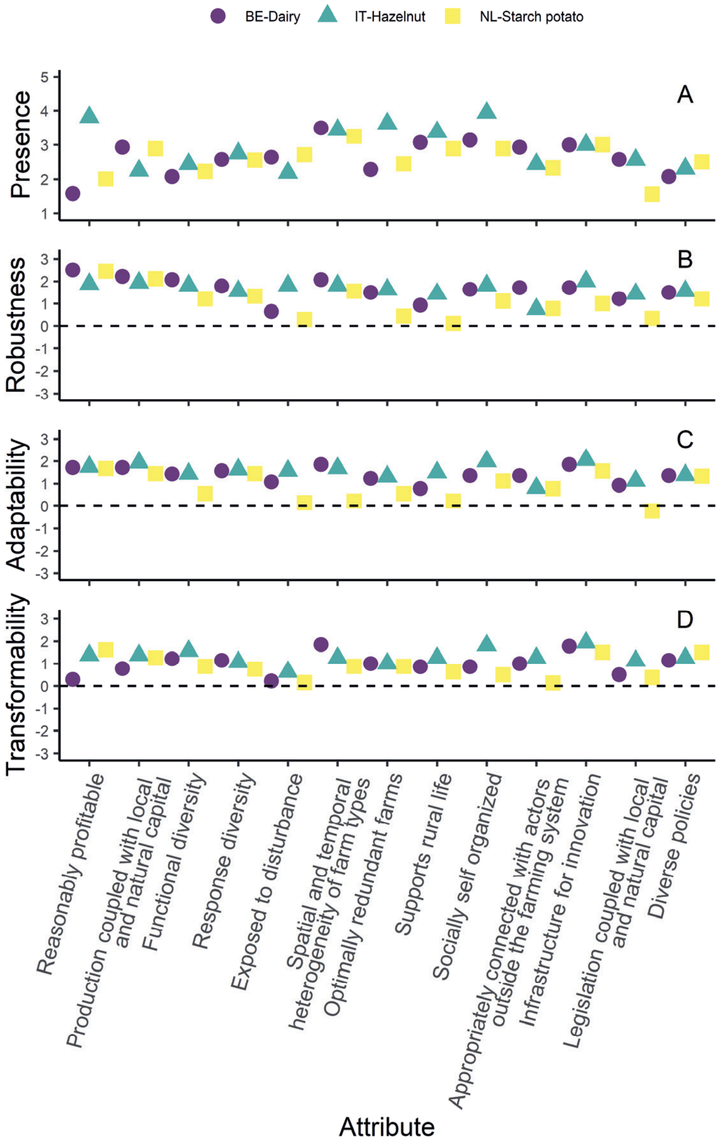

Figure 2.4. Perceived level of presence of resilience attributes (A) and their perceived contributions to robustness (B), adaptability (C) and transformability (D). Level of presence was assessed on a scale from 1 to 5 and contribution to robustness, adaptability and transformability was assessed on a scale from -3 to 3 (Table 2.3).

2.4 Discussion

2.4.1 Farming system sustainability assessment

The studied intensive, specialized farming systems are perceived to primarily provide economic viability, to provide food and, in NL-Starch potato and BE-Dairy, to maintain natural resources. Farmers (participating in the workshops) put more emphasis on economic viability compared to other participants, who divided importance more equally over farming system functions. This difference in perception indicates that no optimal solution exists across all stakeholder groups and that a balance between differing views needs to be found (in line with Robards et al. 2011). Detecting the difference between stakeholder groups was possible because participants assessed the same set of functions. The top-down approach of our method, dividing 100 points over eight functions, forced participants to make choices between economic, environmental and social functions and indicators. In our case studies, this revealed a lack of attention for social functions such as quality of life and attractiveness of the area, which might result in missing out on important feedbacks from the social domain. The identification of this knowledge gap is an important result of our participatory method. Mosse (1994) points out that the identification of the boundaries of local knowledge is an important, but often overlooked, goal of participatory research. Performance of functions was generally perceived to be moderate, with a few low and well performing functions in each case study. Contrary to perceptions on function importance, perceptions on function performance were similar between the stakeholder groups in most case studies. The remarkable variety in allocated importance of functions, together with an only moderate performance of more important functions, suggests the presence of interactions and trade-offs between functions. Further indications of trade-offs were found in the studied farming systems (SM2.4). Existence of trade-offs may influence stakeholders perceptions, which emphasizes the importance to have both information on perceptions of stakeholders as well as observational data.

2.4.2 Farming system resilience assessment

Based on perceived presence and potential contribution of resilience attributes the case studies were perceived to show more robustness than transformability, which is typical for specialized systems aiming to control external factors as much as possible (Hoekstra et al., 2018). Strategies applied in the past 20 years, mainly with regard to economic functions and food production, show that the studied farming systems mainly use their adaptability to increase robustness, e.g. increasing farm size in BE-Dairy and NL-Starch potato to better cope with small margins. It should be noted that regarding the strategies, the method is biased towards the interest of stakeholders for specific functions. This interest may also have resonated within the stakeholders' mind when reflecting on resilience attributes.

All farming systems were perceived to have a relative low presence of functional and response diversity, and contribution of diversity to resilience is perceived low. According to Hoekstra et al. (2018), the lack of diversity is an indication that production systems are operating more under a control rationale rather than a resilience rationale. Hoekstra et al. (2018) pose that for systems to optimally perform, a balance needs to be found between the control and resilience rationales. In the case studies, this balance between rationales might be partly found in the spatial heterogeneity of farm types, which relates to diversity (see also Reidsma and Ewert 2008). Heterogeneity of farm types is assessed to have relatively high presence, and especially in BE-Dairy and IT-Hazelnut this resilience attribute was perceived to contribute to resilience. Common building blocks for resilience in all case studies were profitability, production coupled with local and natural capital, social self-organization and infrastructure for innovation. Profitability was perceived as having a large potential for improving robustness and adaptability in all case studies, but was currently perceived to be low in BE-Dairy and NL-Starch potato. Higher profitability was perceived to mainly increase robustness and adaptability in BE-Dairy. To attain higher profitability in BE-Dairy, many strategies in the past required large investments, which can explain the perceived negative contribution of these strategies to transformability. Production being coupled with local and natural capital is also assessed to have a large contribution to resilience in all case studies, but was currently considered to be low in IT-Hazelnut and moderate in BE-Dairy and NL-Starch potato. Loss of natural capital such as loss of ecosystem quality might be more visible in the quickly intensifying and expanding IT-Hazelnut (Biasi and Botti, 2010). This could explain why the other case studies, which actually have more intensive systems, scored higher. Self-organization is commonly accepted as enhancing resilience (Cabell and Oelofse, 2012) However, too much connections between actors in a system can increase the risk for co-dependency and reduce modularity. This could be the case in NL-Starch potato where the transformative capacity of the local cooperative has provided a pathway towards higher profitability. However, to stay on this pathway, the cooperative maintains a high demand of starch potatoes, resulting in a very narrow rotation and an increased pressure from nematodes in the soil. Our study indicates that infrastructure for innovation is an important resilience attribute for specialized farming systems, especially for adaptability and transformability, and should receive more emphasis. Although Gunderson and Holling (2002) emphasized the importance of innovation for resilience, resilience literature often lays more emphasis on social and ecological aspects (e.g. Cabell and Oelofse, 2012).

Assessing perceived sustainability and resilience allows to reflect on both concepts simultaneously. In the studied farming systems, function indicators relating to sustainability were on average perceived to perform moderately. This suggests that adaptations or even transformations need to be realized. Without those, sustainability might further decline, especially social sustainability that currently seems to receive relatively little attention compared to economic and environmental sustainability. On the one hand further decline could lead to undesired transformational change. On the other hand current perceived lower levels of adaptability and transformability do not seem to allow orchestrated transformations by stakeholders in the farming system: apart from infrastructure for innovation, no other attribute was assessed to support transformability well in any of the three farming systems. A promising resilience attribute for transformability is related to an enabling environment for shared learning and experimentation and should be included in further assessments (SM2.5).

2.4.3 Methodology

The FoPIA-SURE-Farm framework employed in this research captures essential steps to assess farming system resilience (see Meuwissen et al. 2019). The framework encompasses multiple dimensions and perspectives by including lists with many farming system functions and resilience attributes. These lists form a base for knowledge exchange between researchers and participants. Researchers exposed participants to the notion that sustainability and resilience need to be addressed in a structured, integrated approach. Based on this approach, participants could add local meaning to the still abstract system functions and resilience attributes. Adding local meaning enabled further discussions about sustainability and resilience. For instance, for both, researchers and participants, it was informative that most important system parameters, according to participants' perceptions, could be identified and directly discussed. This allowed for identification of important system dynamics and also strategies that were aimed to maintain or enhance system functions. Selection of important system parameters can also support further analyses on systems dynamics. For instance, by zooming in on a specific set of parameters, Kinzig et al. (2006) were able to study critical thresholds of agro-ecological systems. It should be noted, however, that by first identifying main sustainability indicators, a path-dependency is created, which in the application to the three case studies resulted in an emphasis on economic and production indicators in later steps of the workshop. In general, the selection of main system parameters is also a further simplification of reality. This increases the risk of not being able to understand the dynamics of the studied system (Quinlan et al., 2016). Related to adequately understanding farming system behaviour, it should be noted that other levels than the farming system should be taken into account as well when studying multi-level concepts such as sustainability (e.g. Van Passel and Meul 2012, Delmotte et al. 2017) and resilience (e.g. Peterson et al. 2018, Meuwissen et al. 2019). In that sense FoPIA-SURE-Farm needs to be complemented with analyses at farm level (Spiegel et al., 2019) and the level beyond the farming system (Feindt et al., 2019). The level beyond the farming system is not well defined in agricultural literature as there are multiple possibilities, e.g. entire value chains, food systems, and the political or socio-technical environment.

The selected case studies were different in geographical size and had different positions in governmental hierarchy. On the one hand this shows the wide applicability of FoPIA-SURE-Farm to handle various farming systems with different geographical and political boundaries. On the other hand it made the comparison between the three case studies in this paper challenging, i.e. differences observed could be confounded with size and hierarchical level of the case study. Differences could also be confounded with the influence of the individual research teams in each case study. Also culturally defined inclinations, e.g. towards optimism or pessimism, could play a role. To deal with these challenges in this paper, we did not compare scores between case studies directly, e.g. stating that a function was performing better in one case study compared to another, or by performing statistical tests on differences between case studies. Instead, we treated scores as being relative to other scores within the same case study. This revealed certain patterns such as the relative absence of attention for social functions, the emphasis on robustness and the relative importance of the resilience attributes related to profitability, social self-organization and infrastructure for innovation in all case studies.

Summarizing weighted indicator scores into sustainability indices is a common practice in sustainability science (Mayer, 2008), and for instance applied in the original FoPIA-approach (König et al., 2013; Morris et al., 2011). However, letting participants divide 100 points over functions and indicators is less commonly applied. We argue that this method helps to raise awareness of trade-offs between functions, in case such trade-offs are until then only implicit or part of a subconscious process. Dividing 100 points over functions and indicators resembles the Q-methodology (McKeown and Thomas 2013; qmethod.org), in which participants are forced to allocate scores to a number of items, while following a predefined distribution in which extreme values are more rare than moderate values. In the approach taken in this study, the participants themselves effectively determine their own distribution. This makes that an imbalance between function or indicator importance can be interpreted as an outcome of the study rather than a design input as is the case for the Q-methodology.

Using Likert items and scales poses another challenge for interpreting the results from FoPIA-SURE-Farm. In this paper, the performance of functions can be seen as Likert scales, where the representative indicators are weighted Likert items, allowing for presenting the mean as summarizing statistic (Guerra et al., 2016). Regarding the scoring of strategies and resilience attributes, we chose to present the mean as well, which is not entirely correct according to some, but acceptable to others (e.g. Norman 2010) and more intuitive compared to using the median an quartiles in communicating results (Guerra et al., 2016). This is especially true for the strategies where the number of observations is low. SM2.2 provides means as well as individual observations, which shows that means and medians, basically the observations in the middle of the data, do not differ much. Moreover, for testing significant differences, non-parametric tests were used that correspond with the ordinal nature of the data. It can be argued that, although participants may have different points of reference regarding whether a function for instance is performing poorly or perfectly, perceptions of performance between stakeholders and across indicators can be compared (e.g. Morris et al. 2011, König et al. 2013). The possibility that participants have avoided extreme values on the provided scoring scales, might be reflected in in the moderate scorings that many functions and resilience attributes received. This is an additional reason to look at differences between scores and consequently focus on the patterns of higher and lower scoring items, as is done in this study. This is somewhat similar to the analyses on the outcomes of Q-methodology, where patterns of extreme values for a set of specific items can be interpreted as being expressions of mental models of stakeholder in a system (McKeown and Thomas, 2013). A final point of attention relates to the notion that negative and positive values are for various reasons not true opposites of each other, possibly leading to a method bias (Alexandrov, 2010). In our study, all Likert-type items were phrased in a positive way, thus reducing the impact of a possible method effect (Alexandrov, 2010). Practically, this reduces the likelihood that for instance the positive scoring of resilience attributes is partly a methodological artefact.

Another point of discussion is that participants showed signs of fatigue towards the end of the FoPIA-SURE-Farm workshop. This coincided with the intellectually challenging scoring exercise on presence of resilience attributes and their contribution to robustness, adaptability and transformability. Still, this exercise was completed correctly in six out of eight other European case studies (Paas et al. 2019). Dependent on the research question, scoring on presence and contribution could be combined into a score that summarizes the overall importance of the resilience attribute for the farming system. Especially filling out forms was experienced as tedious. Moreover this method was top-down, which is advised to be avoided in participatory approaches that deal with the topic of resilience (Callo-Concha and Ewert, 2014). In FoPIA-SURE-Farm we could not avoid top-down questions in order to save time of participants, to enhance comparability between case studies, and to identify knowledge gaps. However, we stimulated participants to influence the content of the workshop, e.g. by providing feedback during the plenary and small group discussions that alternated the individual exercises. To further compensate for top-down questions, and to make sure that the right issues are addressed, stakeholders should be consulted again when main indicators of the farming system as identified in this study are used for further analyses. For instance when moving to the planning phase of a project cycle (Ridder and Pahl-Wostl, 2005) where concrete strategies for improved sustainability and resilience have been identified (Chapter 5; Paas et al. 2020).

With the FoPIA-SURE-Farm framework, the underlying system mechanisms that bring current resilience were only revealed occasionally in plenary discussions, rather than being a fundamental part of the framework. For instance, interactions between resilience attributes through competition for resources or co-dependence was not addressed. To complete the resilience assessment and understand underlying mechanisms, further research is necessary that includes the impact of (new) shocks, adaptation measures and future scenarios (Walker et al., 2002). For that reason we continued within the SURE-Farm project with participatory integrated assessments in which we assess performance, interactions and thresholds of important system parameters in different possible futures (Chapters 5 & 6; Paas et al. 2020).

2.5 Conclusion

The framework presented in this paper is based on existing sustainability and resilience frameworks. It provides a method to identify main indicators of a farming system and to obtain a qualitative assessment of its perceived sustainability and resilience, based on opinions of stakeholders from that system. This reveals stakeholder perspectives on importance and performance of functions and resilience attributes accounting for the complex nature of farming systems. Perspectives on importance were sometimes imbalanced, i.e. too little importance was allocated to social and environmental functions. Also attention for resilience attributes was imbalanced. The identification of imbalance is an important outcome of the method, as it indicates the boundaries of local perspectives and knowledge. Perspectives on performance were sometimes deviating from findings presented in literature, which emphasizes the need to have input from quantitative analytical sources as well.

Assessing perceived sustainability and resilience simultaneously allows to reflect on pathways to higher sustainability. Taking the case of specialized systems in the EU, workshop outcomes suggest that function performance relating to sustainability was perceived to be moderate, while presence of resilience attributes was perceived to be low to moderate and contribution of these attributes to resilience was perceived to be weak to moderate. In the studied systems, robustness was perceived to be stronger than adaptability and transformability. This indicates that finding pathways to more sustainability, which requires adaptability and transformability, will be a challenging process.

Strategies to maintain performance of indicators of the studied systems were mainly related to keeping the system economically viable, partly through innovations in the system. Across case studies, profitability, production coupled with local and natural capital, infrastructure for innovation and self-organization were perceived as important resilience attributes. Based on workshop results, we conclude that an additional resilience attribute related to an enabling environment for experimentation and learning is necessary. The relative importance and contribution of some resilience attributes in the studied systems differed from case to case, e.g. heterogeneity of farm types. This indicates that the local context in general, and stakeholder perspectives in particular, are important when evaluating general resilience and policy options based on resilience attributes.

Overall, despite some methodological limitations, the case study specific results seem a good starting point for raising awareness, further assessments, and eventually for developing a shared vision and action plan for improving sustainability and resilience of a farming system.

Supplementary Materials

Supplementary materials 2.1: https://www.ecologyandsociety.org/vol26/iss2/art2/appendix2.pdf

Supplementary materials 2.2: https://www.ecologyandsociety.org/vol26/iss2/art2/appendix3.pdf

Supplementary materials 2.3: https://www.ecologyandsociety.org/vol26/iss2/art2/appendix4.pdf

Supplementary materials 2.4: https://www.ecologyandsociety.org/vol26/iss2/art2/appendix5.pdf

Supplementary materials 2.5: https://www.ecologyandsociety.org/vol26/iss2/art2/appendix6.pdf

How do Stakeholders Perceive the Sustainability and Resilience of European Farming Systems?

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Abstract

An increasing variety of stresses and shocks provides challenges and opportunities for European farming systems. This article presents findings of a participatory assessment on the sustainability and resilience of eleven European farming systems, to inform the design of adequate and relevant strategies and policies. According to stakeholders that participated in workshops, the main functions of farming systems are related to food production, economic viability and maintenance of natural resources. Performance of farming systems assessed with regard to these and five other functions was perceived to be moderate. Past strategies were often geared towards making the system more profitable, and to a lesser extent towards coupling production with local and natural resources, social self-organisation, enhancing functional diversity, and facilitating infrastructure for innovation. Overall, the resilience of the studied farming systems was perceived as low to moderate, with robustness and adaptability often dominant over transformability. To allow for transformability, being reasonably profitable and having access to infrastructure for innovation were viewed as essential. To improve sustainability and resilience of European farming systems, responses to short-term processes should better consider long-term processes. Technological innovation is required, but it should be accompanied with structural, social, agro-ecological and institutional changes.

3.1 Sustainability and resilience of European farming systems

With further liberalization of markets, a changing policy context and climate change, agriculture in Europe is increasingly subject to a variety of stresses and shocks. These disturbances provide challenges and opportunities for farming systems and affect their ability to deliver private and public goods. The recent COVID-19 outbreak provides an additional challenge. Farming systems in Europe vary widely in terms of characteristics, production, actors involved and challenges faced. Dependent on the context, they function differently and show different degrees of sustainability and resilience, two complementary concepts (see SM 1.1. for definitions and concepts). Sustainability can be defined as an adequate performance of all system functions across the environmental, economic and social domains (Morris et al., 2011). We define resilience of a farming system as its ability to ensure the provision of the system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability (Meuwissen et al., 2019). A proper understanding of the local context and underlying mechanisms of resilience is essential for designing adequate and relevant strategies and policies (Biesbroek et al., 2017). In the case of European farming systems, these strategies and policies should help to improve the system functions to 1) deliver healthy and affordable food products, 2) deliver other bio-based resources for the processing sector, 3) ensure a reasonable livelihood for people involved in farming, 4) improve quality of life in farming areas by providing employment and decent working conditions, 5) maintain natural resources in good condition, 6) protect biodiversity of habitats, genes and species, 7) ensure that rural areas are attractive places for residence and tourism with a balanced social structure, and 8) ensure animal health and welfare (Figure 3.1.). Not every farming system needs high performance levels on all functions and attributes that support those functions. Stakeholders can provide insights in requirements of particular farming systems and indicate where adjustments in systems and policy incentives are needed.

Hence, in this article, we assess stakeholder perceptions regarding sustainability and resilience across European farming systems (see Section 1.6. for case studies and Chapter 2 for methods), focusing on:

- the importance and performance of the farming system functions, which we interpreted as aspects that determine sustainability levels,
- resilience-enhancing strategies based on historical dynamics, and perceived contribution to robustness, adaptability, and transformability,
- presence of attributes that enhance resilience and their perceived contribution to robustness, adaptability, and transformability.

This leads to conclusions regarding overall perceived resilience of the farming systems and policy implications.

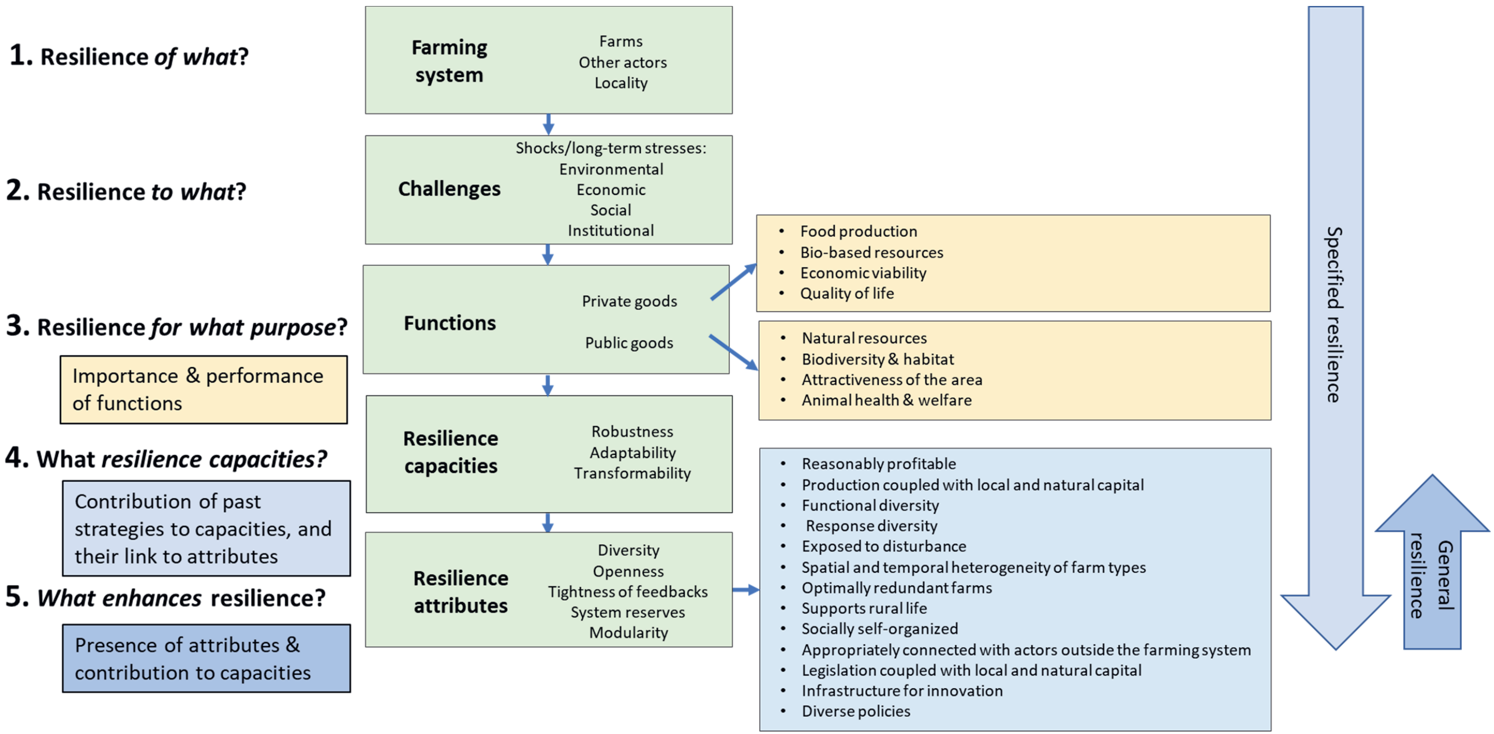

Figure 3.1. Framework to assess resilience of farming systems (adapted from Meuwissen et al., 2019), with the three boxes under step 3, 4 and 5 indicating assessments presented in this article. The complete description of the functions is provided in the first section of the text, in the same order. Explanation statements of resilience attributes are provided in Table 2.5.

3.2 Farming system functions

According to stakeholders, the main functions of the studied farming systems related to food production, economic viability and the maintenance of natural resources (Figure 3.2). Most studied farming systems were perceived to perform moderately for most functions, indicating moderate levels of economic, social and environmental sustainability. Often there was cause for concern for at least one function with low performance. For example, the attractiveness of the area scored relatively low in terms of performance across case studies.

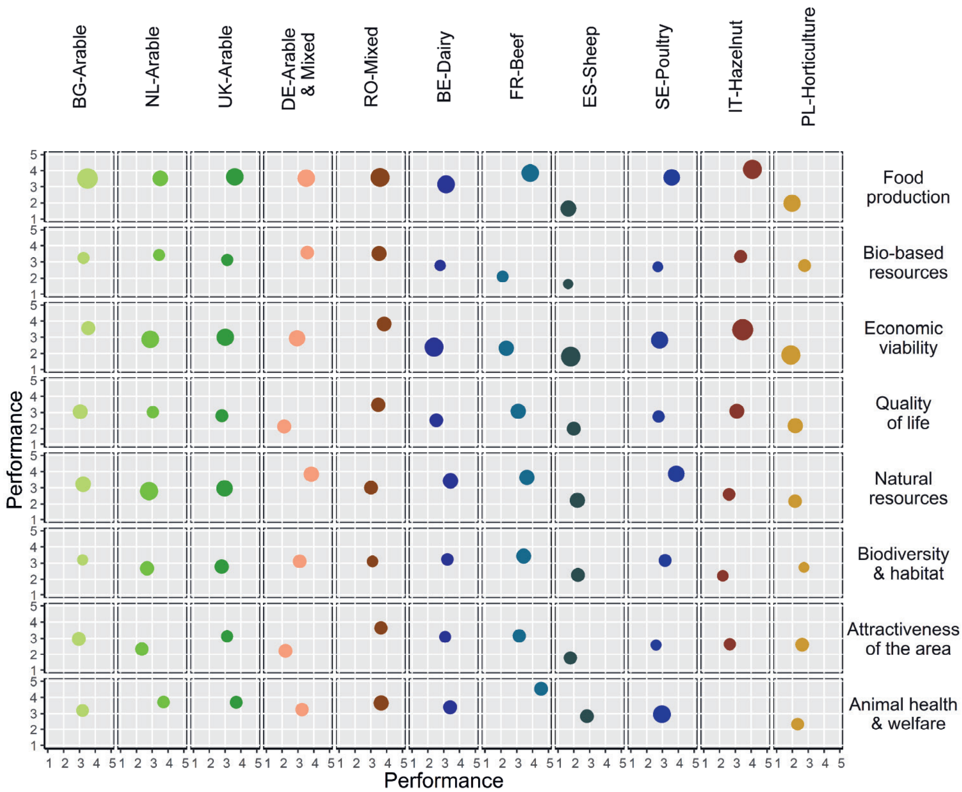

Figure 3.2. Relative importance (size of bubbles; 100 points could be distributed among 8 functions) and performance of functions of all case studies. Performance scores are from 1 to 5, where 1 is very low, 2 is low, 3 is moderate, 4 is good and 5 is very good performance. Performance is presented on both axes to allow comparison of case studies and/or functions.

Clearly, there were differences in perceived function performance among farming systems. The level of food production was considered moderate to high in all case studies, except ES-Sheep and PL-Horticulture (see Section 1.6. for country codes). In the latter countries, also the performance of farming systems with regard to other functions was perceived as low. This related to recent policy changes (decoupled payments in ES-Sheep and accession to the EU in PL-Horticulture) affecting economic viability (less net subsidies, as farmers have to rent land to keep the payment rights in ES-Sheep and lower product prices in PL-Horticulture) and consequently other functions. Performance of private functions including economic viability was particularly high in IT-Hazelnut and RO-Mixed. The hazelnut production system in IT-Hazelnut was very profitable and expanding, while in RO-Mixed the presence of EU subsidies, of various selling channels and a large agricultural employment drove the positive assessment.

In RO-Mixed the high performance of private functions was accompanied by a high performance of public functions. While there had been some decline in environmental sustainability in the past, the accession of

Romania to the EU and cross-compliance policies have increased awareness to maintain natural resources and biodiversity. In IT-Hazelnut on the other hand, the expansion of monoculture hazelnut production caused environmental concerns (Nera et al., 2020). The increased awareness for environmental sustainability observed in RO-Mixed after accession to the EU was less visible and not explicitly mentioned in BG-Arable, where larger farms dominate. Perceived performance of public functions was on average moderate, but perceptions differed per stakeholder type. Specifically in more intensive or intensifying systems (e.g., NL-Arable, BE-Dairy, BG-Arable), farmers perceived the performance as better compared to other stakeholders. Perceived performance of public functions was particularly high in FR-Beef, and generally scored higher for livestock systems compared to arable, horticultural and perennial systems.

Interestingly, functions that represent the social domain (quality of life, attractiveness of the area) were not given much importance. These functions were considered to perform low to moderately in most systems. For the studied farming systems, we found an imbalance in the importance given to the economic, environmental and social domains. This imbalance could be caused by more or less conscious trade-offs encountered by farming system actors, who, facing direct, immediate challenges in the economic and environmental domains, might pay less attention to the social domain.

3.3 Resilience-enhancing strategies

Strategies applied in the past 20 years suggest that farming systems were generally resilient, but mainly in terms of robustness. Still, participants in workshops often perceived positive contributions of past strategies to adaptability and transformability.

In all case studies, the most frequently mentioned strategies related to reducing costs, technology implementation, and increasing farm size, in order to increase production and/or cost efficiency and make the farming system "reasonably profitable" (Table 3.1). These strategies were emphasized in BE-Dairy, BG-Arable and ES-Sheep. In BE-Dairy, these strategies were seen as enhancing robustness while constraining transformability. This was explained by the relative high investment costs which cause a lock-in on the pathway to higher efficiency. In ES-Sheep and BG-Arable, these strategies were considered to enhance adaptability, but also transformability. Specifically, in a more extensive system like ES-Sheep increasing efficiency could also improve transformability, as increased efficiency was needed for the reorganization of the system.

Strategies that have coupled production with local and natural capital (e.g., manure recycling in BE-Dairy) were mentioned quite frequently, but less than half as often as the ones above. Stakeholders perceived the contribution to robustness, but less to adaptability and transformability. As an example, agri-environmental schemes in UK-Arable tend to tie farmers into fixed approaches: new schemes need to be flexible to allow farmers to react to external stresses.

Only in a few case studies stakeholders mentioned that strategies related to diversification (at different levels) had been applied in the past (BE-Dairy, ES-Sheep, UK-Arable, PL-Horticulture). Such strategies were perceived to have high and (relatively) balanced contributions to all three resilience capacities, although in PL-Horticulture participants saw a negative effect in the short-term.

Table 3.1. Resilience attributes and results from the assessment.

Resilience attribute	number of strategies linked to attribute†	Implementation level of strategies‡	Contribution of linked strategies to* robustness	adaptability	transformability	Presence§	Contribution of attribute to| robustness	adaptability	transformability
Reasonably profitable	54	3.4	1.5	1.5	0.3	2.2	1.8	1.5	0.9
Coupled with local and natural capital (production)	22	2.5	1.4	1.0	0.7	2.9	1.8	1.6	1.1
Functional diversity	15	2.6	1.7	1.7	1.2	2.2	1.4	1.3	1.2
Response diversity	8	3.1	2.1	1.5	0.7	2.4	1.3	1.4	1.0
Exposed to disturbance	4	3.8	2.6	1.2	0.3	2.5	0.6	0.7	0.3
Spatial and temporal heterogeneity (farm types)	3	2.2	1.8	1.9	1.9	3.1	1.5	1.4	1.2
Optimally redundant (farms)	1	n.a.	n.a.	n.a.	n.a.	2.5	1.0	1.1	0.9
Supports rural life	12	4.5	2.3	1.0	0.5	2.6	1.2	1.1	0.8
Socially self-organized	21	2.81	1.9	1.9	1.0	3.0	1.6	1.6	1.2
Appropriately connected with actors outside the farming system	5	4.2	1.7	1.8	1.3	2.3	1.1	1.0	0.8
Coupled with local and natural capital (legislation)	12	3.9	1.1	1. 5	1.2	2.8	0.7	0.6	0.4
Infrastructure for innovation	13	3.5	1.7	1.8	0.3	2.1	1.6	1.6	1.7
Diverse policies	3	2.6	1.0	1.2	1.2	2.1	1.2	1.1	0.9

† Past strategies to cope with challenges are linked to attributes (one strategy can be linked to multiple attributes). Attributes with more linkages are coloured in darker blue.

‡ Implementation level of strategies was scored from 1-5 and averaged across case studies, with 2-2.5 in light blue (poor), 2.5-3 in blue (towards moderate), 3-3.5 in dark blue (above moderate), 3.5-4 in darker blue (towards good) and 4-5 in darkest blue (good to very good).

** The perceived contribution of strategies to resilience capacities was averaged across strategies, with yellow representing a score between 0-1 (very weak to weak), light green 1-1.5 (weak), green 1.5-2 (towards moderate), and dark green 2-3 (moderate to strong). In FR-Beef, strategies were not scored.*

§ The perceived presence of attributes was averaged across case studies, with 2-2.5 in light blue (poor), 2.5-3 in blue (towards moderate) and 3-3.5 in dark blue (above moderate).

| The average assessed contribution of attributes to capacities, with a similar colour scheme as for strategies. In FR-Beef and ES-Sheep, attributes were not scored.

3

In seven out of 11 case studies stakeholders indicated that strategies related to the organizational forms of farming system actors (social self-organization; e.g., cooperatives) were applied; mainly to improve the production and economic functions. These strategies were perceived to enhance robustness and adaptability, while the contribution to transformability differed depending on the strategy and case study. For example, cooperatives and producer organizations in IT-Hazelnut were perceived to have a moderate to strong positive contribution to transformability, while vertical cooperation was perceived to have a strongly negative contribution in PL-Horticulture.

Six case studies emphasized strategies that focus on infrastructure for innovation (e.g., mechanization, improved varieties). Similar to strategies that aimed to improve profitability, these were often seen to enhance robustness and adaptability, but when investment costs were large, to constrain transformability. One of the few transformability-enhancing strategies was to extend knowledge on soil and varieties in NL-Arable, i.e. a strategy that also addressed public functions instead of only food production and economic viability.

3.4 Resilience attributes

In general, resilience attributes were perceived to be weakly to moderately present in the case studies (Table 3.1; see Paas et al. (2019), for details). IT-Hazelnut and SE-Poultry were an exception with multiple resilience attributes that were assessed to have a moderate to good presence. PL-Horticulture often received the lowest scores. "Diverse policies" was scored low in all case studies. Except for IT-Hazelnut, "reasonably profitable" was also assessed to have a low to very low presence. Surprisingly, the mixed systems RO-Mixed and DE-Arable&Mixed did not score higher for perceived presence of "functional diversity" compared to other case studies. However, for "response diversity", RO-Mixed and DE-Arable&Mixed were among the higher scoring case studies. "Spatial and temporal heterogeneity of farms" (similar to previous attributes related to diversity) scored relatively high in all case studies, compared to other attributes. The related attribute "optimal redundancy of farms", however, scored lower. The low score for NL-Arable was mainly related to the difficulties for potential farm successors to take over the farm. In ES-Sheep, participants emphasised that each farmer dropping out created a problem for the system, indicating that redundancy was low.

Although scores for the contribution of resilience attributes to resilience capacities were generally positive (Table 3.1) – which is in line with previous research – they are generally low. The contribution to robustness was generally considered higher than to adaptability and transformability. Sometimes trade-offs between resilience capacities were observed. For example, in some case studies the attribute "reasonably profitable" was perceived to be the most important for robustness, while it was seen as a negative contributor to transformability. The reasoning was that as long as economic returns were above a certain level, other incentives needed to be very convincing before change would be considered. However, in some cases the contribution to both robustness and transformability scored high, as profitability was seen as essential for building up economic reserves that could help to support system transformations.

On average, "production coupled to local and natural capital", "reasonably profitable", "socially self-organized" and "infrastructure for innovation" were seen as contributing mostly to robustness and adaptability, while "infrastructure for innovation" was seen as specifically important for transformability. Hence, while strategies implemented in the past related to "infrastructure for innovation" (e.g. mechanization in IT-Hazelnut and investment in buildings and technology in SE-Poultry) were seen as constraining transformability, stakeholders perceive the role of infrastructure that facilitates diffusion of knowledge and adoption of cutting-edge technologies as important to allow for transformability.

Participants concluded that "diverse policies" that equally aim at robustness, adaptability as well as transformability would contribute weakly to all three capacities. As strategies in the past mainly contributed to robustness, specific policies will be needed to improve adaptability and transformability.

3.5 Overall resilience

Taking into account the assessed contribution of resilience attributes to each capacity, resilience was considered to be low. The arable systems and the horticulture system were among the lower-scoring case studies regarding resilience attributes. SE-Poultry and IT-Hazelnut scored higher. In most case studies, robustness was perceived to be higher than adaptability and transformability. In case studies with immediate challenges, however, the capacity to adapt and transform was more similar to the capacity to remain robust. In UK-Arable, it was specifically argued that adaptability and transformability of the farming system were likely to be essential in the future, driven by new agricultural policies (focusing on environmental land management) and future trade deals, following the UK's exit from the EU.

The relatively high presence of robustness was also observed when assessing historical dynamics of main indicators and strategies applied to deal with challenges (Table 3.1). Despite fluctuations and some declining functions, most functions were seen as still being viable. However, when evaluating results from a variety of methods used in SURE-Farm (Reidsma et al., 2019b), it was concluded that in all case studies adaptation, and in some transformation, is required. For many of the intensive or intensifying production systems (e.g., NL-Arable, UK-Arable, BG-Arable, SE-Poultry, BE-Dairy), strategies to increase efficiency are losing their positive impact on private functions, while having accumulated negative impacts on public functions. This implies that alternative strategies are needed to improve sustainability and resilience. On the other hand, more extensive small-scale systems (e.g., RO-Mixed, ES-Sheep) may still benefit from increased efficiency to improve both private and public functions. In IT-Hazelnut and PL-Horticulture there is still room for growth, mainly because of expanding markets for hazelnuts and fruits, but also here the delivery of public goods is a concern.

3.6 Policy implications

The observed preference for functions related to food production and economic viability resulted in a trade-off with functions related to the environment and society. Many stakeholders were primarily concerned with the more immediate stress signals from the faster processes in the farming system (e.g. year-to-year variation of income or production levels) compared to slower processes (e.g. development of soil quality and social well-being of the population in the farming system). This preference induces myopia among farming system actors, at least as long as performance in the environmental and social domain is considered to be acceptable. In other words, when biodiversity decline is not clearly visible and social infrastructure is still available, little action is taken.

Options to shift focus towards slower processes consist of policies that reduce stress signals from faster processes (e.g. through insurance), while improving noticeability of feedback signals from the slower processes (e.g. monitoring adapted to the scale of the process, of for instance biodiversity). Improving noticeability of these signals will help to assess and communicate long-term impacts of developments in farming systems.

Moreover, policies should be designed to safeguard the presence of resilience-enhancing attributes, especially in the light of ongoing trends of intensification and scale-enlargement that could diminish these attributes in European farming systems. Currently, attributes that mostly contribute to all three resilience capacities relate to having appropriate infrastructure for innovation, self-organization of actors in the farming system, the coupling of agricultural production with local and natural capital, and different aspects of diversity. Concluding, technological innovation is required to enhance sustainability and resilience, but should be accompanied with structural, social, agro-ecological and institutional changes (see also Mann 2019). Farmers can change, but they cannot do it alone.

Supplementary Materials

The dataset used in this study can be downloaded at https://zenodo.org/record/5005175#.Ym-q8dpByUk

Temporal and inter-farm variability of economic and environmental farm performance: a resilience perspective on potato producing regions in the Netherlands?

This chapter will be submitted as:

Paas, W., Meuwissen, M.P.M., van Ittersum, M.K., Reidsma, P. Temporal and inter-farm variability of economic and environmental farm performance: a resilience perspective on potato producing regions in the Netherlands?

Abstract

In the context of resilience and sustainability of farming systems it is important to study the trade-offs and synergies between economic and environmental variables. In this study, we selected food production, economic and environmental performance indicators of farms in three potato producing regions in the Netherlands: Flevoland, Zeeland and Veenkoloniën. We studied the period 2006 to 2019 using farm accountancy data. We used threshold regressions to determine gradual development and year-to-year variation of those indicators. Subsequently we applied a sparse Partial Least Square (sPLS) regression to study the response of performance, gradual development and year-to-year variation under different conditions regarding weather, market and farm structure. sPLS-model performance was at best moderate. Models could explain most of variability of the data in Veenkoloniën, a region with relatively little inter-farm variability and relatively stable economic prices. Model results were very sensitive for the selection of response variables. We found that food production, economic and environmental performance levels and gradual developments were primarily determined by intensity levels. How these levels are determined by intensity, i.e. positively or negatively, differed per case study. Year-to-year variability was determined by average yearly weather conditions and weather extremes. Overall, we conclude that results do only provide insights that confirm existing knowledge at case study level. sPLS can be seen as a filter and projector of high-dimensional data that accentuates patterns in the data. In the context of resilience of farms, while using a relatively small dataset, our methodology seems limited to a rather homogeneous farm population in a stable economic environment. Researchers intending to apply this method to (arable) farming systems should be well aware of the influence they can have on the results through their selection of response variables.

4.1 Introduction

In an increasingly variable climatic and socio-economic context, a sustainable and resilient performance of farming systems is challenging (Meuwissen et al., 2019). Sustainable performance is important regarding the provision of system functions in the long-term, while resilient performance is important to maintain function performance in the face of disturbances in the short-term (Tendall et al., 2015). Sustainability and resilience of a farming system is dependent on a balanced performance regarding social, economic and environmental functions (Walker and Salt 2012, Chapter 5). However, trade-offs between those functions are common in farming systems (Kanter et al., 2018; Klapwijk et al., 2014), thus destabilizing the base for sustainability and resilience. One can imagine that these trade-offs only become sharper when faced with disturbances that require an immediate response.

Resilience and sustainability of farming systems are complementary concepts that need to be studied simultaneously in integrated assessments (Meuwissen et al. 2019, Chapters 2 & 5). Many theoretical and qualitative studies have suggested attributes that increase resilience and sustainability (e.g. Cabell and Oelofse, 2012; Resilience Alliance, 2010). For example, diversity is often suggested to increase both. However, few studies have quantitatively studied resilience of farming systems (Dardonville et al., 2021), and even fewer address both sustainability *and* resilience indicators. Hence, assessing the performance in terms of both types of indicators, quantitatively, is the focus of this paper.

Existing agro-econometric methods often use production functions to assess resource allocation efficiency and thus assess sustainability. The general notion behind these methods is that increased agronomic and economic efficiency, and thus sustainability, of farming systems can be achieved by increased output efficiency of individual farms. Silva et al. (2021), for instance use a yield gap analyses based on an approach that combines concepts from econometrics and production-ecology (van Dijk et al., 2017; Van Ittersum and Rabbinge, 1997). Production functions require specific input regarding the shape of functions and are primarily developed for evaluating a single good, e.g. (food) production or economic output. Reidsma et al. (2009) include trans-log distance functions and, interestingly, consider multiple response variables simultaneously. Other, purely econometric methods are geared towards assessing the potential for increasing production or economic performance, such as the Just-Pope production function (Just and Pope, 1978) and damage abatement functions (Hall and Norgaard, 1973). These methods do not include environmental response variables, which makes these less useful for an integrated sustainability study. In addition, these methods usually employed datasets with a limited number of years.

As to resilience, a concept relating to the dynamics of the system, the element of time becomes more important, requiring longitudinal data. There are few studies on the quantitative analysis of resilience in general and in particular studies using longitudinal data are rare (Dardonville et al., 2021). In absence of longitudinal data, cross-sectional data may be used in which the performance or resilience of regions is evaluated relative to one another (e.g. Abson et al., 2013; Reidsma et al., 2007; Van Passel et al., 2017). Also model-based methods including future scenarios may be used (e.g. Herrera et al., 2022). Longitudinal data can be used in different ways to study resilience. Reidsma et al. (2009a, 2009b) studied yield variability in relation to weather conditions and farm characteristics. More recently, Sneessens et al. (2019) proposed a framework that includes multiple variables that also include resilience concepts such as the recovery time after a shock. In another recent study, Slijper et al. (2021) used longitudinal data to study the resilience capacities in terms of robustness, adaptability and transformability for agricultural regions in 11 European countries.

In a review on quantitative resilience studies, Dardonville et al. (2021) note that environmental indicators are hardly included as response variables. Martin et al. (2017) propose a framework that allows to explore covariation of multiple explanatory and response variables over time without the need to pre-define a production function. This provides opportunities to evaluate economic as well as environmental response variables for which no production function can be defined. The framework of Martin et al. (2017) has been applied to livestock systems (Bouttes et al., 2018; Martin et al., 2017), but to the best of our knowledge not to arable systems. In specialized livestock systems, intermediate activities, such as the growth of grass, are ultimately used to produce one or two outputs, e.g. milk (Bouttes et al., 2018) and/or meat. In arable farms, the cultivation of multiple crops are parallel activities with parallel outputs, i.e. the output is usually not concentrated in one or two outputs. As a consequence, variability of output at farm level may play out differently than at crop level (Mandryk et al., 2017).

In this paper we aim to study economic and environmental sustainability and resilience simultaneously and quantitatively. We apply and evaluate the framework of Martin et al. (2017) to arable systems for this purpose. We selected three different potato growing regions in the Netherlands as case studies. Employing the method we aim to identify resilience attributes at farm level, i.e. farm characteristics, that support sustainability and resilience regarding market and climatic conditions.

4.2 Methods

4.2.1 Case studies

In this study, three potato growing regions in the Netherlands are compared. Veenkoloniën (VK) is a region in the North-East of the Netherlands with sandy and peaty soils. In this region it is common to find a crop rotation with starch potato up to once in two years in combination with mainly sugar beet and cereals. Since about ten years, onion is increasingly cultivated in VK. Zeeland (ZE) in the South-West and Flevoland (FL) in the middle of the Netherlands on the contrary, have clayey soils with somewhat wider crop rotations including mainly ware potatoes, sugar beet, cereals and onions (once in three to five years is common). Common additions to crop rotations are carrots in ZE and carrots, vegetables and tulips in FL. Arable farming in VK is less profitable compared to ZE and FL and more prone to the impacts of weather variability and climate change (Diogo et al., 2017). However, due to the cooperative structure of starch potato cultivation and processing in the area, cultivated area and farm gate prices of starch potato are relatively stable compared to the ware potato prices in ZE and FL.

4.2.2 Data

We used farm accountancy data collected by Wageningen Economic Research (WEcR) for the Farm Accountancy Data Network (FADN; Poppe, 2004; Veen et al., 2014). This data is mainly collected to study economic and environmental performance at farm level, while economic data at crop level is also available. Because of privacy regulations, individual farm data cannot be presented in this study. The data in this study include time series for the period 2006 to 2019 of seven to 14 subsequent years of potato growing arable farms from the three case study regions. The final number of individual farms per region included in the analysis was 15 (FL), 19 (VK) and 17 (ZE). (See also Table A1.1 and A1.2 in SM4.1). Weather data was retrieved from the data platform Agri4Cast (JRC of the European Commission, 2021). Market data was retrieved from different online sources (Kadaster, 2021; OECD, 2021; WEcR, 2020).

4.2.3 Variable selection

Overview

The variable selection in this paper is guided by the resilience framework of Meuwissen et al. (2019) (Figure 4.1). Meuwissen et al. (2019) propose five steps to assess the resilience of farming systems: identification of 1) the farming system, 2) challenges, 3) functions, 4) resilience capacities and 5) resilience attributes. The farming systems are described in the case study section above (Step 1). Explanatory variables related to weather and market conditions represent challenges that are hypothesized to affect the response variables (Step 2). The response variables are related to functions of farms (Step 3), e.g. food production. Resilience capacities (e.g. adaptability) are deduced based on the outcomes of this study (Step 4). Explanatory variables related to farm characteristics, e.g. farm area and crop diversity, represent resilience attributes that possibly affect response variables directly, but possibly can also moderate the impact of challenges (Step 5; Figure 4.1). Variable selection and links to the framework of Meuwissen et al. (2019) are elaborated below. All variables and abbreviations of these variables are presented in Table A2.1 in SM4.2.

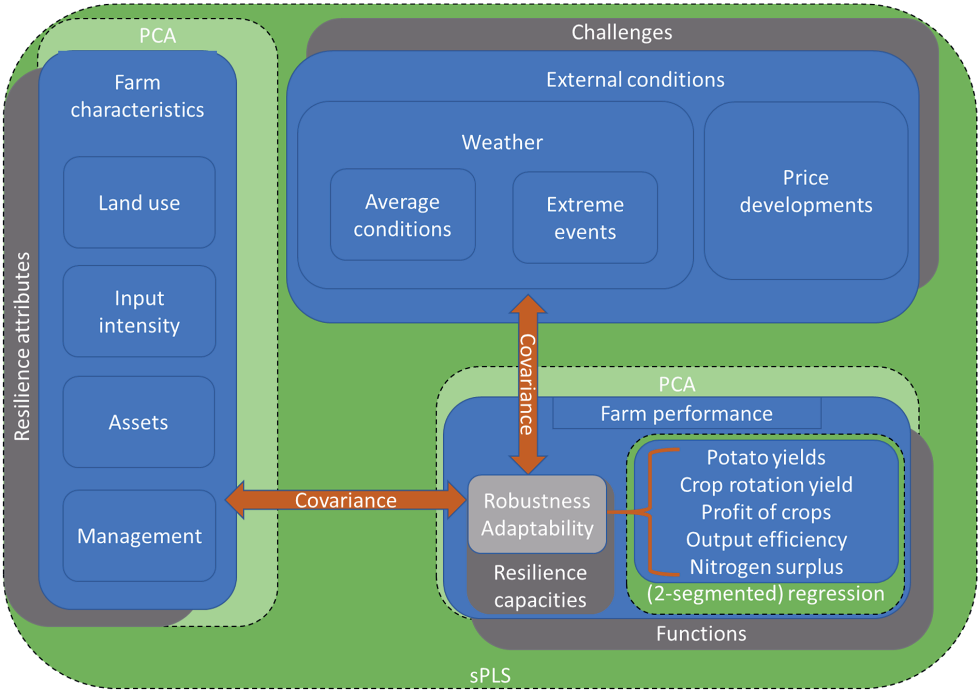

Figure 4.1. Overview of variables included in the analyses (blue blocks) and their link to the steps in the resilience framework of Meuwissen et al. (2019) (grey blocks). Green blocks indicate the different analyses that are performed on the data. Orange arrows indicate the type of patterns that are studied in the sPLS regression. PCA: Principle Component Analysis, sPLS: sparse Partial Least Squares.

Response variables characterising system functions

For an integrated analysis, we included response variables that cover production, economic and environmental functions at crop, crop rotation and farm level. For the production at crop level we used the average yield of potato (tons/hectare). For the production at crop rotation level we calculated the consumable energy produced (kJ/ha; Silva et al., 2017). Energy content per crop was based on Meul et al. (2007). Energy produced was only calculated for the main crops (potatoes, sugar beets, wheat, barley, onions), resulting in a value that was on average representing more than 85, 91 and 80% of the farm area in FL, ZE and VK. Average operating profit of crops (€/ha) is taken as economic indicator at crop rotation level. At farm level, all monetary output (revenues; excluding off-farm income) per monetary input (all fixed and variable costs) represents the output efficiency of the farm (€ output/€ input). Having an indicator that expresses efficiency may help to explore possible trade-offs between efficiency and variability that are hypothesized in resilience literature, i.e. more efficient systems are more vulnerable to disturbance (e.g. Cumming and Peterson, 2017; Hoekstra et al., 2018; Resilience Alliance, 2010). The nitrogen surplus at farm level is used as an environmental indicator. Nitrogen surplus contributes to expulsion of greenhouse gases, acidification of nearby nature areas and leaching or runoff of N leading to eutrophication of water bodies. N-surplus is calculated based on a nutrient balance at farm level that includes all nitrogen inputs, outputs and stock changes (Eurostat, 2013; Lamkowsky et al., 2021; Poppe, 2004).

Table 4.1. Overview of response variables.

Type of variable	Sub-category	Abbreviation	Unit
Response variables	Output efficiency	OutputEff	€ output / € input
		OutputEff_resi	€ output / € input
		OutputEff_slope	€ / € /year
	Potato yield	Potatoyield	ton / ha
		Potatoyield_resi	ton / ha
		Potatoyield_slope	ton / ha / year
	Crop rotation energy yield	Energyperha	kJ / ha
		Energyperha_resi	kJ / ha
		Energyperha_slope	kJ / ha / year
	Profit crops	ProfitCropsperha	€ / ha
		ProfitCropsperha_resi	€ / ha
		ProfitCropsperha_slope	€ / ha / year
	Nitrogen surplus	Nsurplus	kg / ha
		Nsurplus_resi	kg / ha
		Nsurplus_slope	kg / ha / year

High observed levels for potato yield, crop rotation energy yield, profit of crops, output efficiency and low observed levels for N-surplus were seen as positive for sustainability. Slopes and residuals of trendlines were used as additional variables that describe the resilience of farms (Figure 4.2; Bouttes et al. (2018) and Martin et al. (2017)). Positive slopes for potato yield, crop rotation energy yield, profit of crops and output efficiency, and negative slopes for nitrogen surplus were seen as signs of adaptation towards more sustainability. Small residuals were seen as indicative for farm stability and therefore positive for farm robustness. See also Table A2.1 in SM4.2 for the response variable abbreviations.

Trendlines were fitted using one and two segmented linear regression analyses allowing for an evaluation of structural change in the observed values over time (Zeileis et al., 2002; details in SM4.3). We argue that, besides the trends themselves, structural changes in trends leading to positive or negative developments can also be seen as indicators for the presence or absence of farm adaptability.

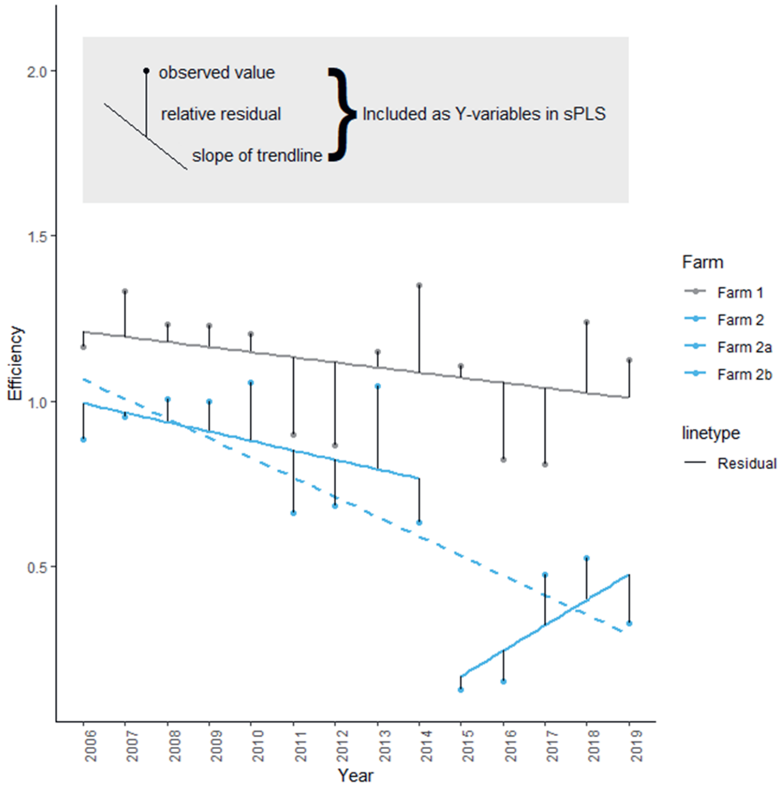

Figure 4.2. Fitted trend lines for two imaginary farms regarding a unitless efficiency indicator. For the farm with observed values in blue, a two-segmented trendline gives a significant better fit than a single trendline. Three types of Y-variables are eventually included in the analyses: the observed values, residuals and the slope of the trend lines.

Explanatory variables linking to resilience attributes

Explanatory variables related to farm characteristics are divided into the following sub-categories: land use, input intensity, assets and management (Table 4.2; Figure 4.1). These sub-categories can be linked to resilience attributes, which are system characteristics that convey general resilience to a farming system (Chapters 1 & 2). Land use indicators can be used as a proxy for crop diversity, for instance the share of cereals or potatoes in the rotation. Diversity is generally seen as buffer against perturbations and is also considered as a source of renewal after a perturbation (Cabell and Oelofse, 2012). In the case of crop diversity, we see specialization as the inverse of crop diversity, i.e. a large cultivation area dedicated to main crops. Regarding diversity we took the fraction of cereals, the fraction of the main crops (potato, sugar beet and cereals) and the effective number of crops (also known as true diversity index). The indicators under input intensity could be seen as proxies for the degree to which the system is coupled with local and natural capital. For instance, a low input of crop protection products may suggest a better coupling of farm practices with the environment. From a resilience perspective, high dependence on external inputs (e.g. mineral fertilizer) for a high and stable production in the face of environmental fluctuations (e.g. weather, pests & diseases), may imply a lower degree of autonomy (Cabell and Oelofse, 2012). Certain European crop-livestock systems, for instance, may not be robust enough to withstand a situation in which the import of mineral nitrogen fertilizers is halted (Pinsard et al., 2021). Asset indicators relate most to system reserves that can be used in difficult times. Modernity of machines and buildings (actual value/value when new) is linked to the availability of infrastructure for innovation. However, modernity of machines and buildings could also be related to the absence of adaptability and transformability due to sunk costs, i.e. money invested that cannot easily be re-invested (Westley et al., 2011). Management indicators, such as the number of full time equivalent (fte) managers per hectare, relate to the degree of experience and attention that is available for agricultural practices. This relates to the potential for learning from past experiences and building human capital, both being important for general resilience (Cabell and Oelofse, 2012).

Explanatory variables related to external influences are classified into the following sub-categories: market prices, average weather conditions and extreme weather events. Average market indicators per year include: oil price (€/ 100 literWEcR, 2020), fertilizer price (€/kg; NPK12:10:18; WEcR, 2020), land prices (€/ha; (Kadaster, 2021), interest rates (%; OECD, 2021) (Table A2.2 in SM4.2). Average weather conditions included in the analysis are average temperature (degree Celsius), average daily precipitation (mm/day) and average daily precipitation deficit (mm/day) for the whole year, spring (April-June) and summer (July-September)[1] (See SM4.2 for more details). Based on the average daily precipitation and temperature, extreme weather events for potato production were calculated using the AgroClimateCalendar (ACC; Schaap et al., 2011, 2013; Table A2.1 in SM4.2). Included weather extremes were wet (and warm) conditions, heatwaves, late frosts, warm winters and drought (Table A2.3 and A2.4 in SM4.2). Descriptions of the effect of weather extremes are described in Table A2.3 in SM4.2. Throughout the observation period, weather extremes were observed in all three case studies.

[1] To cover the whole growing season of potatoes from planting (April) till harvesting (September), we have deviated from the meteorological definition of spring (1 March – 31 May) and summer (1 June – 31 August)

Table 4.2. Overview of explanatory variables included in the analysis.

Sub-category (1st)	Sub-category (2nd)	Abbreviation	Unit
Farm characteristics	Land use	AreaCereals	ha
		AreaMainCrops	ha
		TrueDiversity	#
	Input intensity	Monetary input intensity[†]	€/cultivated ha
		Labour	AWU / cultivated ha
		Crop protection products (CPP)	€/ cultivated ha
		Nitrogen	€/ cultivated ha
		Phosphate	€/ cultivated ha
		Energy	€/ cultivated ha
		TotalCostsperha[‡]	€/ cultivated ha
	Management	FarmManagement	# fte managers / ha
		AgeFarmer	Years
		OtherRevenue	€/ cultivated ha
	Assets	Area	ha
		AreaOwned	owned ha / total ha
		OwnCapital	€ own / € total assets
		ModernityBuildings	# (0-100)
		ModernityMachines	# (0-100)
		Depreciation	€ / cultivated ha
Weather conditions	Average	Temperature_Spring	degree Celsius
		Precipitation_Spring	mm / day
		Temperature_Summer	degree Celsius
		Precipitation_Summer	mm / day
		Temperature	degree Celsius
		Precipitation	Mm / day
	Extremes*	ExtPrec45_1 (extreme precipitation in 1 day)	#
		ExtPrec60_3 (extreme precipitation in 3 days)	#
		HWave (heat waves)	#
		Frost	#
		WarmWinter	#
		WarmWet	#
		D_Spring (drought in spring)	#
		D_Summer (drought in summer)	#
		WetHumPlant (wet and humid at planting)	#
		WetHumGrow (wet and humid in growing phase)	#
		WetHumHarv (wet and humid at harvesting)	#
Market indicators[§]		OilPrice	€/ 100 L
		FertilizerPrice	€/ 100 kg
		LandPrice	€/ha
		Interest rate	%

*[†]Monetary input at farm level, i.e. all fixed and variable costs. [‡]Cultivation costs, i.e. variable costs for crop cultivation. *See Table A2.3 in SM4.2 for more information. [§]See Table A2.2 in SM4.2 for more information.*

4.2.4 Detecting the underlying data structure

Principal component analyses

To obtain insight in the underlying data structure, correlation plots were created for response and explanatory variables. In addition, principal component analyses (PCA) were performed, separately for the response and explanatory farm variables for each case study area. Strongly correlated response variables were removed from further analyses as they can distort the results. We illustrate this potential for distortion by presenting additional model runs with highly correlated response variables (for details see SM4.3).

sparse Partial Least Squares regression

We used sparse Partial Least Squares regression (sPLS) with year and farms as random effects to study the impact of explanatory variables on the response variables. In sPLS-regressions, explanatory variables (X-variables) are projected on latent variables in such a way that the projected variables can explain as much variation of the response variables (Y-variables) that are also projected on latent variables. Latent variables represent the most dominant patterns in the data. Leave-one-out cross-validations were conducted to determine the performance of the sPLS-model. Resulting Q2 -scores were used to determine the number of latent variables (components) in the sPLS-model. Q2-scores express the marginal contribution of components to increase the covariation between the original X- and Y-Variables. A component with a Q2-score larger than 0.095 is considered to have a significant contribution. (Lê Cao et al., 2008). We performed multiple sPLS analyses in which we varied the number of Y-Variables (2-5) and X-Variables (2-9) per component. The best model was selected based on the aggregated Q2-score over all components. We compared the correlation matrix of projected values of continuous explanatory variables and response variables of the sPLS-model with the correlation matrix of the original data (for details see SM4.3).

PCA and (s)PLS were performed with the software package "mixOmics" (Cao et al., 2017) in the software environment R (R Core Team, 2015). "mixOmics" does not facilitate the inclusion of interaction terms.

4.3 Results

4.3.1 Response variables

General observations

Observed levels of potato yield and profit of crops were highest in FL (Figure 4.3). The inter-farm variability of potato yields and profit of crops within ZE and FL were much higher than for VK (Figure 4.3). Observed levels of crop rotation energy yield and nitrogen surplus were lowest in ZE. On average, observed levels of output efficiency were lowest in VK (1.05 €/€) and ZE (1.02 €/€) and highest in FL (1.12 €/€) (Figure 4.3). In ZE and VK there were multiple outliers regarding N-surpluses of more than 200 kg/ha. In the context of earlier work (Silva et al., 2021b) these values were however not surprising.

The pattern of output efficiency levels from 2006 till 2012 was similar in ZE and FL, with relatively high levels in 2006, 2010 and 2012 (Figure 4.3). In VK, output efficiency was highest in 2012, which coincided with a high potato yield. Potato yield in all regions was relatively low in the dry year of 2018. Interestingly, output efficiency and profit of crops in FL were relatively high in 2018. Nitrogen surplus levels seemed stable in all case studies. Based on a visual inspection of Figure 4.3, there were no particular years in which nitrogen surplus was deviating substantially, except for 2018 in VK when it was high, probably because of low yields due to drought.

Structural change

Breaks in trends were mostly detected in VK for the output efficiency between 2011 and 2013 (15 farms) and crop profit in the years 2011 and 2012 (12 farms) (Table A4.1 in SM4.4). This corresponds with the increase in output efficiency and profit of crops until 2012 in VK that can be observed in Figure 4.3. In FL and ZE, breaks in trend were observed for a few farms, mostly in 2012, for potato yield (FL), crop rotation yield (FL, ZE), output efficiency (ZE) and nitrogen surplus (FL, ZE) (Table A4.1 in SM4.4).

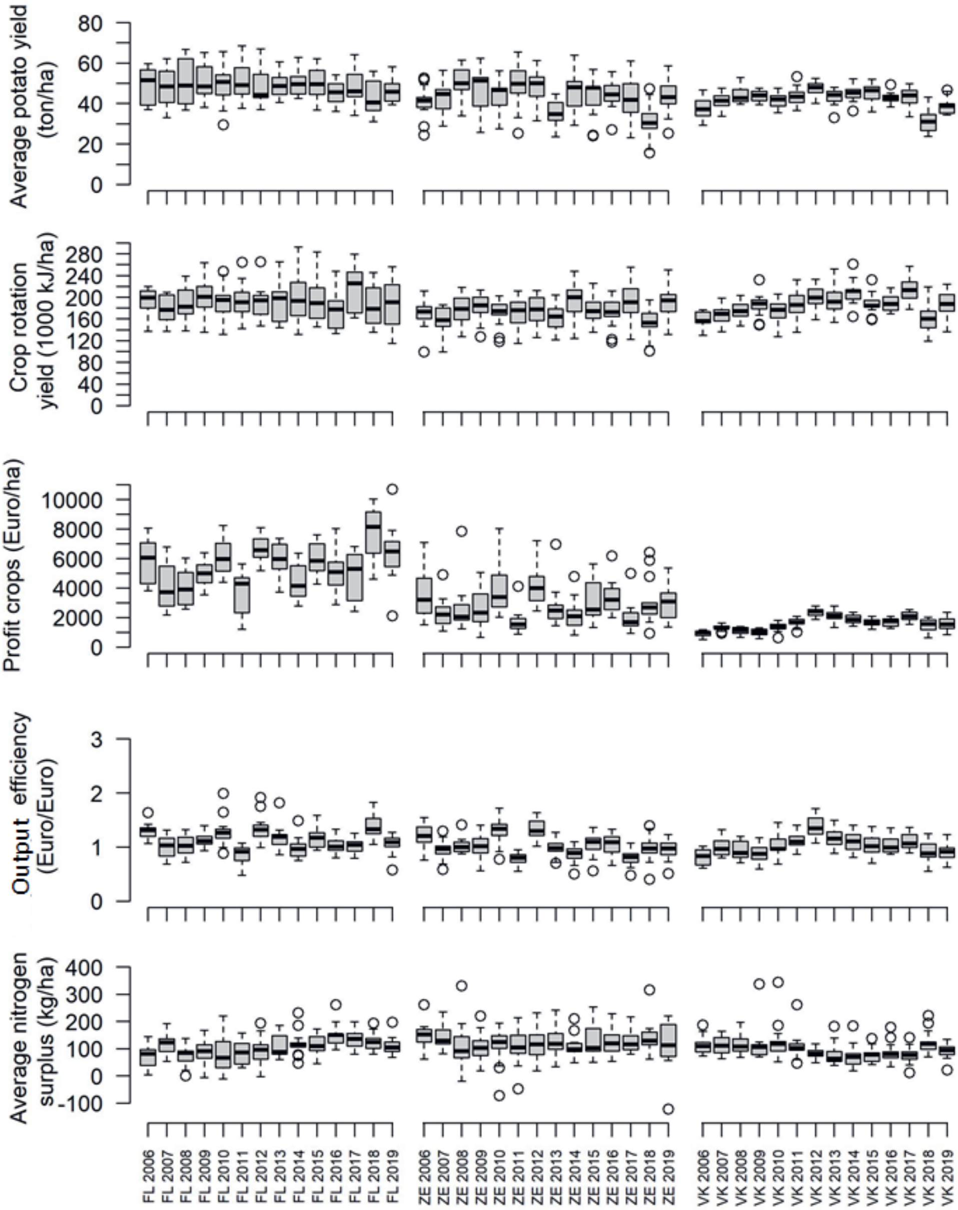

Figure 4.3. Observed levels of potato yields, crop rotation energy yield, profits from crops, output efficiency and nitrogen surplus for three regions (FL = Flevoland, ZE = Zeeland, VK = Veenkoloniën).

4

Yield, profit and output efficiency

Explained variance of the PCA on response variables (levels, residuals and slopes of potato yield, crop rotation yield, profit from crops, output efficiency and nitrogen surplus) per region was between 50-57% over the first three components. Important variables for the first component in all three regions (accounting for 19-29% of variation) were levels of potato yield and crop rotation yield, often accompanied with their residuals, indicating larger absolute variation at higher crop yield levels (Figure A5.1, A5.3, and A5.5 in SM4.5). In VK, profit of crops and output efficiency were positively associated with higher crop yields (Figure A5.5 in SM4.5). Potato is the largest crop in VK in terms of area and volume, partly explaining the positive relation with energy yield and profit. The positive relation between yield and profit could also be attributed to the local cooperative structure. With relatively inelastic prices for starch potato products, the cooperative benefits from larger volumes to be able to pay a good farm gate price to farmers (Herrera et al., 2022) as long as prices of processed products stay relatively inelastic. In FL, residuals of output efficiency and profit of crops and the slope of profit of crops were negatively associated with potato yield and crop rotation energy yield (Figure A5.1 in SM4.5). This suggests that farmers in FL somehow can benefit from relatively high prices when yields are relatively low. By contrast, in ZE, level of profit of crops and residuals of profit of crops and output efficiency (second component), had no or very little association with crop yield levels (Figure A5.3 in SM4.5).

Synergies and trade-offs with nitrogen surplus

In FL, the second component (17% of variation) was mostly correlated with observed levels and residuals of nitrogen surplus, associated negatively with residuals and level of profit of crops and residuals of output efficiency (Figure A5.1 in SM4.5). Overall, this suggested that years with (relatively) high nitrogen surplus coincided with (relatively) low profit of crops and low output efficiency, and vice versa. Farms associated with high levels of nitrogen surplus also showed declining profit of crops (3rd component; 14% of variation; Figure A5.2 in SM4.5).

On the first component of ZE and VK, higher crop yield levels and residuals were negatively associated with residuals of nitrogen surplus (Figure A5.3, A5.5 in SM4.5). Moreover, in ZE, on the third component (14% of variation), increasing potato yields were associated with farms that had low and decreasing nitrogen surpluses (Figure A5.4 in SM4.5). In VK, on the second component (18% of variation), decreasing nitrogen surplus was mostly correlated with increasing output efficiency, potato yield and energy production (Figure A5.5 in SM4.5). Residuals of nitrogen surplus were mostly negatively correlated with residuals of profits of crops and output efficiency (third component; 10% of variation; Figure A5.6 in SM4.5).

Pre-selection of response variables

Based on the high correlation found between response variables in the PCA and additional correlation analyses (SM4.5), we continued our analyses with crop rotation energy yield, profit of crops and nitrogen surplus (SM4.6). We performed additional analyses with all five response variables and with a different selection of three response variables (i.e. with output efficiency instead of profit of crops). These additional analyses were used to assess the impact of selecting different sets of response variables (SM4.7).

4.3.2 Explanatory variables

Farm characteristics

Explained variance of the PCA on explanatory farm variables per region was between 45-50% over the first three components (Figure A5.9-A5.14 in SM4.5). In the PCA's for the three regions, years appeared to be clustered, indicating that years explained part of the variation.

In all case studies, most of the variation (1st component; 22-27% of variation) could be related to many correlated indicators on input intensity in terms of fixed and variable costs (Figure A5.9, A5.11, A5.13 in SM4.5). Values of variables related to input intensity did increase over the years. In particular, cultivation costs increased (Table A2.1 in SM4.2). In FL and ZE, the second component was related to the area of main crops and area of cereals (Figure A5.9, A5.11 in SM4.5). Area of main crops and cereals seemed to have decreased in the observation period, suggesting decreased specialisation (Figure A5.9, A5.11, A5.13 in SM4.5; Figure 4.4). In FL more specialized farms were associated with less modern machinery, i.e. depreciated machinery (Figure A5.9 in SM4.5). In ZE, more specialized farms were associated with higher nitrogen inputs (Figure A5.11 in SM4.5). In FL and ZE, the third component was associated with larger farm sizes, lower shares of land owned, lower number of farm managers per hectare and lower labour input intensity (FL; Figure A5.10 in SM4.5) or modernity of buildings (ZE; Figure A5.12 in SM4.5).

In VK, the second largest part of the variation was captured by labour input intensity (second component; 12% of variation; Figure A5.13 in SM4.5). A third part of the variation could be explained by the number of full time equivalent managers per hectare and the age of the farmer (third component; 10%; Figure A5.14 in SM4.5). These indicators seemed unrelated with the indicators describing the degree of intensity.

Market indicators

Land prices increased from 2006 till 2008, after which prices stabilized at just above 50,000 €/ha until 2013. From 2013 onwards, land prices increased till over 70,000 €/ha in 2019. Interest rates went up from 3.8% in 2006 to 4.3% in 2007, after which interest rates steadily decreased to negative values in 2019. Interest rates often dropped more than 0.5% per year. Oil prices varied from 64 in 2006 to over 100 €/100 L in 2019 and fluctuated over time with a peak in 2013 and 2014. Fertilizer prices increased from 27.75 €/100 kg fertilizer in 2007 to 61.50 €/100 kg in 2009 after which they fluctuated between 41 and 47 €/100 kg. (Figure 4.5; Table A2.2 in SM4.2 for absolute values)

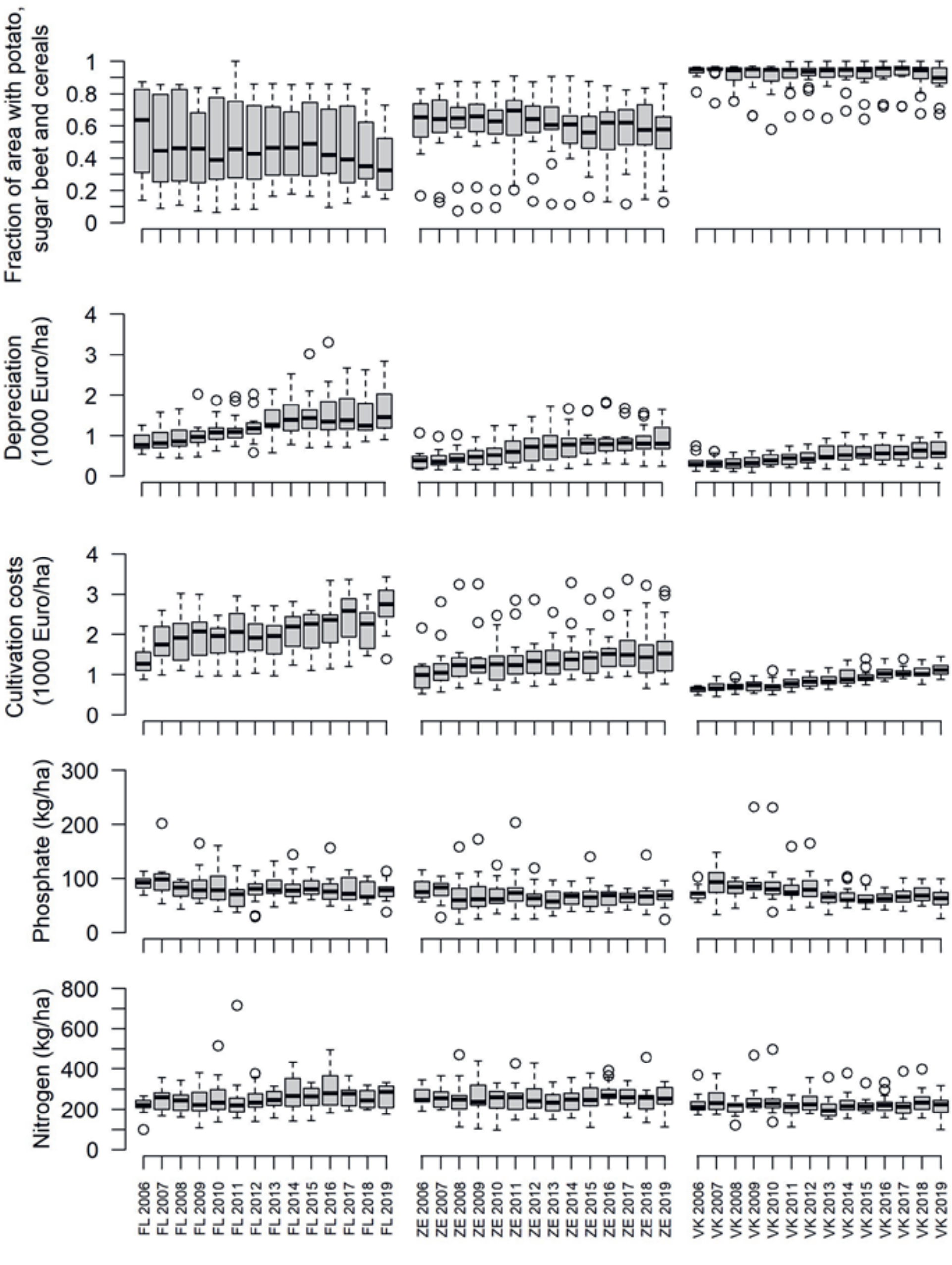

Figure 4.4. Observed levels of important farm characteristics (explanatory variables) for Flevoland, Zeeland and Veenkoloniën.

Figure 4.5. Development of relative values of market indicators over time. Absolute values can be found in Table A2.2 in SM4.2. Absolute values in 2006 were 44506 €/ha (land price), 3.8 % (interest rate), 64 €/100L (oil price), and 27.35 €/100 kg (fertilizer price).

Weather conditions

The three case studies were similar in terms of average temperatures per year and per season (spring, summer). With regard to the precipitation deficit, the three case studies had similar values for spring (1.5 +- 0.4-0.5 mm/day precipitation deficit; Figure 4.6), but for summer, FL had a lower average deficit (0.3 +- 1.0 mm/day) than VK (0.6 +- 0.9 mm/day) and ZE (0.8 +- 1.0 mm/day), which was probably related to the higher precipitation in FL (2.6 +- 0.8 mm/day) than in VK and ZE (both 2.3 +- 0.7 mm/day). No significant trends in temperature, precipitation and precipitation deficit could be detected over the measured period (2006-2019; Table A2.1 in SM4.2). Weather extremes occurred regularly (Table A2.4 in SM4.2).

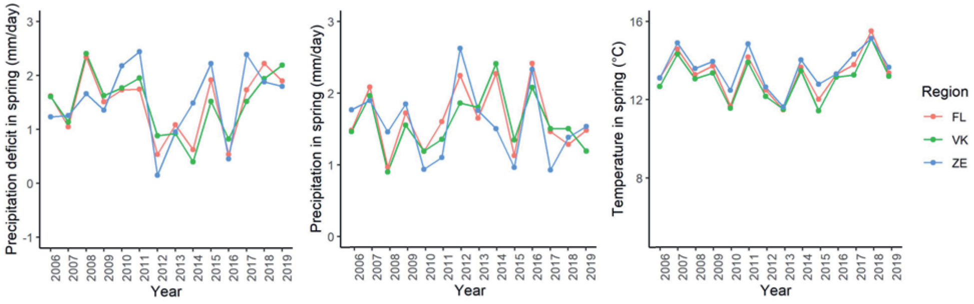

Figure 4.6. Precipitation deficit, precipitation and temperature in spring in the three case study areas.

4.3.3 Sparse Partial Least Squares regressions

Model performance

On average, across the three case studies, best performing sPLS models included the response variables related to profit of crops, nitrogen surplus and crop rotation energy yield. In all case studies, the predictive power of selected components was at most moderate. The variation in X-Variables explained by the X-components was low (Table 4.3). The explained variation in the Y-Variables was higher but still moderate. The best model in VK had three components with a varying number of response variables across components (Table 4.3). In ZE, sPLS-models performed better when including output efficiency instead of profit of crops (SM4.7). Because the interpretation of sPLS models including either profit of crops or output efficiency is almost identical, we proceed with sPLS models including profit of crops.

Table 4.3. Number of variables and performance per component of selected sPLS-models with the response variables crop rotation energy yield, nitrogen surplus and profit of crops. All X-variables included. Bold font indicates Q2-scores that are above the selection threshold of 0.095 (see section 4.2.4).

Region	Component	Q2-score	R2-score	Number of variables kept		Variation explained	
				X-space	Y-space	X-space	Y-space
FL	1	**0.113**	0.185	6	4	0.154	0.274
	2	**0.127**	0.133	9	2	0.078	0.210
VK	1	**0.227**	0.351	9	3	0.147	0.298
	2	**0.304**	0.234	9	2	0.096	0.299
	3	**0.170**	0.093	9	5	0.098	0.184
ZE	1	0.073	0.129	2	5	0.175	0.193
	2	0.064	0.186	4	2	0.081	0.164

Interpretation

In all case studies, there was one component associated with weather conditions that covaried with the residuals of nitrogen surplus (FL, VK), profit of crops (FL,ZE) and/or crop rotation energy yield (VK). In FL, nitrogen surplus was affected mostly by drought in spring, or wet conditions later on in the growing period, while profit of crops was positively affected by heatwaves, and generally high temperatures in summer (see 2nd component in Figure 4.7 and Figure 4.8; Table A6.3 in SM4.6). Interestingly, in contrast to droughts in spring, precipitation deficiency in spring seemed to somewhat improve profits and reduce nitrogen surplus. In ZE, profit of crops was affected negatively by high temperatures, specifically in spring, which was also related to precipitation deficit in that season (SM4.6). Interestingly, farms in ZE seem to benefit from warm winters. The availability of water (precipitation, absence of drought) was correlated to high crop rotation energy yields in VK.

In all case studies, the other component was associated with at least one indicator related to input intensity, the most important being monetary input intensity (all fixed + variables costs of a farm expressed per ha)(ZE, FL; Figure 4.7; SM4.6), total costs per hectare (ZE,VK), depreciation (FL) and labour (VK). These were negatively correlated with phosphate (VK) and nitrogen (VK, FL) and true diversity (FL). The high intensity in FL in combination with low nitrogen inputs and low diversity, resulted in high and increasing profits, low crop rotation energy yields and a declining nitrogen surplus (Figure 4.7 and Figure 4.8). For "expensive" crops, relatively little money is spent on nutrients. The high intensity in ZE was associated with declining profits from crops, low crop rotation energy yields, and to a lesser extent with low, but increasing nitrogen surpluses. In VK, profit of crops, crop rotation energy yield and to a lesser extent nitrogen surplus were positively linked with phosphate input and low intensity. However, for VK, additional indicators related to economic conditions were associated with lower profit of crops (oil prices, interest rates, land prices), while labour input, farm management and other revenues seemed to compensate for this to a small extent.

In VK, a third component was associated with input indicators of which nitrogen, energy and crop protection products were the most important. These were negatively associated with the share of cereals in the crop rotation. Higher levels of nitrogen and energy input were associated with higher crop energy rotation yield, higher, but over time decreasing, nitrogen surplus and higher and increasing profit of crops. Vice versa, a higher share of cereals in the rotation seemed to reduce nitrogen surpluses.

Interestingly, the strong positive correlation between nitrogen input and nitrogen surplus in the original data of all three case studies (Figure A6.18, A6.19, A6.20 in SM4.6), was only included in the final sPLS model in VK. In the sPLS-models with fifteen response variables, the correlation between nitrogen input and surplus was absent in all three case studies (Figure A7.1, A7.2, A7.3 in SM4.7).

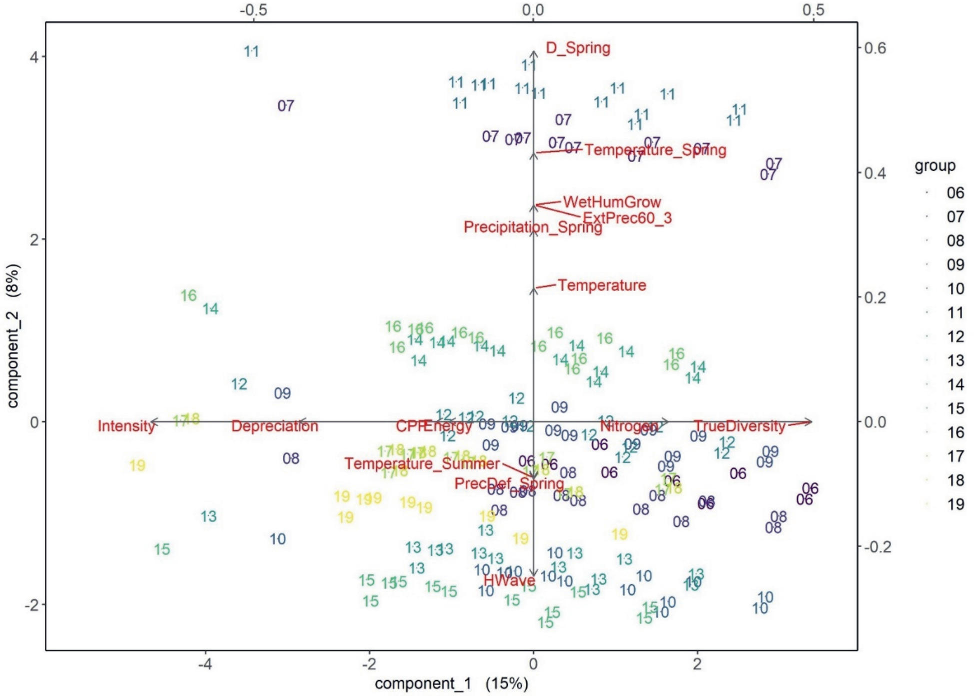

Figure 4.7. sPLS model results for the first and second X-component in Flevoland. Groups indicate the different years. The left and bottom axis indicate the position of observations in the projected X-space. The top and right axes indicate the correlation of explanatory variables with the first and second component.

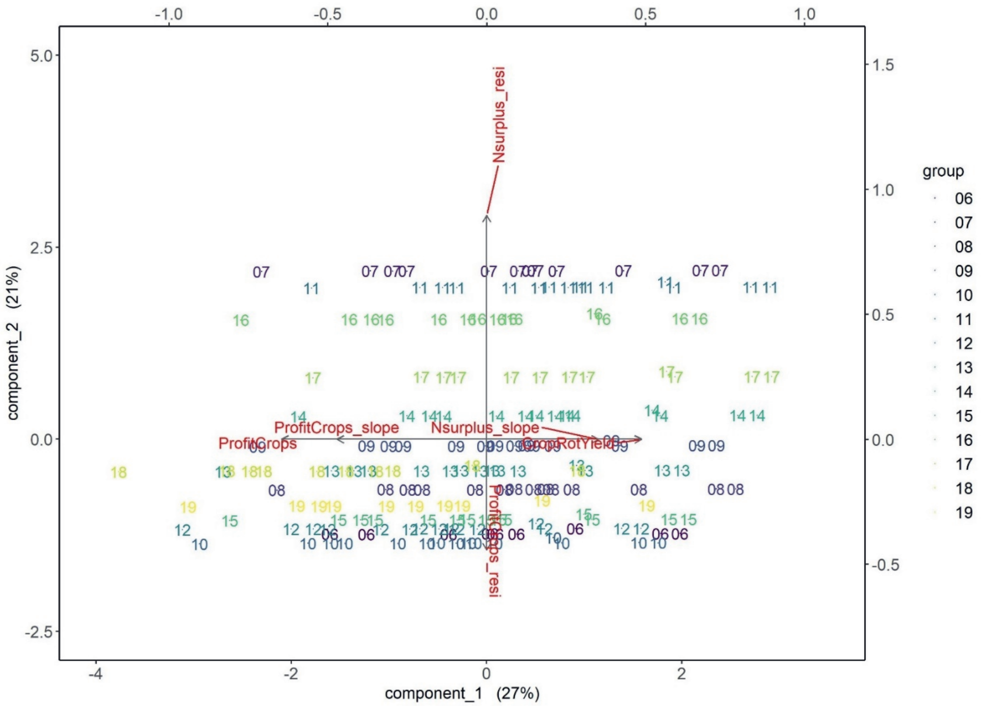

Figure 4.8. sPLS model results for the first and second Y-component in Flevoland. Groups indicate the different years. The left and bottom axis indicate the position of observations in the projected Y-space. The top and right axes indicate the correlation of response variables with the first and second component.

4.4 Discussion

4.4.1 Interpretation of results from a sustainability and resilience perspective

In this paper we aimed to study economic and environmental sustainability and resilience simultaneously and quantitatively. In particular, we aimed to identify resilience attributes at farm level, i.e. farm characteristics, that support sustainability and resilience regarding market and climatic conditions.

Intensity and farm performance levels and trends

Overall, intensity levels played out differently in the three case studies, thus limiting us in generalizing the role of intensity of crop management on economic and environmental farm performance. Higher intensity of farms in terms of euros spent was primarily associated with higher profits from crops in FL and ZE, indicating improved economic sustainability through intensification. In FL, the increased intensity and profit covaried with having additional crops next to the main crops potato, sugar beet and cereals, i.e. diversification. In ZE, this pattern of a relatively positive effect of crop diversity on profit was also visible in the original data, but not included in the final sPLS-model. In FL, a higher intensity level in terms of euros spent, including higher expenditure on crop protection products and energy, was associated with reduced nutrient inputs leading to a declining nitrogen surplus, indicating some gain in the environmental performance. By contrast, in ZE, intensity levels in terms of euros were positively associated with nitrogen input levels, but these were not related to any response variable on nitrogen surplus. In VK, intensity in terms of euros and in terms of nutrients applied were positively related, which positively affected energy yield, profit and nitrogen surplus. Only in VK, input intensity was linked to economic conditions, indicating that increasing production costs are potential direct drivers of intensification that lead to higher yields and profits. Increasing production costs are indeed identified as a major challenge and intensification as an important strategy in VK (Chapters 2 & 6, Herrera et al. 2022).

Weather conditions and variability of farm performance

Intensity levels explained levels of farm performance, but not the year-to-year variability (residuals). Instead, weather conditions seemed to explain the year-to-year variability of farm performance.

In FL, farms seemed to benefit from drought in summer. In 2018, when drought in summer was experienced throughout Europe, the clay soils with their high water holding capacity and the opportunity of irrigation may have reduced the impact of drought, while prices were relatively good in this year. In FL and ZE, relatively high temperatures in spring seemed to be associated with the downward fluctuations in profits of crops per ha. In our dataset for FL and ZE, high temperatures in spring coincided often with high yearly temperatures and precipitation deficits.

The results for ZE also suggested that warm winters were actually beneficial for farm economic productivity, rather than being a weather extreme that causes early sprouting of potatoes in storage (Schaap et al., 2013). A possible explanation could be that warm winters, if extended into spring, lead to early sowing of potato and subsequently can lead to higher yields (Mulders et al., 2021; Silva et al., 2020). Yet another explanation could lie in the specific dataset under study: warm winters occurred seven times from 2006 till 2019, while high temperatures in spring and warm winters coincided only twice (2014 en 2019) (Table A4.5 in SM4.4). The seemingly positive effect of warm winters could therefore be an artefact, i.e. the coincidental opposite of the observed negative effect of high temperatures in spring. Longer time series would reduce the possibility of having results that could be considered an artefact.

In VK, residuals of crop yield and nitrogen surplus were affected by weather extremes. This suggests that nitrogen supply to fields is adapted to average conditions, resulting in nitrogen surplus peaks during or after years in which extreme weather events occurred. With expected increases of heat waves and droughts towards the future, adjusting nitrogen applications to possible lower yields becomes even more important. This finding may also apply to the other two case studies where nitrogen application is also high and correlated with nitrogen surplus, at least in the original dataset (Figures A6.18, A6.19, A6.20 in SM4.6). Unfortunately we were not able to verify this based on the final sPLS-models (Figure A6.3, A6.6, A6.9 in SM4.6) that seemed to mask the correlation between nitrogen supply and surplus.

4.4.2 Methodology

General reflections

sPLS can be seen as a projector and filter of high-dimensional data that accentuates certain patterns in the data. However, some patterns may also be overlooked. A general example is the loss of details in sPLS, compared to the PCA analysis. A specific example is the correlation between nitrogen input and nitrogen surplus in the correlation maps of the original (Figure A6.18, A6.19, A6.20 in SM4.6) and projected (Figure A6.3, A6.6, A6.9 in SM4.6) data: the correlation in the original data structure has disappeared in the projected data. Also the level of detail as provided by the PCA-analyses is not reached. For our case studies, the models reproduced generally well-known knowledge and experience that could be embedded in an already existing narrative. Including more management specific indicators and following individual farms as was done before by Martin et al. (2017) could improve model performance and the interpretation of results, but a large part of the variability is likely to remain unexplained (see e.g. Bouttes et al., 2018; Martin et al., 2017). At best, this positions the used methods as being explorative (hypothesis forming).

The method simplifies reality by assuming linearity over time and linearity regarding response to explanatory variables. Regarding time, the threshold regression analysis has compensated somewhat for this (see also SM4.6). Regarding explanatory variables such as input intensity levels, it should be noted that these are known to have a non-linear impact on food production and economic productivity. However, due to large differences in input use efficiency among farmers, de facto a linear function may be approaching the data well enough. Interaction effects, for instance of farm characteristics on the impact of weather extremes, could not be studied well. In our case studies, the combination of sPLS (instead of

PLS) and random effects improved model performance considerably, but also resulted in a focus on the general impact, rather than a farm specific impact, of weather conditions on farm residuals. In Figure 4.7 and 4.8, for instance, farms seem to be impacted in the same extent by weather conditions ,i.e. farm characteristics don't seem to influence this. However, it should be noted that weather conditions only explain a small part of variability. Moreover, sPLS (artificially) reduces co-variation between the different model components, compared to PLS as, for instance, was used by Martin et al. (2017). Studying interaction terms in multi-variate ordination techniques, such as PLS and redundancy analyses, are notoriously difficult (ter Braak and Šmilauer, 2015). In ter Braak and Šmilauer (2015), a few coarse methods are provided for (visually) assessing interaction effects for data from controlled experiments. Further development of such methods is needed before they can be applied to the datasets used in our analysis, i.e. relatively small, multi-level datasets with continuous and discrete values from an uncontrolled real life context.

sPLS in a sustainability and resilience context

By putting response variables in the context of resilience, a general idea about system's resilience could be obtained. It should be noted that the resilience of an individual farming system should in the end be evaluated in a broader context. For example, lower dependence on externally sourced nitrogen input may be good for reducing the environmental foot print and increasing resilience through increased autonomy. Some reduction in nitrogen input in the Netherlands is not expected to necessarily lead to yield decrease (Silva et al., 2021b; van Grinsven et al., 2019). Thus, there seems little risk of externalising environmental pressure to other regions through a decrease in production.

In our analyses, sPLS performed lower in more diverse regions, i.e. in FL and ZE, where farms were more different from one another and where crop prices are more variable compared to VK. This could imply that, when using relatively small datasets, sPLS should be applied to systems with rather uniform farms in a relatively stable economic environment, in order to detect patterns in farm data that is known to usually contain a lot of noise. Interestingly, diversity, in particular in the form of farming system heterogeneity, is considered important in the context of building resilience (Cabell and Oelofse 2012, Chapters 2 & 3). Moreover, stable economic environments are uncommon for most contemporary, intensive farming systems as most are exposed to (fluctuating market prices of) global markets (Giller et al., 2021; Nyström et al., 2019; Therond et al., 2017). Considering the reflections above, datasets containing more farms over a longer time span are needed to increase the usefulness of our methodology. However, even with large datasets of farms, finding patterns and good explanatory power is not guaranteed (Silva et al., 2020).

Small residuals were seen as indicative for farm stability and therefore positive for farm resilience regarding robustness. Some argue that stability is not the same as robustness and that more specific indicators are needed (e.g. Sneessens et al. 2019, Slijper et al. 2020). Interesting in the work of Sneessens et al. (2019) is the use of absolute benchmarks, e.g. for minimum wage reflecting economic performance, while our study and for instance Bouttes et al. (2018) look at deviations from the mean or trend without referring to standards. Similarly, yield indicators could be benchmarked against potential yields and environmental indicators to existing environmental standards. Using standards could put results of our type of work more into perspective of (societal) desired sustainability levels.

Selection of models and response variables influences results

Although sPLS is largely data-driven, the study design has influenced the results. With regard to the selection of components, the acceptable level of the Q2-score is arbitrary (Cao et al., 2017). We therefore presented the R2-values as well. Some of the components included the maximum or minimum number of indicators per component as specified a priori, i.e. for the sake of interpretability, arbitrariness was included here as well. Additional analyses suggested that model performance was relatively robust regarding the inclusion of strongly correlated explanatory variables (Table A5.3 in SM4.5). In contrast, in the case studies in this paper, strong correlations among response variables lowered model performance (Table A5.1 in SM4.5). More specifically, the strong correlation between nitrogen input and nitrogen surplus in the original dataset was disfavoured over correlations of other explanatory variables with response variables related to yield and economic response variables. This "finding" can be seen as an illustration how an abundance of the relatively easy measurable indicators in the economic domain can mask patterns of generally less abundant and more difficult to measure environmental indicators. To avoid neglecting important environmental variables, overrepresentation of economic indicators should be discouraged.

4.5 Conclusions

Overall, our statistical analyses of farm accountancy data from three regions over a period of 14 years mostly confirmed already existing knowledge. Current levels of farm output and thus sustainability were mainly related to variables related to farm structure, in particular intensity-related indicators. Year-to-year variability of farm performance was mainly related to weather conditions and weather extremes. The usefulness of our method to test hypotheses on resilience attributes at farm level seems therefore limited, which may be at least partly due to the dataset.

The presented methods in this paper can be seen as a way to filter and project high-dimensional data and to accentuate patterns in the data. As such it is a useful way of getting to know the data. In the context of resilience of farms, while using a relatively small dataset, our methodology seems limited to a rather homogeneous farm population in a relatively stable economic environment. Larger datasets in terms of the number of farms and time span included should be used to increase the usefulness of our methodology. Researchers intending to apply this method in (arable) farming systems should be well aware of the influence they can have over the results through the selection of response variables. In particular regarding the relative abundance of economic indicators that could mask environmental indicators that are generally more difficult to measure and therefore less abundant.

Supplementary Materials

Supplementary materials 4: https://zenodo.org/record/6511120#.Ym-pC9pByUk

Assessing future sustainability and resilience of farming systems with a participatory method: a case study on extensive sheep farming in Huesca, Spain.

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Abstract

Finding pathways to more sustainability and resilience of farming systems requires the avoidance of exceeding critical thresholds and the timely identification of viable alternative system configurations. To serve this purpose, the objective of this paper is to present a participatory, integrated and indicator-based methodology that leads researchers and farming system actors in six steps to a multi-dimensional understanding of sustainability and resilience of farming systems in the future. The methodology includes an assessment of current performance (Step 1), identification of critical thresholds whose exceedance can lead to large and permanent system change (Step 2), impact assessment when critical thresholds are exceeded (Step 3), identification of desired alternative systems and their expected improved performance of sustainability and resilience (Step 4), identification of strategies to realize those alternative systems (Step 5), and an assessment on the compatibility of alternative systems with the developments of exogenous factors as projected in different future scenarios (Step 6). The method is applied in 11 European farming systems, and the application to extensive sheep production in Huesca, Spain, is presented here, as its problematic situation provides insights for other farming systems. Participants in the participatory workshop indicated that their farming system is very close to a decline or even a collapse. Approaching and exceeding critical thresholds in the social, economic and environmental domain are currently causing a vicious circle that includes low economic returns, low attractiveness of the farming system and abandonment of pasture lands. More sustainable and resilient alternative systems to counteract the current negative system dynamics were proposed by participants: a semi-intensive system primarily aimed at improving production and a high-tech extensive system primarily aimed at providing public goods. Both alternatives place a strong emphasis on the role of technology, but differ in their approach towards grazing, which is reflected in the different strategies that are foreseen to realize those alternatives. Although the high-tech extensive system seems most compatible with a future in which sustainable food production is very important, the semi-intensive system seems a less risky bet as it has on average the best compatibility with multiple future scenarios. Overall, the methodology can be regarded as relatively quick, interactive and interdisciplinary, providing ample information on critical thresholds, current system dynamics and future possibilities. As such, the method enables stakeholders to think and talk about the future of their system, paving the way for improved sustainability and resilience.

5.1 Introduction

Agriculture in the European Union (EU) is generally highly specialized and intensive (Andersen et al., 2007), resulting in an abundant food production, but also often leading to the degradation of natural resources (Tilman et al., 2002). In addition, labour productivity and farm income is low in many farming systems in the EU (DG-AGRI, 2017). From a social point of view, quality of life in rural areas in the EU is often perceived to be low as well, especially in the poorer countries (Eurofound, 2019; Shucksmith et al., 2009). To improve sustainability, a balanced attention for social, environmental and economic system dimensions is important (Kharrazi et al., 2019; Kinzig et al., 2006). Inadequate management of natural resources, for instance, can be seen as a failure to understand how social, economic and environmental dimensions are interrelated (Allison and Hobbs, 2004). Interrelation of these dimensions often results in feedback loops in a system, resulting in non-linear behaviour. This makes it challenging to assess and interpret the effect of shocks, stresses and management options on the provision of system functions. In response to this challenge, several resilience frameworks have been developed to study agricultural systems (e.g. Callo-Concha and Ewert, 2014; Meuwissen et al., 2019; Tendall et al., 2015). Sustainability and resilience can be seen as two complementary concepts (Marchese et al., 2018; Meuwissen et al., 2019). Resilience in the form of robustness, adaptability or transformability is needed to maintain or improve sustainability. At the same time, sustainability is needed to ensure the access, availability and quality of resources to buffer shocks and set in motion adaptation or transformation.

For the context of a farming system (FS), Meuwissen et al. (2019) define resilience as the ability to ensure the provision of the system functions in the face of increasingly complex and accumulating shocks and stresses. By emphasizing the importance of system functions, Meuwissen et al. (2019), provide a practical way to combine the concepts of resilience and sustainability in a complementary way. To better understand the potential dynamics of farming systems, current as well as future sustainability and resilience need to be studied. Current resilience of European farming systems was for instance studied by Nera et al. (2020), Meuwissen et al. (2021) and in Chapters 2 & 3. Towards the future, system behaviour may differ according to the development of factors that are exogenous to the farming system (such as population growth and economic development), especially when shocks and stresses increase or when enabling conditions for changes are realized. Trespassing critical thresholds could for instance initiate cascading effects leading to a system decline (Kinzig et al., 2006). To avoid this, institutional actors may deliberately aim at changing threshold levels to enable innovation that provides an alternative to the dominant ways of producing (Westley et al., 2011).

Quantitative models are often used to assess, ex-ante, system performance and behaviour. Different types of studies and associated models can be distinguished (Van Ittersum et al., 1998). Based on statistical models, projections or predictions can be made about the average and probable performance for future conditions (e.g. Van Passel et al. 2017). However, because statistical models depend on (data) patterns from the past, only a limited range of all possible futures will be captured. Including a broader range of possible futures (scenarios) increases the opportunity to evaluate farming system resilience under different exogenous conditions that are all possible to happen. Incompatibility of farming systems with certain futures can be seen as a sign of non-resilience in case those systems have no capacity to adapt or transform. In itself, comparing farming systems with a broad range of futures directly contributes to foresight information supporting the capacity to anticipate shocks, which is seen as important for resilience (Mathijs and Wauters, 2020). In so-called explorations, optimization models (e.g. Rabbinge and van Diepen 2000, Ten Berge et al. 2000, Reidsma et al. 2015) and system dynamics models (Herrera, 2017b) can consider multiple possible futures, using scenarios capturing uncertainty on climate change and socio-economic developments. However, these models need parameters which are sometimes also derived from statistical models based on past and current trends. Moreover, optimization models are of limited use for modelling dynamic transformations, as they are generally static.

Participatory methods can take into account multiple scenarios (Delmotte et al., 2013; Walker et al., 2002) and allow for input regarding transformational change (Quist and Vergragt, 2006) and resilience concepts such as critical and interacting thresholds (Resilience Alliance, 2010; Walker et al., 2002). It should be noted, however, that qualitative methods also are influenced by input from statistical sources and experts that extrapolate past trends into the future. We argue that quantitative and qualitative approaches can be complementary. Participatory methods can be quick, interactive and flexible to start discussions about sustainability and resilience in the future, thus laying a base for further discussions and quantitative model-based analyses (Chapter 2). Participatory methods allow for taking into account the voice of individual stakeholders as well as support stakeholder discussions to arrive at a common understanding and a shared vision for improvement of the system or problem under study. Stakeholder participation is important as stakeholders are usually involved in follow-up processes and thus need to agree with the problem definition and proposed action plan (Quist and Vergragt, 2006). Participatory input is valuable because system actors are able to provide empirical knowledge about their system (Delmotte et al., 2013) that reduce knowledge gaps of researchers (Sieber et al., 2018; Vaidya and Mayer, 2014). Vice versa, participatory methods are also important to identify the boundaries of local knowledge (Mosse, 1994). Stakeholder’s perceptions are particularly precious, as they can explain or drive system dynamics as stakeholders are important components of socio-ecological systems (Walker et al., 2002). Hence, participatory methods can provide a first exploration of farming system structure, mechanisms, performance and behaviour in possible futures.

Discussions with stakeholders about future change can be challenging because stakeholder’s mental models usually focus on maintaining the status quo with little imagination of alternative futures (Meuwissen et al., 2020). Other limitations for discussing farming system transformations may relate to the focus of experts on improving efficiency, vested interests, co-dependencies among system actors and institutional path dependence (Meuwissen et al., 2020). Participatory methods should therefore provide opportunities to go beyond the usual extent of stakeholder’s mental models. Alternative systems, that avoid critical thresholds and increase sustainability and resilience simultaneously, should be explored, and new strategies to realize those alternative systems identified. To ensure the soundness of intended pathways towards the future, alternative systems need to be compatible with possible future developments of exogenous factors as projected in different future scenarios. High compatibility of desired alternative systems with future scenarios increases the likelihood that those more sustainable and resilient systems will be realized. Consequently, this also decreases the likelihood that critical thresholds will be exceeded, resulting in farming systems with even lower sustainability and resilience levels.

We argue that a quick and flexible assessment of future resilience and sustainability of farming systems is still lacking in literature. In response to this research gap, this paper presents a participatory, integrated and indicator-based method to improve understanding of farming system sustainability and resilience. The method uses the concepts of critical and interacting thresholds to challenge stakeholders in a workshop setting to think about potential non-linear and undesired behaviour of their farming system. Following, stakeholders are elicited on desired alternative systems that avoid critical thresholds and thus improve sustainability and resilience (and vice versa). The method is flexible regarding: a. the information sources used as input for the workshop, b. the possibility to include case specific indicators and c. the stakeholder input during the workshop, i.e. alternation of individual input, small group discussions and plenary discussions. We illustrate the usefulness of the approach with an application to the extensive sheep farming system in Huesca, Spain. In this farming system, ongoing, interrelated economic, social as well as environmental developments are increasingly reducing the system’s sustainability and resilience.

5.2 Methodology

5.2.1 FoPIA-SURE-Farm 2

The proposed methodology presented in this paper extends the Framework of Participatory Impact Assessment for Sustainable and Resilient European farming systems (FoPIA-SURE-Farm 1) approach for assessing sustainability and resilience of current systems (Chapters 2 & 3; Nera et al. 2020) with participatory assessments on resilience of European farming systems in the future (FoPIA-SURE-Farm 2). FoPIA-SURE-Farm 1 and 2 are based on the SURE-Farm resilience framework (RF; Meuwissen et al., 2019): 1) defining and delineating the farming system, 2) identifying main challenges, 3) assessing farming system functions, 4) assessing the system's resilience capacities (robustness, adaptability and transformability), and 5) assessing the system's resilience enhancing attributes (system characteristics that convey resilience to a system). While FoPIA-SURE-Farm 1 was mainly aimed at performance levels of main indicators, that represent main functions of the system, and resilience attributes, FoPIA-SURE-Farm 2 includes resilience concepts such as critical thresholds, interactions between thresholds (e.g. Kinzig et al., 2006), and regime shifts (e.g. Biggs et al., 2018).

In this paper we define the basis of a farming system as the farms producing the main products of interest in a regional context. Farming system actors included in the farming systems are the producers of main products and other actors that mutually influence one another (Step 1 RF). The perceived complementarity of sustainability and resilience is operationalized by distinguishing system challenges, function indicators and resilience attributes. In the context of resilience, challenges relate to the question "resilience to what?", such as resilience to weather extremes (Step 2 RF). Function indicators are case-study specific representatives for important system functions, such as "Food production" or "Maintaining natural resources", as direct metrics for those functions are often not available (Step 3 RF; Table A1 in SM5.1). In the context of resilience, function indicators relate to the question "resilience for what?". This relates to sustainability, which is defined as an adequate performance of all system functions across the environmental, economic and social domain (Chapter 2, Morris et al. 2011, König et al. 2013). Resilience attributes are characteristics that convey general resilience to a system (Step 5 RF; Table A2 in SM5.1). These resilience attributes can often be linked to system resources (Chapter 2), e.g. natural or social capital, that can only be maintained when system functions are performing adequately. To improve the flexibility of the methodology and the clarity and saliency of participatory input, just like for functions, case-study specific indicators may be used for resilience attributes, as well as for challenges. Based on workshop results, inductions are made about the resilience capacities of the studied farming system (Step 4 RF). For more details on the concepts used in this study, see Table A1.1 in the Appendix of Chapter 1.

FoPIA-SURE-Farm 2 consists of a preparation phase, a participatory workshop and an evaluation phase, and was developed for application and comparison across 11 European farming systems (Paas and Reidsma, 2020) (Figure 5.1). In this paper we present six key steps of the methodology (Figure 5.1). In Step 1, current performance and trends of function indicators and resilience attributes are assessed by the research team in the preparation phase. This assessment can be largely based on FoPIA-SURE-Farm 1 (Chapter 2), but other (grey) literature can also be used. In Step 2, critical thresholds of important system challenges, function indicators and resilience attributes are assessed by workshop participants. Based on Biggs et al. (2018) and Kinzig et al. (2006), we define critical thresholds as the levels at which challenges, function indicators or resilience attributes are expected to cause large and permanent system change. System's closeness to thresholds is consequently evaluated by the research team based on participants' comments and (grey) literature, e.g. based on ongoing trends identified in Step 1. In Step 3, performance of main function indicators and resilience attributes is assessed when critical thresholds of main challenges would be exceeded. Possibilities of interacting thresholds can be discussed during the workshop and in the evaluation phase, following the framework of Kinzig et al. (2006). Interacting thresholds are thresholds, that, when exceeded, lead to the exceedance of another threshold, i.e. there are cascading effects. In summary, Step 1, 2 and 3 provide an overview of possible system performance in case no adaptations for improved sustainability and resilience are made.

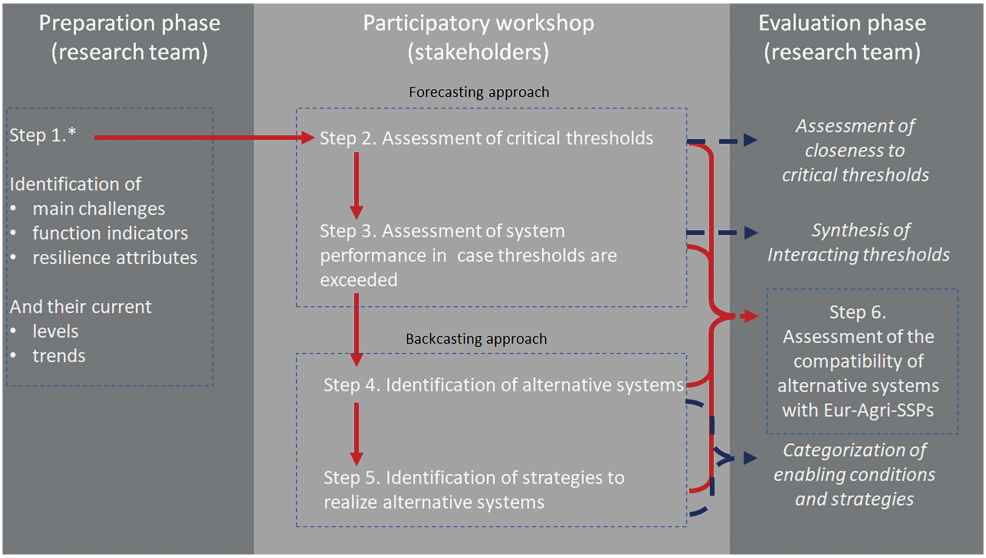

*Figure 5.1. Workflow of FoPIA-SURE-Farm 2 during the preparation phase, participatory workshop and evaluation phase. Parentheses at the top of each block indicate who does the action. Dashed arrows and italic font indicate the respective parts of Step 2-5 that are conducted in the evaluation phase. *Step 1 can be based on outcomes from FoPIA-SURE-Farm 1 (Chapter 2) and/or other sources of information.*

Keeping the sustainability and resilience of the current system and the impact of exceeding critical thresholds as a point of reference, Step 4 addresses possible desired changes of the farming system towards the future. Participants can indicate and discuss what alternative systems are possible when challenges would become more severe, and when/how certain function indicators and resilience attributes would improve compared to the current system configuration. Step 5 aims to gain information on the strategies that are needed to realize alternative systems. We indicate these strategies as "future strategies". Steps 2 to 5 correspond largely to the participatory workshop phase. In the workshop, individual, break-out and plenary sessions are alternated. Individual and break-out sessions are included to ensure that all participants can provide input, which can be used as input for further discussions in plenary sessions. The proposed session format in each step can be changed according to needs of the participants, as long as a balance between individual, break-out and plenary sessions is maintained. In Step 6, in the evaluation phase, researchers evaluate whether desired future systems, i.e. the current system maintained in the future and the alternative systems, are compatible with developments in Shared Social Pathways for European agriculture (Eur-agri-SSPs; Mitter et al. 2019, Mitter et al. 2020) and hence match exogenous developments at European level. The time horizon for the future is 2030 in all steps. In the next sections we present details of each of the six steps.

5.2.2 Current performance (Step 1) and critical thresholds (Step 2)

A pre-selection is made of most important system function indicators and resilience attributes, their qualitative description of performance (very low, low, moderate, good, very good performance) and developments (no change, strong or moderate negative or positive change) (Step 1). Step 1 can be based on FoPIA-SURE-Farm and/or other information sources. Participants individually evaluate the existence of critical thresholds related to function indicators, resilience attributes and challenges (Step 2). Walker and Salt (2012) mention that it is impossible to determine critical thresholds for resilience attributes because they all interact. However, we include resilience attributes as it stimulates thinking about resilience. Moreover, participatory input on thresholds can be interpreted as formulations of potential concerns for which management goals and strategies may be developed (Walker and Salt, 2012). In plenary sessions, individual input is discussed. Participants are free to discuss and conclude on the relative closeness of their system to critical thresholds. In case closeness of the system to critical thresholds is not indicated by participants, the research team evaluates closeness based on the current performance levels, and magnitude of variation and/or trends. "Not close", "somewhat close" and "close" to thresholds are defined as respectively unlikely, somewhat likely and likely that the distance to critical thresholds will be trespassed in the coming ten years, based on knowledge on possible variation and/or trends. A fourth category is identified as current levels being already at or beyond the critical threshold ("at threshold or beyond").

5.2.3 What if thresholds of challenges are exceeded? (Step 3)

Per identified main challenge, it is evaluated in a participatory forecasting approach what the effect of a change beyond the indicated thresholds would be on main indicators and resilience attributes (Step 3). For this, the group is split in small groups of participants, each discussing one challenge. First, the expected direction of change of the challenge is clarified. Secondly, the relation between challenge and function indicator or resilience attribute is discussed. In each group, a moderator synthesizes this with a score of --, -, +-, + and ++ alongside arrows from challenges to function indicators and resilience attributes (Figure 5.2). A + relation implies that if the level of the challenge increases, the function indicator or resilience attribute also increases (i.e., a decrease in the level of the challenge also leads to a decrease in the function indicator or resilience attribute). Verifications are also made in relation to possible interactions among and between function indicators and resilience attributes. Optionally, the expected impact on the function indicator or resilience attribute is indicated. This impact is scored referring to the expected performance level from 1-5, similar to FoPIA-SURE-Farm 1 (Reidsma et al., 2019a). In a plenary session, each moderator feeds back the results of the small group in a 1-minute pitch, after which participants can respond.

Based on the outcome of questions on critical thresholds and forecasting the impacts of exceeding them, the possibility of interacting critical thresholds is evaluated by researchers in the evaluation phase using the framework of Kinzig et al. (2006). Kinzig et al. (2006) specifically assess critical thresholds and cascading effects across 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). A good balance between developments in the different domains and levels may improve sustainability and resilience of a system (Walker and Salt, 2012). In systems with strong interactions between system variables at lower levels, vulnerability of the system at the focal level may increase (Resilience Alliance, 2010). This is especially the case when variables at lower levels are all aligned with regard to their closeness to critical thresholds (Resilience Alliance, 2010). An (almost) simultaneous exceedance of critical thresholds at lower levels may result in further cascading effects and ultimately result in an alternative, undesired system state at focal level, which in this study is the farming system. In the context of this paper we distinguish the environmental, economic and social domains and the field, farm and farming system levels.

5.2.4 Desired transformations of the farming system (Step 4)

In a forecasting approach for improved sustainability, results are largely based on dominant trends and causal mechanisms that often lead to low sustainability. Solutions for improved sustainability, therefore, ideally need to break these trends and causal mechanisms (Dreborg, 1996; Quist and Vergragt, 2006). In this part of the workshop, we therefore shift from a forecasting approach to a backcasting approach. A backcasting approach has greater problem-solving capacities in long-term challenges, because it is concerned less with what is likely to happen and more with what is desirable in the future (Quist and Vergragt, 2006). Picturing future systems may stimulate system actors to widen their perspectives and improve their understanding of the concept of sustainability (Dreborg, 1996). In this study, the backcasting approach is focused on alternative farming systems that have improved performance of function indicators and resilience attributes (Step 4).

To identify these alternative systems, all participants are asked to write on post-its alternative systems they desire if challenges cross thresholds and/or functions need improvement. This ensures that stakeholders can give their own input and are not directly influenced by others. If input is low, thinking can be stimulated among participants by presenting alternative systems that are identified by the research team in the preparation phase. Based on the post-its, several alternative future systems are identified in a plenary session. These alternative systems may be combinations of suggestions of different participants. Some may be adaptations and some transformations of the current system. After giving them a name, per alternative system, one small group of participants is formed to further discuss which main function indicators and resilience attributes will change. In addition, changes in land use, sectors, objectives and other relevant aspects may be discussed. Participants in small groups also discuss the enabling conditions, i.e. how challenges and other drivers should change in order to be able to reach these alternative systems. Small groups consist of at least one moderator from the research team and three participants. In the evaluation phase, enabling conditions are categorized by researchers under the following domains: agronomic, economic, environmental, institutional, social.

5.2.5 Strategies to realize desired transformations (Step 5)

Taking alternative systems as the points of reference, the backcasting approach is continued by identifying strategies to realize the alternative systems, in the small groups. A strategy is seen and communicated to workshop participants as a "plan of action, or part of it, implemented by actors within and outside the farming system to maintain or reach a desired farming system in 2030". The workshops ends with a plenary session, in which participants are asked whether there is a shared vision about the future farming system. If such a shared vision is present, the discussion on the strategies to select is tailored towards this vision. If not, all possible alternatives and strategies are kept in mind. These strategies for future systems are compared with the strategies that have been implemented in the past and current system, as derived from FoPIA-SURE-Farm 1, to understand what should change.

5.2.6 Compatibility of future systems with Eur-Agri-SSPs (Step 6)

In the evaluation phase, carried out by researchers, the level of functions, resilience attributes, required strategies and enabling conditions in the different future systems are compared with future scenarios (Step 6). Future systems include the continuation of the current system in the future as well as the proposed desired alternative systems. As future scenarios we use the storylines of the Shared Socio-Economic Pathways adapted for European agriculture (Eur-Agri-SSPs; Mitter et al., 2019, 2020). The five Eur-Agri-SSPs include: agriculture on sustainable paths (1), on established paths (2), on separated paths (3), on unequal paths (4) and on high-tech paths (5). Mitter et al. (2019; 2020) take into account multiple indicators (Eur-Agri-SSP-indicators) that are categorized under the themes "Population", "Economy", "Policies & institutions", "Technology" and "Environment & natural resources". Per Eur-Agri-SSP-indicator researchers indicated how important an increase of this indicator is for the alternative system, where 0 is "not important", 1 is "somewhat important" and 2 is "very important". Expected developments of SSP-indicators are taken from Mitter et al. (2020), where ↘,→ and ↗ were translated into the values -1, 0 and +1, indicating negative, no and positive changes, respectively. Multiplication of importance of positive developments for future systems {0; 1; 2} with expected developments of Eur-Agri-SSP-indicators {-1; 0; 1} is used as an approximation for compatibility. If, for instance, natural resources need to improve in a certain alternative system, this is aligned with the improvements foreseen for the Eur-Agri-SSP-indicator "natural resource management" in the sustainable paths scenario. This makes the alternative system and this scenario compatible, at least for this specific Eur-Agri-SSP-indicator. In a next step, compatibility scores are aggregated and transformed (sum of the compatibility scores divided by the sum of the importance scores) per theme (Population, Economy, etc.). Final compatibility scores per future system per Eur-Agri-SSP are an average of the overall section scores per theme, where values -1 to -0.66 imply 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.

5.3 Application to extensive sheep farming in Huesca, Spain

5.3.1 Case study description

The case study is the extensive sheep farming system located in the Huesca province, Northeast Spain. Huesca covers about 15,000 km^2 and two main regions can be distinguished: 1) The Pyrenees and pre-Pyrenees in the North, covering about 6,000 km^2, where agricultural activities are confined to extensive livestock; and 2) the southern part of the province, characterised by the plains of the Ebro depression (about 9,000 km^2), where extensive farming (sheep, goat and cattle), intensive farming (pigs and broiler) and crop farming (rainfed and irrigated) are present.

In Huesca, the number of (ovine and caprine) decreased from 2,902 (1995) to 1,018 (2019) and the number of sheep from 923,399 (2005) to 521,501 (2019) (Gobierno de Aragón, 2019, 2016; MAPA, 2019a). The size of farms has shown an upward trend in the last years. The current size of a herd is between 200 - 1,000 sheep (Gobierno de Aragón, 2019). These trends are a result of the convergence of a range of economic, institutional, social and environmental challenges the farming system is facing. The extensive sheep farming system is highly dependent on EU and national subsidies, and hence, vulnerable to changing agricultural policy goals and increasing bureaucracy and control requirements. Regarding the social challenges, the case study area suffered a vast population decline over the last century (Bosque and Navarro, 2002) that comes along with a lack of skilled labour, social services and infrastructures. The low attractiveness of the farming system and the agricultural specialization result in the lack of new entrants. Finally, the extensive sheep farming system is increasingly limited in the access to pastures. The strategies that farmers have been implementing over time to deal with these challenges follow four management patterns, i.e. intensification, extensification, diversification and conservation (Bertolozzi-Caredio et al., 2021)

In addition to the provision of private goods, such as to ensure sufficient farm incomes and deliver high-quality food at affordable prices the extensive farming system also provides public goods. Grazing helps to maintain and preserve the natural resources contributing to keep soil quality (Peco et al., 2017) and biodiversity by maintaining landscape heterogeneity (Ornai et al., 2020; Rodríguez-Ortega et al., 2014; Silva et al., 2019). Extensive livestock activity is also important to prevent forest fires by keeping the area clean from dry biomass (weeds and scrubs), which act as fuel in Mediterranean areas (Casasús et al., 2007; Ruiz-Mirazo and Robles, 2012). Grazing activities also provide recreational areas demanded by society (Bernués and Olaizola, 2012) and keep the rural areas attractive. As a result of the challenges mentioned in the previous paragraph, levels of functions in the farming system are generally perceived to be low (Chapter 3, Becking et al. 2019).

The clear presence of interacting economic, social and environmental domains makes the extensive sheep farming system in Huesca, an interesting case study for studying sustainability and resilience. In addition, there are signs of low sustainability, low resilience and consequently a pending decline of the farming system (Becking et al., 2019). The FoPIA-SURE-Farm 2 workshop was conducted on 14 February 2020 from 9.00 am till 3.00 pm with one break in the middle and lunch at the end. Eighteen people participated in the workshop, of which seven were farmers (five of the seven farmers belonged to an association). The rest of participants belonged to the agri-food value chain (veterinaries (3), cooperatives (1) and distributors (1)), and public sector (research institutes and Universities (3), and local public administration (4)).

5.3.2 Current sustainability and resilience performance (Step 1)

Participants agreed with FoPIA-SURE-Farm 1 results (Becking et al., 2019) on current performance of main indicators related to the functions of ensuring economic viability, food production and quality of life: gross margin, number of sheep and number of farms, respectively (Step 1). Two main resilience attributes discussed in the workshop were 'production coupled with local and natural capital' and 'diverse policies' (see also Tables B1 and B2 in SM5.1). As proxies for those resilience attributes, "availability of pastures" and "subsidies" were used, respectively, to ease the communication. The current performance of function indicators and presence of resilience attributes was considered low, with no change or moderately negative change (Table 5.1; 3rd column).

Table 5.1. Main function indicators and resilience attributes performance in the current situation and developments of performance as expected for future systems (results based on Step 1-4 of the methodology). → implies no change (yellow), ↗ moderate positive change (light green), ↑ strong positive change (dark green), ↘ moderate negative change (orange), ↓ strong negative change (red). Arrows in bold font are results obtained in the workshop. Arrows in normal font are deductions from what has been said in the workshop in the evaluation step.

				Expected future developments			
						Alternative systems (Step 4)	
Function (F)/ Resilience attribute (RA) / Challenge (C)	**Indicator**	**Current level (Step 1)**	**Closeness to threshold (Step 2)**	**Current system (Step 1)**	**Critical thresholds exceeded (Step 3)**	**Semi-intensive system**	**High-tech extensive system**
F: Economic viability	Gross margin	**Low**	(Somewhat) close	→	↘|↓	↗	↗
F: Food production	Number of sheep	**Very low**	At threshold or beyond	→	↓	↗	↑
F: Quality of life	Number of farms	**Low**	At threshold or beyond	↘	↓	↗	↗|→
RA: Production coupled with local and natural resources	Availability of pastures	**Low**	(Somewhat) close	↘	↘|↓	↘	↑
RA: Diverse policies	Subsidies	**Low**	At threshold or beyond	→	↘|↓	↘	↗
RA: Socially self-organized	-	Moderate	Not close	→	↘|↓	→	↑
RA: Supports rural life	-	Low	Close	↘	↘|↓	↗|→	↗
RA: Infrastructure for innovation	-	Low	Close	↘	↘|↓	↗	↗
RA: Reasonably profitable	-	Low	At threshold or beyond	↘	↘|↓	↗	↗
C: Decreasing national lamb meat consumption	Consumption per inhabitant	-	At threshold or beyond	-	-	-	-
C: Increasing feeding costs	-	-	At threshold or beyond	-	-	-	-
C: Increasing wild life attacks	-	-	Not close	-	-	-	-
C: Lack of workforce	Workforce per farm	-	At threshold or beyond	-	-	-	-

5.3.3 Critical thresholds (Step 2)

When discussing critical thresholds (Step 2), participants argued that these were already reached and that the farming system was on the edge of collapse/decline (Table 5.1). When participants resisted to participate individually, the flexibility of the methodology allowed for slightly adapting the procedure in Step 2[2]. In order to stimulate the discussion and obtain values for thresholds, the trend and current value of the indicators according to the official statistics were presented to participants. In case of disagreement, participants were asked to define the current value of the indicators in a plenary session, which helped the researchers to determine how the discussed values were more or less close to the threshold. Based on the plenary discussions on thresholds, researchers deduced a number of enabling conditions that are needed to maintain the current system in the future. In the next sections, actual levels, developments and threshold levels of function indicators, indicators of resilience attributes and challenges are presented.

Main functions and related indicators

Economic viability: gross margin

Participants indicated that the gross margin is the decisive variable that determines whether the farming system is on the edge of collapse or not. Participants indicated that the gross margin threshold of the farms is 25-30 €/head. According to the literature, gross margins in the farming system vary among farms depending on feeding costs, size of herds (Milán et al., 2003; Pardos et al., 2008) and aids (Bernués and Olaizola, 2012; De Rancourt et al., 2006). This implies that not every farm is similarly close to the gross margin threshold. While the gross margin of the farms in the flat areas is at threshold and beyond (25-30 €/head), the distance of gross margins to the thershold appears larger in the farms located in the mid-mountain areas (40-45€ (MAPA, 2017)). The latter have lower feeding costs than the former because the herd feeding relies almost enterely on the availability of pastures. Herd size in mountain areas used to be higher allowing farmers to benefit from economies of scales. Farmers in mountain regions also receive least favoured area aids that increase their income.

Food production: number of sheep

Participants agreed that the current number of sheep has reached the tipping point in the area. There are currently about 521 thousand sheep heads in the province of Huesca, with a reduction of 43.7% since 2005 (Gobierno de Aragón, 2019; MAPA, 2019a). The decrease in the number of sheep in the farming system has not been as sharp as that of the number of farms. The reason that the decrease of sheep number has not been so marked in the last 10 years is because herds of quitting farms have been acquired by the farms that stayed.

The strategy of buying sheep from quitting farmers allowed other farmers to increase their margins and remain in the farming system. Pardos et al. (2007) found an average increment of 85 sheep per farm from the period 1996-2001 to period 2002-2005. Currently, farmers are investing a great effort and time managing between 500 - 1,000 sheep/shepherd, but the gross margins are not enough to hire new shepherds and increase the herd. Consequently, from now on the number of sheep is expected to decrease with each farm disappearing from the system.

Quality of life: number of ovine farms

Providing quality of life by means of creating rural employment with decent working conditions came up as one of the main functions of the farming system. This function is measured by the number of farms, as suggested by researchers and agreed upon by participants. Creating rural jobs contributes to keeping the rural areas attractive for residence and tourism. As also indicated by participants, the rural depopulation is an important challenge that this farming system has been facing since the last century (Bosque and Navarro, 2002). The depopulation seems to have more to do with the general socio-economic context of the farming system (lack of workforce, migration to urban centers, etc.), than with the sheep farming

[2] Due to the perceived closeness to critical thresholds in the studied system and participants' subsequent difficulty in following the normal procedures, the flexibility of the methodology was used to adapt procedures. While adapting the procedures, a balance between individual, small group and plenary activities was maintained to improve the chances that all participants could provide their input.

system itself (Bernués and Olaizola, 2012). The number of farms has decreased by 65% in the period 2005-2019, to the current value of 1,018 (Gobierno de Aragón, 2019, 2016), which is considered to be at the threshold or beyond.

Main resilience attributes and related indicators

Coupled with local and natural capital: availability of pastures

All participants agreed that the costs of feeding are strongly related to the availability of pastures. During the workshop, availability of pastures was assessed by looking at the total available surface of pastures (ha). In the province of Huesca the total amount of pastures has decreased by 65% in the period 2003-2018, with a current total of 160,000 ha in the province of Huesca (MAPA, 2019b). Participants concluded that the availability of pastures meets the farming system's needs, especially now the number of sheep has decreased.

However, in some areas such as the flat areas and those surrounding the Natural Parks and other protected areas (Sierra y Cañones de Guara Natural Park), the access to pastures is limited or nil. Although grazing contributes to modulate the vegetation dynamics (Bernués et al. 2005), bureaucracy and regulations limit the access to the pastures in the protected areas. Simultaneously, the increasing intensification of the agriculture in the flat areas is limiting the area of grazing lands. Moreover, the intensification of the farming system has led to the abandonment of lands, mainly in the mid-mountain areas. This abandonment causes a simplification and homogenization of the landscape due to the increase of the tree and shrub stratums, which lead to decrease in biodiversity and increase of fires (Lasanta-Martínez et al., 2005; Vicente-Serrano et al., 2000). Participants found it difficult to provide a minimum value of pasture surface they need for grazing, but they pointed out that the authorities must ease the access to pastures as well as compensate for environmental services delivered by the ovine farming system. Based on the input from participants, the research team estimated that the system is somewhat close to a critical threshold regarding the availability of pastures.

Diverse policies: subsidies

Participants explained that if basic payments would be lower than the current level, the gross margin would be null or negative, indicating that a critical threshold is reached. Farmers' incomes in the extensive sheep farming indeed depend greatly on aids (Bernués and Olaizola, 2012; De Rancourt et al., 2006). The basic payments was around 24 € per sheep (MAPA, 2019c). Participants claimed that payments should increase at least by 30% to reach suitable gross margins. In fact, the decoupling of aids and the Common Agricultural policy (CAP) modulation have reduced the farms' income (Pardos et al., 2008).

Challenges

Lowering national lamb meat consumption

According to participants, the lamb consumption should not decrease more than the current level, indicating that the current level in fact is the critical threshold. Lamb meat consumption has declined strongly in the period 2006-2019 (50% of reduction), with a current value of 1.3 kg/inhabitant/year (MAPA, 2020). Participants mentioned that in the short term this challenge has a negative influence on the gross margin and the number of sheep, whereas, in the long term, it can lead to the closure of farms.

Participants identified several drivers that explain the lowering demand: consumers preferring other type of meats, mainly pork and chicken; disappearing culinary traditions; upcoming vegetarian and veganism trends; and the increasing campaigns against livestock farming influencing the negative perception of the sheep farming system (SM5.2). Overall, decreasing demand is indeed related to urban trends (Martin-Collado et al., 2019) and social-economic conditions such as consumer preferences and family structures (Corcoran, 2003). The quality of products from the case study area may give a competitive advantage (Bernués et al., 2006).

Increasing feeding costs

The feeding costs are a key element in the gross margin per head and at or beyond a critical threshold according to workshop participants. According to MAPA (2019c), the current average value of the feeding costs is about 30€ per sheep in extensive sheep farms in Aragon. Participants agreed with this current value. According to Pardos et al. (2008) feeding costs depend on the type of farm. Intensive farms implementing feeding practices that rely more on feeds will deal with greater feeding costs (20-30 €/head) than extensive farms that rely more on the availability of pastures (14-17 €/head).

Droughts have been increasing in the last years (Hernández-Mora et al., 2012; Turner, 2005). Droughts are an important driver for increasing feeding costs, especially for those farms highly dependent on the availability of pastures for feeding the herds. For example, to overcome the low productivity of pastures caused by droughts in 2019, the European Commission allowed grazing in ecological focus areas (EFA) in Andalucía (Commission implementing decision (EU) 2019/1389, of 4 September 2019).

Increasing wild fauna attacks

Participants in the workshop are extremely worried about the increasing number of wolves and bears. The wild fauna attacks are recent and there are no clear statistics, but there is great concern about the potential impact. Participants did not provide the value of a critical threshold for wild fauna attacks in the ovine farming system. They indicated that the wild fauna attacks are more frequent in the mid-mountain than in the flat areas, where the attacks rarely occur. Participants mentioned that the attacks not only negatively affect the profitability of the farm, but also the farmers' quality of life as attacks imply more time and investments to take care of the herd. Based on the input from participants, the research team estimated that the system is not close to a critical threshold regarding wild fauna attacks.

Lack of workforce

The Annual Work Unit (AWU) per farm has shown a downward trend over the last years. The current value in the farming system is 1.9 AWU per farm. Participants agreed that this current value is the critical threshold for the workforce in the farming system. The low farm margins do not allow farmers to offer attractive labour conditions and hire personnel. Farmers run the farm alone or with family support. The socio-economic context of the farms such as the distance to major cities and the availability of public services in rural areas also explain the lack of workforce (García-Martínez et al., 2009).

The AWU per farm indicator is also indicative for the quality of life. A decrease in the AWU/farm value indicates a greater workload by the person(s) running the farm. Participants mentioned that the ovine farming system is very time consuming, mainly due to the shepherding. Shepherding is conditioned by the availability of pastures. In several occasions, pastures are far away from farms and farmers need to move long distances with the herds, spending a lot of time far from their families. The low number of shepherds limits the options to cooperate in shepherding and get time free.

5.3.4 Assessing the impact of exceeding critical thresholds (Step 3)

To compensate for the plenary input in Step 2, the research team decided that each participant should individually assess the impact when critical thresholds are exceeded (Step 3). In a plenary session all participants discussed the effects of exceeding critical thresholds of challenges and interactions between critical thresholds. Overall, exceeding the critical threshold of one of the challenges was expected to lead to moderate to strong decline in performance of main functions and resilience attributes (Table 5.1). Plenary discussion results are presented in detail in SM5.2.

In the evaluation step, interactions of thresholds across domains and scales (Figure 5.2) resulted in a vicious circle which explains the expected decline in system functioning when critical thresholds are approached and exceeded (Table 5.1). To adequately describe interacting thresholds in Figure 5.2, some additional indicators were added that came forward during the discussions with stakeholders. Figure 5.2 can be read as a summary of the information provided in the previous sections on thresholds of main function indicators, challenges and resilience attributes. Gross margin, a main function indicator of the system, plays a pivotal role in the interaction of thresholds and affects the number of farms and consequently the number of sheep in the area. Gross margins are directly affected by three main challenges: reducing subsidies, decreasing consumption and increasing feeding costs. Reducing gross margins and the closure of farms further reduces the available workforce, which reinforces the closure of remaining farms directly and indirectly via increasing feeding costs, which is why a lack of labour is seen as a main challenge. The challenge of increasing feeding costs is indirectly affected by increasing occurrence of droughts and wild fauna attacks, two other identified challenges. These challenges reduce the access and use of pastures, a proxy for the resilience attribute "production being coupled with local and natural capital". Reduced access and use of pastures is eventually leading to shrub encroachment. Shrub encroachment is further stimulated when the number of sheep becomes insufficient to graze all available pastures. From a social perspective, the closure of farms and the decreasing workforce is expected to lead to a decreasing rural population.

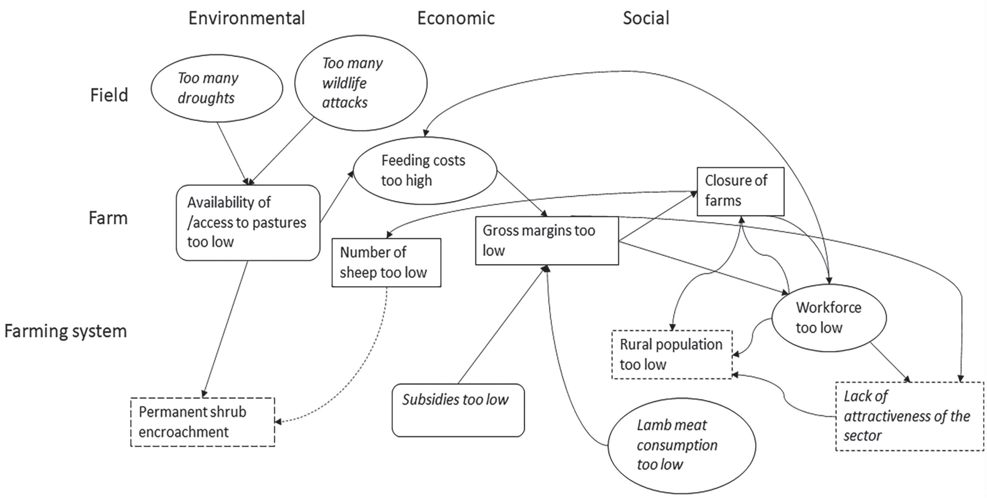

Figure 5.2. Interacting thresholds between levels and domains for function indicators (rectangular shapes with sharp edges), indicators of resilience attributes (rectangular shapes with rounded edges), challenges (oval shapes) and additional indicators (rectangular shapes with dashed lines).

5.3.5 Alternative systems (Step 4)

Instead of providing defined alternative systems on post-its, participants proposed ideas in a plenary session, thus using the flexibility that the methodology is offering. Two main alternative systems, their goals, functions and resilience attributes (Table 5.1) and enabling conditions (Table 5.2) came up in the brainstorming.

Table 5.2. Relevance of enabling conditions categorized per domain. V implies that an enabling condition is relevant for maintaining the current system in the future and/ or moving to an alternative system. Tick marks in bold font are results obtained in the workshop. Tick marks in normal font are deductions from what has been said in the workshop in the evaluation phase. FS: farming system.

Domain	**Enabling conditions**	**Current system**	**Alternative systems (Step 4)** Semi-intensive system	**Alternative systems (Step 4)** High-tech extensive system
Agronomic	New technology applied to sheep FS farm management	-	**V**	**V**
Agronomic	Farmers training in new technology	-	**V**	**V**
Agronomic	Improved sanitary conditions	V	**V**	**V**
Agronomic	Improved animal handling	V	**V**	**V**
Agronomic	Geo-localization technology	-	**-**	**V**
Agronomic	Use of sub-products	-	**V**	**-**
Economic	New financial products	V	**V**	**V**
Economic	New commercialization channels and market niches	V	**V**	**V**
Economic	Public aids for public goods provision	V	**-**	**V**
Environmental	Broader access to pastures and stubble fields	V	**-**	**V**
Environmental	Sustainable pastures management	V	**-**	**V**
Environmental	Research relationship nature-ovine FS	-	V	**V**
Institutional	Reduced bureaucracy control	V	**V**	**V**
Institutional	FS oriented legislation (sanitary, environmental and urban)	V	**V**	**V**
Institutional	Rural development	V	-	**V**
Social	Public awareness of the contribution of FS	V	V	**V**
Social	Improved cooperation among actors	V	-	**V**

The first alternative system is the semi-intensive system. The main goal in this system is to improve the provision of private goods, i.e. increased meat production and improved labour conditions. Several enabling conditions at farm level were identified to reach this end (Table 5.2). This alternative system would fit better in the southernmost and flat areas where crop diversification is easier to implement.

The second alternative system is the high-tech extensive system. The aim is to improve farms' profitability by reducing feeding costs based on an improved pasture management. Participants highlighted the need for the innovation in herd geo-location, weather information and wild fauna surveillance (Table 5.2). In addition, subsidies are essential in this system to support the provision of public goods as well as a legal framework to regulate and protect the access to land for grazing purposes. This alternative system would be more suitable in the northernmost and mountainous locations, where there are more pasturelands and geography makes other types of farming systems less appropriate.

Current challenges, such as the reduced consumption of lamb meat by consumers, the lack of workforce and the increasing feeding costs, are still important in the future alternative systems. The feeding costs are more important in the semi-intensive alternative system due to a greater dependency of feed inputs (fodders) and lower dependency on the availability of pastures. On the other hand, wild fauna attacks will only pose a challenge in the high-tech extensive alternative system. In the alternative systems, all main functions are expected to increase in a moderate way (Table 5.1). The gross margins would increase in both systems, although margins seem to differ depending on the degree of intensification or extensification of the farms, as well as the areas where the farms are located. The increase in gross margin in both systems is the main change that is expected to allow to increase the number of sheep and farms, and are therefore moving away from other critical thresholds as well. The location of the farm determines the agro-ecological potential and the access to markets (Geoghegan et al., 1997). Thus, the semi-intensive alternative system is more likely in the flat areas where pastures are more scarce and payments for the less favourable areas are not applicable (Pardos et al., 2008). In the high-tech extensive alternative system, the production is not expected to change. However, its performance in less favoured areas (mid-mountains) and the provision of public goods services is supported by European subsidies that could increase the current margins. Greater gross margins would lead to a greater number of farms in the farming system, although this increase would be limited by the access to lands in the high-tech extensive system. The increase of the number of sheep is expected in both alternative systems, although this increment would be greater in the high-tech extensive alternative system. According to participants the lower production in this system would be compensated with greater herd sizes.

While some resilience attributes of the farming system ("infrastructure for innovation", "reasonable profitable" and "supports rural life") are expected to improve in both alternative systems, participants agreed that all the resilience attributes of the FS could improve in the high-tech extensive system (Table 5.1). The "social self-organization" resilience attribute in the high-tech extensive system would be improved as cooperation is needed to manage pastures and herds; it can also be argued that "production coupled to the local and natural capital" will improve as herd feeding will be coupled to the availability of pasture lands; and "diverse policies" will be enhanced as new policies will be tailored to support the provision of the public goods provided by the farming system. Moving towards the semi-intensive alternative scenario could constrain the resilience attributes "production coupled to the local and natural capital" and "diverse policies" leading to a deeper unbalance between the economic, social and environmental dimensions.

5.3.6 Strategies (Step 5)

Several current strategies, with currently low implementation levels, could be enhanced in the alternative systems. Some current strategies (in italics in Table 5.3) are compatible with the alternative farming systems. These strategies are mainly oriented to the economic domain, specifically related to the on-farm economic administration (investments in farm, savings, sales contracts, etc.) (Soriano et al., 2020).

Moreover, there were several new strategies identified during the workshop that match with current strategies (underlined in Table 5.3). Most of these strategies are economic strategies such as opening new marketing channels and developing new financial products and sales contracts that contribute to increase the robustness of the farming system to face hard times. Some institutional strategies are related to the public awareness campaigns about the positive contribution of the extensive sheep farming system to nature conservation and health. In the system, public awareness is expected to stimulate lamb meat consumption, which results in improved incomes. Public awareness is also expected to improve regulations for improving management of pastures, which in turn could lead to even more public awareness.

Most of the strategies proposed in the workshop are applicable for both systems and are mainly related to the need for improved technologies and innovation (normal font in Table 5.3). The number of proposed strategies was higher for the high-tech extensive system. The extra strategies in this system relate to the environmental and social domains, due to its more environmental-based and social nature. Institutional changes need to be made that improve the access to lands and the management of pasturelands, and the recognition of the farming system's contribution to the conservation of natural resources. This is expected to pay off in the economic domain, through subsidies and the lower feeding costs due to the use of pastures. Social measures are related to the promotion of generational renewal, which would increase the workforce in the farming system. The workforce availability improves the farmers' quality of life, stimulating the attractiveness of the farming system.

The quality of life is also improved with the implementation of new technology related to management of pastures and animal handling – in the semi-intensive alternative system the animal handling strategies are very important, mainly related to sanitary and production issues. The technology and innovation requires the cooperation between different actors in the exchange of knowledge and training in the technology (i.e., shepherds schools and GPS training in the high-tech extensive alternative system, and the management of more prolific breed and implementation of sanitary measures in the semi-intensive alternative system). The cooperation between farmers is also expected to increase the bargaining power and margins.

In any case, strategies regarding innovation and cooperation among system actors would be necessary, no matter what future system unfolds (no-regret strategies). It should be noted that the import of feed in the semi-intensive system reduces the coupling of production with local and natural resources. This could result in an opposite direction where, because of a worsening public image, less meat is consumed and regulations are getting stricter.

In both alternative systems, several strategies are oriented to technology implementation. The implementation of new technology generally does not allow for experimentation because of the great investments involved in new technology. For instance, in the high-tech extensive system the use of satellite images or the GPS per ewe is expensive. In the semi-intensive system, the replacement of more prolific ewes requires high investments. Strategies with low investment costs are related to the sanitary prevention, which lend robustness to the farming system (healthier animals that respond better to diseases), or the coordination among actors.

The probability of unfolding the high-tech extensive alternative system is expected to be larger than that of the semi-intensive system. The reason is that the semi-intensive system is going to compete with other intensive farming systems (e.g., pork) that are more profitable. The high-tech extensive system might highlight its importance in the contribution to the public goods and the conservation of the local breed *Rasa aragonesa*. As mentioned before, the greater availability of pastures makes the high-tech extensive system more suitable to mid-mountain areas. Farmers mentioned the high-tech extensive system as the preferable option in the future but also the most complicated to accomplish, especially without supporting policies in place. Besides, some of the technology for pasturelands and herds management is still in a development phase. In contrast, the lower presence (or absence) of pastures in flat areas of the farming system make the semi-intensive systems more appropriate in those areas. Participants pointed out that both alternative systems could attract young people to the farming system. Riedel et al. (2007) have related young farmers to a greater dynamism and technology adoption in the ovine production system and to the reduction of shepherding. Technology is indeed important in both alternative systems and (partly) replaces the need for actual shepherding.

Table 5.3. Current strategies and future strategies for different future systems. Current strategies are based on FoPIA-SURE-Farm 1. Strategies proposed for future systems that are currently being implemented are underlined. Current strategies (not explicitly indicated in the workshop for future systems) are indicated in italics. Strategies in normal font are the strategies that were proposed for future systems and that are not implemented in the present. Bold font checks indicate that these strategies were mentioned during the workshop for a specific system. Normal font checks indicate that, based on the discussions during the workshop, it seems likely that strategies will be applied in certain systems. FS: farming system

			Future systems	
Strategy	**Domain**	**Current system**	**Semi-intensive system**	**High-tech extensive system**
Use of technology for management efficiency improvement (electronic readers, blood test, etc.)	Agronomic		**V**	**V**
Research in more prolific and productive breeds	Agronomic	V	**V**	
Research for sanitary conditions of the ovine FS (new vaccines, medicaments, etc.)	Agronomic		**V**	**V**
Implementation of sanitary conditions (hygiene, spaced animals, etc.)	Agronomic	V	**V**	**V**
Use of technology for animal positioning (GPS, mobile phone, etc.)	Agronomic			**V**
Farmers training in new technology	Agronomic		**V**	**V**
Financial products to cover market volatile prices	Economic	V	**V**	
Financial products to cover droughts	Economic	V		**V**
Opening up a foreign market	Economic	V	**V**	**V**
Boosting of local consumption	Economic	V		**V**
Openness of local slaughterhouses	Economic			**V**
Diversification (on-farm)	Economic	V	**V**	
Alternative income sources (off-farm)	Economic	V		**V**
Investment in the farm assets	Economic	V	V	V
Costs reduction and flexibility	Economic	V	V	V
Sales contracts	Economic	V	V	V
Access to market information	Economic	V	V	V
Improvement of the access to pastures and stubble fields	Environmental			**V**
Use of technology for control of grazed pastures	Environmental			**V**
Research in methane emissions from ovine FS	Environmental		**V**	**V**
Use of technology for real-time communication with administration	Institutional		**V**	**V**
Trained administration staff in FS specificities	Institutional		**V**	**V**
Reduction of bureaucracy and excessive and specific regulations	Institutional		**V**	**V**
Tailored legislation in environmental management	Institutional			**V**
Tailored legislation in sanitary conditions	Institutional		**V**	**V**
New urban legislation	Institutional			**V**
Remuneration to the FS for contribution to public goods	Institutional			**V**
Improvement of legislation in relation to wild fauna	Institutional	V		**V**
Innovation of laws for products origin and certification	Institutional		V	**V**
Promotion of generational renewal (early retirements, access to land, etc.)	Institutional/Social		**V**	**V**
Creation of shepherd schools	Institutional/Social			**V**
Promotion of lamb meat consumption	Institutional/Social	V	**V**	**V**
Promotion of local breeds outside the FS	Institutional/Social			**V**
Improvement of awareness of FS contribution to public goods	Institutional/Social	V	V	**V**
Associations and cooperatives	Social	V	V	V
Improvement of quality of life (work intensity reduction with technology)	Social	V	**V**	**V**

5.3.7 Compatibility with Eur-Agri-SSPs (Step 6)

Based on the challenges, enabling conditions and strategies of the current and alternative systems, the extensive ovine farming system in the province of Huesca seems to be most compatible with a scenario on a pathway to higher sustainability with improved attention for the maintenance of natural resources (Eur-Agri-SSP1; Table 5.4), especially in the case of a high-tech extensive system. Compatibility with Eur-Agri-SSP1 is largely due to the increment of support for environmental services. As the current system is close to collapse, the compatibility with a scenario where the status quo is maintained as much as possible (Eur-Agri-SSP2) for the current state is limited. The establishment of the semi-intensive system is more compatible with Eur-Agri-SSP2 due to its production orientation. Eur-Agri-SSP3, with regional rivalry leading to amongst others slow technological process, is moderately to strongly incompatible with the current system and the alternative systems. In Eur-Agri-SSP3, specifically for the semi-intensive system, the lack of internationalization of markets, and for the high-tech extensive system the lack of environmental services valorization reduces compatibility. The semi-intensification of the farming system is evaluated as the only alternative system moderately compatible with Eur-Agri-SSP4, a scenario driven primarily by increasing social inequality, and Eur-Agri-SSP5, a scenario primarily driven by improvements in technology. The high-tech extensive system is even less compatible with Eur-Agri-SSP4 and Eur-Agri-SSP5 than the current system. Although the high-tech extensive system is most compatible with Eur-Agri-SSP1, the semi-intensive system seems the safest bet regarding its overall compatibility with all Eur-Agri-SSPs (for more detail see SM5.3 and SM5.4).

Table 5.4. Compatibility of the current system and alternative systems with different Eur-Agri-SSPs. With values -1 to -0.66 (dark red): strong incompatibility, -0.66 to -0.33 (light red): moderate incompatibility, -0.33 – 0 (orange): weak incompatibility, 0-0.33 (yellow): weak compatibility, 0.33-0.66 (light green): moderate compatibility, and 0.66-1 (dark green): strong compatibility.

	Eur-Agri-SSPs				
Future systems	**1: Sustainable paths**	**2: Established paths**	**3: Separated paths**	**4: Unequal paths**	**5: High-tech paths**
Maintaining the current system	*0.51*	*0.32*	*-0.83*	*0.14*	*0.21*
Semi-intensive alternative system	*0.63*	*0.66*	*-0.62*	*0.35*	*0.38*
High-tech extensive alternative system	*0.73*	*0.43*	*-0.70*	*0.07*	*0.16*

5.4 Discussion

5.4.1 Insights from the case study

Critical thresholds and impacts when exceeding these (Step 1-3)

The outcome of the workshop suggested that, currently, the social, economic and environmental performance of extensive sheep farming system in Huesca, Spain is poor and declining. This is a common trend in Europe. Strijker (2005) explained that increasing opportunities outside agriculture, lower product prices, and higher land prices explained the continuous decline of extensive livestock grazing systems in several rural areas across Europe. Bernués et al. (2011) found that the lack of generational succession and the high opportunity cost of labour are also drivers of the disappearance of livestock farming in European Mediterranean countries. Most challenges, system functions and resilience attributes seem to be at or beyond critical thresholds, indicating simultaneously low sustainability and low resilience levels. Interactions between critical thresholds of challenges, functions and resilience attributes across levels and domains are perceived to be present. This emphasizes the importance of including multiple levels and domains when studying the sustainability and resilience of farming systems. This also emphasizes the complementarity between sustainability and resilience, albeit in a negative sense. Overall, the effect of exceeding thresholds is expected to strongly reduce system performance in terms of sustainability and resilience. Economic viability at farm level plays a pivotal role regarding interacting thresholds. Participants indicated that exceeding the critical threshold for gross margin would result in a collapse of the farming system. This supports the idea that interacting indicators being close to critical thresholds at lower levels (field, farm) increase the vulnerability of the focal system (farming system) (Resilience Alliance, 2010). Interestingly, the level of gross margin is artificially maintained by subsidies that farms receive. This suggests a current focus on mainly economic sustainability, which in the long run may not be sustainable at all: subsidies may keep the fast responding "gross margin" away from critical thresholds, while the indicators relating to slower processes such as declining access to pastures in the environmental domain and lower attractiveness of the countryside in the social domain are not countered. Amalgamation of farms and livestock partly slows down the decline in sheep numbers and subsequent lower maintenance of the landscape. However, in the absence of subsidies and the limitations in managing huge herds, amalgamation is no longer profitable, which explains why participants expected a collapse. Biggs et al. (2018) mention that large shifts in socio-ecological systems are uncommon. The provisioning of agricultural subsidies could be seen as a main reason for continuing the status quo in some other agricultural systems in Europe as well. In the case of Huesca, change goes farm by farm, in terms of quitting and growing. However, there are limits to growth, relating to financial margins and availability of labour. Also the perspective of farmers that stay may change: it depends on how much the social fabric in a rural area is already eroded whether and how many farmers still can benefit from nearby facilities and off-farm work (Kinzig et al., 2006).

Alternative systems, strategies and Eur-agri-SSPs (Step 4-6)

Strong feedback mechanisms from the environment to the farming system seem not to be perceived by farming system actors. This seemed also lacking in participants' mental models in other case studies where the methodology was applied (Paas et al., 2020). This lack may reveal the boundaries of local knowledge. Instead of feedback from the environment, "lamb meat consumption" and "regulations" are perceived to provide strong feedback signals: a low natural state of pastures and dependence on feed imports pays off negatively via the public image of the extensive sheep farming system, which in turn may lead to lower lamb meat consumption and stricter regulations regarding pasture management. These feedback loops are expected to stay important in both proposed alternative systems that stimulate economic viability in order to steer away from other thresholds. It could therefore be argued that the alternative systems are adaptations in reaction to challenges rather than transformations in which farming system structure and functioning changes radically. Bernués et al (2005) also found adaptation alternatives to reinforce the sustainability and resilience of the extensive farming systems. They proposed adaptations such as to define work organisation schemes that allow variations in labour needs, to explore the product mix that facilitates to transfer risks, and to increase the utilisation of on-farm resources (fodder and grazing) and the productivity (lambs per ewe or kg per lamb).

In the high-tech extensive system, more attention is given to landscape maintenance, which increases the number of enabling conditions and strategies compared to the semi-intensive system. For the high-tech extensive system this implies continued dependence on subsidies and in general more dependence on cooperation with actors inside and outside the farming system. The higher level of enabling conditions and strategies of the high-tech system compared to the semi-intensive system reduce the likelihood of matching all developments in each specific Eur-Agri-SSP, which is reflected in the reduced compatibility with most Eur-Agri-SSPs. On the one hand, this could be interpreted as having low resilience. On the other hand, the high-tech scenario moves towards an improved balance between economic, social and environmental functions. Improving this balance is suggested to improve general system resilience (Walker and Salt, 2012). The semi-intensive system seems more resilient regarding its higher compatibility with Eur-Agri-SSPs. However, focus in this alternative system is mostly on economic functions, which could undermine general resilience. Participants also perceived that this alternative system has less chances of being realized, as there is more competition over land with other farming systems, compared to the high-tech extensive system. In addition, lamb meat consumption and subsidies are expected to further reduce when production is becoming less pasture based. This leads to two methodological reflections. First, combining information on system trends and mechanisms, based on a forecasting approach, and requirements for realizing alternative systems based on a backcasting approach, shows the complementarity between the two approaches (Quist and Vergragt, 2006). Second, the local context seems very important when assessing compatibility of alternative systems with Eur-Agri-SSPs at farming system level. At the same time, the methodology raises awareness that depending on which scenario is unfolding, the local context may change, which could leave certain alternative systems unviable. Shifting between system and scenario perspectives thus provides a means to triangulate stakeholder input with researchers' perspectives.

5.4.2 Methodology

A quick and flexible method

The proposed methodology provides a rapid and flexible way to assess multi-dimensional sustainability and resilience of future farming systems. Although qualitative in nature and covering many different topics, the methodology provides outputs that can be summarized and communicated in few key tables and a figure (Tables 5.1-4, Figure 5.2). The concept of critical thresholds is key to stimulate participants to think about potential permanent and large changes in their system. The notion of interaction between critical thresholds stimulates participants to think about interactions between challenges, functions and resilience attributes in the social, economic and environmental domain. Rapid resilience assessments are not widely available (Nemec et al., 2014) and are often inferring resilience solely based on expected presence of resilience attributes (e.g. Nemec et al. 2014, Tittonell 2020). Regarding the preparation phase, the method is flexible regarding the information sources used: results from FoPIA-SURE-Farm 1 or other sources of information. Other sources could be for instance (grey) literature, statistical databases and expert interviews. Provided time is managed strictly, the methodology turned out to be also flexible enough to be tailored to the local context and requirements with regard to changing individual, small group and plenary activities. Content-wise, the method also turned out to be agile with regard to including case study specific indicators, while the overarching concepts such as functions and resilience attributes allow for comparisons with other case studies. The same method was successfully applied in eight other SURE-Farm case studies in Europe (Accatino et al., 2020), allowing , for instance, to compare critical thresholds across case studies. In two case studies, desk studies were performed based on the method (Accatino et al., 2020), also representing the flexibility of the method. Unfortunately, time-wise, the workshops did not allow for an extensive discussion of all relevant elements and topics. An extension of one hour to the workshop would enable a better discussion on strategies to realize alternative systems, e.g. by discussing the prioritization of strategies, which actors and what resources need to be involved to implement strategies (Mathijs and Wauters, 2020), and whether there are trade-offs among strategies.

Influence of the research team

In case participants would not have assessed closeness to critical thresholds, the methodology suggests the research team to do this assessment. Such an assessment would be based on current levels and trends of main function indicators, resilience attributes and challenges. These levels and trends also serve as a points of reference (Table 5.1) and are based on previous work and other sources of information. This introduces an influence of the research team on the outcome of the workshop. Likewise, it should be noted that the method to assess compatibility of systems with scenarios, although transparent and useful for triangulating results, is also influenced by arbitrariness and subjectivity of researchers. For instance, when determining whether a development is important or very important for an alternative system, or when weighing the importance of the different groups of scenario indicators. The introduction of arbitrariness reduces the reproducibility of results. However, influence of researchers can also be explicitly accepted as a necessary part of an iterative, action-oriented process. In that process, researchers are actors aiming to develop, together with stakeholders, a shared, multi-dimensional understanding of current and future system performance (Wittmayer and Schäpke, 2014).

Participation and influence

The proposed methodology in this paper is designed to provide a voice to individual stakeholders as well as give room to develop a common understanding and vision for the studied farming system. Working with (a limited number of) participants also brings in subjectivity and arbitrariness. Suggestions from participants to make individual exercises plenary in this Spanish application may be the result of participants' interests to influence the flow and content of the workshop. For instance, to present private interests as formal knowledge (Mosse, 1994). In the case of extensive sheep farming in Huesca, Spain, collapse of the farming system seems pending, which may stimulate the expression of private as well as public interests to preserve the current system. The perception that the farming system has reached already certain thresholds could be a legitimate reason to avoid a discussion about where thresholds would lie exactly. The flexibility of the methodology allowed compensating the lack of individual input on critical threshold assessment by letting participants assess some other parts of the workshop individually. When discussing alternative systems, participants also expressed the need for a plenary discussion. Again, a pending collapse of the farming system may explain the need for immediate action, and thus not allowing for opportunities where time-consuming differences in opinion could arise. Another explanation could be that individual assessments were seen as dull, administrative tasks, resulting in reduced engagement and influence of certain stakeholder groups. Having plenary instead of individual input however also reduced the chance of having radical different ideas on alternative systems.

Adaptations or transformations?

By focusing on only a few system function indicators and resilience attributes, the likelihood of proposing alternative systems that integrate for instance new goals is reduced: importance of function indicators and resilience attributes in the current system may need to be re-evaluated in the light of possible alternative systems. In that sense, the followed methodology is to a certain extent path-dependent. This coincides with path dependency of social-ecological systems in general where actors have stakes and often change needs to be realized based on the resources that have been built up in the system so far. In the presented case study, alternative system goals shifted somewhat, but were largely emphasizing differences among goals of lowland and highland farming. Also in applications in eight other European farming systems, alternative systems proposed were adaptations rather than transformations. Only in an application where a desk study was performed (because of the Covid-19 situation) and main input was from experts, more radical transformations were proposed (Paas et al., 2020). Making farming system actors think about future change is indeed acknowledged as challenging (Meuwissen et al., 2020), but much needed in transition processes (Quist and Vergragt, 2006). As alternative to stakeholder participation, some foresight studies depend on expert opinions (e.g. Boland et al. 2013) or a literature study (e.g De Figueiredo et al. 2017). Although informative, these alternatives do not create a sense of ownership and engagement of local actors. Inviting radical thinkers from outside the system in a complementary workshop could help to challenge current mental models and to expose farming system actors to more radical ideas (Enfors-Kautsky et al., 2018; Westley et al. 2015). Another way to break free from established ways of thinking is to reframe the challenge (Enfors-Kautsky et al., 2018). For instance, by approaching it predominantly from an environmental perspective, a perspective that was not extensively discussed in the context of the workshop in the presented case study.

Representing the farming system

The representation of the farming system in the framework of Kinzig et al. (2006) gives a quick overview of important interactions for a system in decline. It should be noted, however, that getting an adequate system representation is always work in progress (Walker and Salt, 2012) and complementary methods are probably needed. For instance, the framework of Kinzig et al. (2006) does not provide a complete overview on possibilities to avoid or reverse a decline in system performance, based on knowledge of balancing and reinforcing processes in the system. The development of a causal loop diagram provides more insight on where these processes can be expected but is less intuitive and more complicated to interpret. Still, a causal loop diagram could help to qualitatively assess the impact of specific strategies. Further integration of causal loop diagrams and scenarios in system dynamics models could lead to new knowledge on how global or European scenarios play out at farming system level (Herrera and Kopainsky, 2020).

5.5 Conclusions

The methodology presented in this paper leads researchers in six steps to a multi-dimensional understanding of future sustainability and resilience of a farming system. Taking the current system as point of reference, the identification of interacting critical thresholds and assessing in a forecasting exercise the impact of exceeding these can explain how system sustainability and resilience can quickly decline (Step 1-3). Consequently, participants, being aware of this, are stimulated to think about alternative systems and their performance with regard to sustainability and resilience (Step 4). The alternative systems serve well as a point of reference in a back-casting exercise to identify the strategies that are needed to arrive at those alternative systems (Step 5). Although the workshop is originally designed to take five hours, taking more time for the workshop is advised as it will further improve understanding on the role of different strategies, actors and resources. Considering both feedback mechanisms (combining results from Step 1-5) and compatibility of alternative systems with Eur-Agri-SSPs (Step 6) provides a means of triangulation that allows for better understanding of strengths and weaknesses of the farming system, for instance with regard to the complementarity of sustainability and resilience of a system. Potential for decline (Step 1-3) and improvement (Step 4-6), simultaneously for sustainability and resilience, have been made clearly visible in the case study on the extensive sheep farming system that is included in this paper. Overall, the methodology can be regarded as relatively quick, interactive, flexible and interdisciplinary, enabling stakeholders to think and talk about the future sustainability and resilience of their system, paving the way for further discussions and also quantitative methods that can assess, ex-ante, the impact of strategies and scenarios.

Supplementary Materials

Supplementary materials 5.1: https://ars.els-cdn.com/content/image/1-s2.0-S1470160X21009018-mmc1.docx

Supplementary materials 5.2: https://ars.els-cdn.com/content/image/1-s2.0-S1470160X21009018-mmc2.docx

Supplementary materials 5.3: https://ars.els-cdn.com/content/image/1-s2.0-S1470160X21009018-mmc3.docx

Supplementary materials 5.4: https://ars.els-cdn.com/content/image/1-s2.0-S1470160X21009018-mmc4.xlsx

Participatory assessment of critical thresholds for resilient and sustainable European farming systems

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Abstract

Farming systems in Europe are experiencing multiple stresses and shocks that may push systems beyond critical thresholds after which system change is expected to occur. These critical thresholds may lie in the economic, environmental, social and institutional domain. In this paper we take a participatory approach with involvement of farming system stakeholders to assess the presence of critical thresholds in 11 European farming systems, and the potential consequence of surpassing those with regard to system sustainability and resilience. First, critical thresholds of the main challenges, key system variables and their interactions in the studied farming systems were assessed. Second, participants assessed the potential developments of the key system variables in case critical thresholds for main system challenges would be exceeded. All studied systems were perceived to be close, at or beyond at least one identified critical threshold. Stakeholders were particularly worried about economic viability and food production levels. Moreover, critical thresholds were perceived to interact across system levels (field, farm, farming system) and domains (social, economic, environmental), with low economic viability leading to lower attractiveness of the farming system, and in some farming systems making it hard to maintain natural resources and biodiversity. Overall, a decline in performance of all key system variables was expected by workshop participants in case critical thresholds would be exceeded. For instance, a decline in the attractiveness of the area and a lower maintenance of natural resources and biodiversity. Our research shows that concern for exceeding critical thresholds is justified and that thresholds need to be studied while considering system variables at field, farm and farming system level across the social, economic and environmental domains. For instance, economic variables at farm level (e.g. income) seem important to detect whether a system is approaching critical thresholds of social variables at farming system level (e.g. attractiveness of the area), while in multiple case studies there are also indications that approaching thresholds of social variables (e.g. labour availability) are indicative for approaching economic thresholds (e.g. farm income). Based on our results we also reflect on the importance of system resources for stimulating sustainability and resilience of farming systems. We therefore stress the need to include variables that reflect system resources such as knowledge levels, attractiveness of rural areas and general well-being of rural residents when monitoring and evaluating the sustainability and resilience of European farming systems.

6.1 Introduction

Farming systems in Europe are experiencing multiple adverse shocks and stresses, such as weather extremes, price fluctuations and changes in policies and regulations. Under these multiple shocks and stresses, improving or even maintaining generally mediocre levels of sustainability of farming systems is increasingly challenged (Meuwissen et al., 2019).

The presence of critical thresholds adds dynamic complexity for farming system actors and policy makers. This is because beyond such thresholds, drastic system transformations may occur (Groffman et al., 2006; Kinzig et al., 2006) that are difficult to anticipate (Stockholm Resilience Centre, 2020) and to manage. For instance, the speed and scale of system processes after exceeding a critical threshold may be incompatible with the adaptation capacities of current institutions (Walker and Salt, 2012). Exceeding a critical threshold is most often undesirable as it generally leads to lower sustainability levels, e.g. a decline in biodiversity and human well-being (Biggs et al., 2018). Moreover, this state with lower sustainability levels may be more persistent resulting in reduced options to improve sustainability.

Timely knowledge on critical thresholds is therefore needed to prevent exceeding them (Resilience Alliance, 2010), but it is often difficult to anticipate the exceedance of a critical threshold (Stockholm Resilience Centre, 2020). In absence of clear knowledge on thresholds, Walker & Salt (2012) propose to work with thresholds of potential concern (TPCs) that inform management goals that aim to avoid those thresholds, without knowing exactly where they lie. In either case, the threshold level being known exactly or being a TPC, Monitoring is needed in order to detect the closing in on a critical threshold. Current monitoring frameworks of agriculture such as the Common Monitoring and Evaluation Framework (CMEF) in the European Union (EU), are mostly based on available statistics, leading to an overemphasis on economic data and an absence of data on social variables such as the well-being of farmers.

Participatory approaches could help to complement existing monitoring frameworks. Participatory input is a common way to define and assess environmental, economic as well as social indicators in an integrative way based on stakeholder perceptions (Chapter 2, van Calker et al. 2005, Morris et al. 2011, König et al. 2013). From a resilience perspective, closeness to critical thresholds of economic, environmental or social sustainability indicators can be seen as a sign of lower resilience. Perceived closeness to stakeholder-defined thresholds may hence be seen as a stress-signal of perceived low resilience. However, it should be kept in mind that perceived resilience is not always the same as resilience based on objectively defined and assessed resilience indicators (Jones, 2019; Jones and d'Errico, 2019). Although subjective, perceived resilience may explain stakeholder decision-making and resulting dynamics of the farming system. Closeness to critical thresholds may also inform the focus area of certain policies. Participatory input of farming system actors is also useful as it provides opportunities to take into account the local context and causal mechanisms at work. These are important to properly assess resilience and to realize adequate resilience-enhancing policies (Biesbroek et al., 2017).

In this study, we first further reflect on the importance of critical thresholds for resilience, and methods to assess these. Next, we assess in 11 European farming systems the closeness to critical thresholds of challenges and key system variables based on participatory input of stakeholders. The key challenges and system variables were defined based on the local context by researchers and stakeholders in previous studies (Chapters 2 & 3, Nera et al., 2020). We further use participatory input to assess the impact on main system variables in case critical thresholds of challenges are exceeded. Lastly, we use participatory input to reveal the interaction between critical thresholds, i.e. the exceedance of one threshold leading to the exceedance of another threshold. Based on the participatory input we discuss commonalities across farming systems. We finally use the commonalities to translate findings from a local context to national or EU-level policy recommendations and provide some suggestions for indicator development for the Common Agricultural Policy (CAP) 2021-2027.

6.2 Critical thresholds and resilience

In social-ecological systems (SES) research, there is ample evidence for the existence of critical thresholds whose exceedance leads to potentially undesired system transformations (Biggs et al., 2018; Rocha et al., 2015). Evidence in SES research is usually based on empirical data, theoretical models and statistics related to early warning signals (Rocha et al., 2015). Participatory approaches to identify critical thresholds are also proposed (Resilience Alliance, 2010; Walker et al., 2002; Walker and Salt, 2012). Still, large transformations or so-called regime shifts are not commonly observed in SES (Biggs et al., 2018; Carpenter et al., 2005). A hypothesis is that many SES are most of the time operating in a growth or consolidation phase, while their phases of decline and re-organization are usually short (Walker and Salt, 2012). Such a hypothesis may hold for the SES studied by Rocha et al. (2015) and Biggs et al. (2018), e.g. with regard to natural vegetation cover change in terrestrial systems or fish stock collapses in marine systems. In their studies, the focus is predominantly on passing critical thresholds in the environmental domain, as the degree of control over environmental processes or specific ecosystem services seems limited.

In SES such as contemporary European farming systems, anthropogenic inputs and human-induced adaptation processes are primarily aimed at controlling the level of food production. Transformations in farming systems may therefore be the result of gradually implemented adaptations in reaction to a changing environment, such as the gradual change towards agri-industrial entrepreneurship farming after the Second World War encountered in many European farming systems (Hardeman and Jochemsen, 2012). Therefore, in agricultural research, large transformations are often observed based on long-term historical studies on farming systems (e.g. Allison and Hobbs 2004, Termeer et al. 2019, Meuwissen et al. 2020), agricultural landscapes (e.g. Brown and Schulte 2011), or on a combination of both (e.g. Van Apeldoorn et al. 2013). Farming systems operate at a regional level (Meuwissen et al., 2019), a level for which Biggs et al. (2018) indicate that regime shifts develop slowly. This explains why large, gradual transformations can only be observed at longer time scales. In land use dynamics studies, large transformations can be simulated with quantitative models (e.g. Figueiredo and Pereira 2011, Brown et al. 2019). In these models, critical economic thresholds beyond which decision makers change activities are predefined inputs. However, apart from critical thresholds in the economic domain, critical thresholds in the social and environmental domain also need to be taken into account (Kinzig et al., 2006; Walker and Salt, 2012).

The work of Kinzig et al. (2006) is an example of how SES and agricultural systems research on critical thresholds and transformations can converge. Kinzig et al. (2006) and Walker and Salt (2012) propose to study transformations in agricultural regions by looking at interacting thresholds between field, farm and regional level and the social, economic and environmental domains. Critical thresholds are often associated with slow system processes, such as population dynamics and environmental changes (Resilience Alliance, 2010; Walker and Salt, 2012). Generally, indicators at higher levels of integration (e.g. countries) are dependent on slower processes than indicators at lower levels (e.g. farms) (Biggs et al., 2018). Indicators in the environmental domain are also often related to slow processes, while social indicators can be related to slow as well as fast processes (Walker and Salt, 2012). Warning signals of approaching critical thresholds of especially the slower processes in a system may go unnoticed or come too late (e.g. Van Der Bolt et al. 2018), while indicators related to faster processes are generally easier to measure. A distinction between thresholds of fast and slow variables and the identification of their interactions across levels of integration and the social, economic and environmental domain can therefore be useful to timely detect the approaching of critical thresholds.

6.3 Methodology

6.3.1 Farming systems and study design

This study is based on the "Framework of Participatory Impact Assessment for Sustainable and Resilient Farming Systems: future sustainability and resilience" (FoPIA-SURE-Farm 2; Paas and Reidsma 2020) applied to eleven European farming systems: large-scale arable farming in Northeast Bulgaria (BG-Arable), intensive arable farming in the Veenkoloniën, the Netherlands (NL-Arable), arable farming in East of England, United Kingdom (UK-Arable), large-scale corporate arable farming with additional livestock activities in Altmark, Germany (DE-Arable&Mixed), small-scale mixed farming in Nord-Est Romania (RO-Mixed), intensive dairy farming in Flanders, Belgium (BE-Dairy), extensive beef cattle systems in the Massif Central, France (FR-Beef), extensive sheep farming in Huesca, Spain (ES-Sheep), high-value egg and broiler systems in southern Sweden (SE-Poultry), small-scale hazelnut production in Lazio, Italy (IT-Hazelnut), and fruit and vegetable farming in the Mazovian region, Poland (PL-Horticulture).

FoPIA-SURE-Farm 2 consists of a preparation phase, a stakeholder workshop and an evaluation phase. The preparation and evaluation phase were exclusively conducted by the case study research teams. The research teams have been studying the resilience in their own case studies between June 2017 and August 2020. Stakeholder workshops were conducted in nine case studies between November 2019 and March 2020. This was a second round of workshops in a series of two, where the first round was focused on current and the second on future sustainability and resilience of farming systems. Participation in workshops was limited to farming system stakeholders, i.e. farmers and other actors that are influenced by and influence those farmers (Meuwissen et al., 2019), to make sure that participants had a good understanding of the local context. Farmers and participants from the government, (processing) industry, NGOs, agricultural advisors and researchers were present in the workshops (SM6.1). Farmers were the best represented stakeholder group. The stakeholder workshops lasted about half a day. Individual workshop reports are presented as Supplementary Materials to Paas et al. (2020) in Accatino et al. (2020). 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.

6.3.2 Challenges, function indicators and resilience attributes

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In this paper, we distinguish between system *challenges*, *function indicators* and *resilience attributes*. In the context of resilience, *challenges* relate to the question "resilience to what?" (Carpenter et al., 2001; Meuwissen et al., 2019), e.g. resilience to weather extremes. *Challenges* can affect the system regarding the functions it provides. *Function indicators* are case-study specific characteristics of important system functions, such as "Food production" or "Maintaining natural resources", as direct metrics for those functions are often not available (Meuwissen et al., 2019; for a complete overview of system functions see Table 1.1). In the context of resilience, *function indicators* relate to the question "resilience for what purpose?", e.g. resilience to maintain "Food production". Good values for *function indicators* can be seen as signs of high sustainability (Chapter 2, König et al. 2013). *Challenges* can also affect the system regarding its *resilience attributes*, i.e. characteristics that convey general resilience to a system (Chapters 1 & 2, Cabell and Oelofse, 2012, Walker and Salt, 2012; Table 2.5). Resilience attributes address the question "what enhances resilience?" (Meuwissen et al., 2019). High presence of *resilience attributes* is associated with high resilience. We argue that studying *challenges, function indicators*, *resilience attributes* and their possible interactions provides an opportunity to operationalize sustainability and resilience as complementary concepts (Chapter 5). For more details on the concepts used in this study, see Table A1.1 in the Appendix of Chapter 1.

For benchmarking purposes, case study research teams conducted an assessment of the current performance levels and trends of a few main *function indicators* and *resilience attributes* of the farming system. Main *function indicators* and *resilience attributes* were determined in the first round of workshops with farming system stakeholders, which were conducted one year earlier within the same research project (Chapters 2 & 3). In these previous workshops, eight system *functions* were determined (Meuwissen et al. 2019) and *indicators* were selected in relation to these functions. Perceived importance of both *functions* and *function indicators* was assessed by stakeholders, resulting in main *function indicators* important to functioning of the system. For a set of 13 *resilience attributes*, the presence and contribution to resilience was assessed by stakeholders, resulting in an overview of perceived impact that attributes have on the resilience of the farming system. Contrary to the first round of workshops, the assessments in the second round of workshops were limited by the involved researchers to a few main *function indicators* and *resilience attributes* as critical system changes are expected to be determined by a small set of key variables (Kinzig et al., 2006). The main *challenges* of the respective farming system were also listed and described in each case study workshop. Participants were presented with and asked to comment on proposed main *challenges,* and (performance levels of) main *function indicators* and *resilience attributes*. In the following paragraphs, we present the selection of *challenges*, *function indicators* and *resilience attributes* as obtained in the preparation phase, and the expected developments. As they are results of our first round of workshops, we present these here in order to keep a clear distinction from the results obtained in the second round of workshops and the evaluation phase.

Challenges were encountered in the agronomic, economic, environmental, social and institutional domain. We regard the challenges from the institutional domain as exogenous, where challenges from other domains may be endogenous as well as exogenous to the system. Common *challenges* in the economic domain across most case studies were low commodity prices and price fluctuations or high production costs. In the environmental domain, extreme weather events were experienced as a challenge in the studied arable, perennial and mixed crop-livestock systems. When extreme weather was mentioned in case studies, the occurrence of drought was defined as the most important extreme event. Environmental *challenges* damaging main products in case studies were encountered in NL-Arable (plant parasitic nematodes), ES-Sheep (wildlife attacks) and IT-Hazelnut (pests that reduce yield quantity and quality). A challenge in the social domain in multiple case studies was the low attractiveness of the area and labour availability. In the institutional domain, laws and legislations, and their continuous change, were experienced as *challenges* in most studied systems (SM6.1).

Main *function indicators* differed per case study to take into account the local context, but were representative for system functions, allowing for comparisons across case studies (Paas et al., 2019). *Function indicators* for "Economic viability" and "Food production" were most commonly discussed across case studies. *Function indicators* for "Natural resources" were mainly discussed in the arable systems, but also in SE-Poultry and IT-Hazelnut. *Function indicators* for "Attractiveness of the area" were mainly discussed in case studies in which rural isolation or outmigration was experienced (BG-Arable, DE-Arable&Mixed, IT-Hazelnut). In IT-Hazelnut for instance, the retention of young people was perceived to be representative for this *function*. The number of farms in ES-Sheep was perceived to be representative for "Quality of life". The happiness-index-of-farmers in UK-Arable was perceived to be representative for "Quality of life" and also relates to social isolation and to acknowledgement to and acceptance of farmers by society (SM6.1).

Resilience attributes were selected by researchers based on stakeholder perceptions in the first round of workshops. In those workshops, a pre-defined list of 13 attributes (Table 2.5) was used and could, therefore, be directly compared across farming systems. *Resilience attributes* that were discussed in most case studies were "Infrastructure for innovation", and "Production coupled with local and natural capital". *Resilience attributes* related to diversity, policies or connection with actors outside the farming system were least discussed. In SE-Poultry and PL-Horticulture the "Functional diversity" and "Response diversity" was emphasized. In DE-Arable&Mixed, RO-Mixed and to a lesser extent in IT-Hazelnut, "Support rural life" relating to the embeddedness of the farming system in the rural society was discussed because of rural isolation and/or outmigration that is experienced (see also previous paragraph). In ES-Sheep and IT-Hazelnut, the resilience attribute "Diverse policies" was discussed due to the pressure experienced from environmental regulations that reduce the competitive advantage because of higher production costs (SM6.1).

Levels of most of the main *function indicators* and *resilience attributes* are currently perceived to be slightly decreasing. In the perceived moderately performing systems IT-Hazelnut, SE-Poultry and NL-Arable (Chapter 3), overall moderately positive indicator developments were expected. In the perceived low performing systems ES-Sheep and PL-Horticulture (Chapter 3), and also in UK-Arable, negative developments were expected.

6.3.3 Assessing critical thresholds in farming systems

With reference to current performance and ongoing trends it is interesting to know between what levels the main system *challenges*, *function indicators* and *resilience attributes* need to stay in order to maintain the current system configuration. Critical thresholds were defined as levels beyond which performance of all other key system functions is expected to drop below acceptable levels. Although multiple types of critical thresholds can be distinguished, all types have in common that system change after exceeding them is large and that reversing that change is challenging and costly (Kinzig et al., 2006). To not overcomplicate the concept in a participatory setting, we therefore defined a critical threshold as a point beyond which large and permanent, system change is expected. This change can have a positive as well as a negative connotation. However, as *challenges* are the point of departure in this study, overall change has predominantly a negative connotation.

Workshop participants were asked to individually note down critical thresholds of the main system *challenges*, *function indicators* and *resilience attributes*. Participants were encouraged to provide quantitative assessments of critical thresholds. When asked for by participants, members of the research team could suggest units for expressing critical thresholds. Notes with the stakeholders' assessment of critical thresholds were collected and posted on a wall and were left there for the remainder of the workshop. Notes were discussed in plenary sessions to explore possible critical thresholds and to reach consensus on critical thresholds. Stakeholders' notes of enabling conditions that help avoiding the exceedance of critical thresholds, rather than estimations of values for critical thresholds, were included in the plenary discussions and are summarized in a separate paragraph in this paper.

Closeness of *challenges*, *function indicators* and *resilience attributes* to critical thresholds was evaluated by the research team based on participants' comments and (grey) literature, e.g. based on ongoing trends identified in the preparation phase before the workshop. The position relative to the threshold was considered to be either "not close", "somewhat close" or "close" when it seemed respectively unlikely, somewhat likely or likely that the distance to critical thresholds would be trespassed in the coming ten years, based on knowledge on possible variation and/or trends. We relate proximity measures to likelihoods to indicate the approximative nature of our approach. An indicator that is "close", for instance, is likely to exceed a threshold within ten years, but exceedance can also happen after 30 years, which, however, is less likely. A fourth category of indicating the position relative to the threshold was "at or beyond". Detailed argumentation about the evaluation of closeness to critical thresholds is provided in SM6 2.

After discussing critical thresholds, farming system performance was assessed in case critical thresholds of main *challenges* would be exceeded in the near future. For each identified *challenge*, sub-groups of a moderator and at least three participants were formed on a voluntary basis. In those subgroups, the impact of exceeding the critical threshold of a challenge on main *indicators* and *resilience attributes* was discussed. A research team member functioned as moderator and used a poster to draw arrows between the *challenges* and main *indicators* and *resilience attributes* that were expected to be impacted. The strength of the expected impact was indicated by adding ++, +, -, --, representing a strong positive, moderate positive, moderate negative and strong negative expected impact. As the impacts of exceeding thresholds were determined for the current system, challenges and their impact were discussed in the context of other challenges that are already present in the system. In this paper, therefore, we present and consider the overall impact of exceeding challenge thresholds as the impact of simultaneous stresses that have a combined effect at system level (Homer-Dixon et al., 2015; Walker and Salt, 2012).

The possibility of interactions between critical thresholds of *challenges*, *indicators* and *resilience attributes* was discussed during the workshops. Based on this, and based on the information acquired in the previous step and from literature, research teams aimed to reveal interacting thresholds across domains (environmental, economic and social) and levels of integration (field, farm, farming system) that cause farming system dynamics. Interacting thresholds are thresholds that, when exceeded, lead to the exceedance of another threshold (Kinzig et al., 2006). Determining whether thresholds were interacting was based on qualitative argumentation by researchers using input from workshops. Detailed information on interacting thresholds per farming system is provided in SM6.3.[3]

To be able to concisely compare results from 11 case studies, our focus in this paper is on reporting and discussing the perceived relative closeness to critical thresholds and their interactions. The actual thresholds as noted down and discussed by stakeholders during the workshop are often very case-specific. Moreover, the precise level of critical thresholds was in most cases challenging to assess as stakeholders differed in opinion, and used different metrics. The assessments of thresholds are therefore mainly used to illustrate the methodology and our findings.

6.4 Results

6.4.1 Closeness to critical thresholds

More than half of the identified *challenges* were perceived to be "close" or "at or beyond" critical thresholds (Table 6.1). For extreme weather, closeness differed between farming systems: NL-Arable, IT-Hazelnut, PL-Horticulture, were perceived "somewhat close" to, DE-Arable&Mixed and BG-Arable seemed "close" to and RO-Mixed seems "at or beyond" the perceived critical thresholds. For the environmental *challenge* "pest & diseases", NL-Arable, challenged by plant parasitic nematodes, and IT-Hazelnut, challenged by phytophatologies, were perceived to be "somewhat close" to critical thresholds. For *challenges* in the social, economic and institutional domain, participants perceived more often that critical thresholds were reached than for the environmental domain. In ES-Sheep, participants indicated that for all *challenges* critical thresholds were reached, except for wildlife attacks (no threshold defined). In DE-Arable&Mixed, the lack of infrastructure and low attractiveness of the area were perceived to be at or beyond a critical threshold. In SE-Poultry, the perceived mismatch between economic viability on the one hand and the high production standards and strict environmental regulations on the other hand made participants indicate that for both *challenges* critical thresholds were reached. Continuous change of laws and regulations was seen as a main *challenge* in NL-Arable, UK-Arable, PL-Horticulture as well as BG-Arable. Participants in these case studies, for instance, perceived a critical threshold in the case that certain crop protection products would be banned before replacements had become available. A policy implication here would be to study a reasonable time for phasing out/in of policies. In DE-Arable&Mixed, SE-Poultry and RO-Mixed, inadequate alignment of policies and regulations at national and EU level was mentioned: national production quality standards increase production costs, while abiding with EU trade regulations allows for cheaper imports from countries with lower production standards and constraints.

[3] Minor deviations from the methodology described above occurred in multiple case studies. BE-Dairy & FR-Beef: Desk study instead of a workshop. ES-Sheep: Participants argued that the system was already on the edge of collapse/decline. To still stimulate the discussion, the individual assessment of critical thresholds was turned into a plenary discussion. To this end, researchers presented participants with the statistics on the current values of the *challenges*, *function indicators* and *resilience attributes*. In case of disagreement with the presented values, participants were asked to provide the perceived current value of the indicator and the distance to its threshold. To balance plenary and individual activities, the researchers' team asked participants to individually assess s interactions between challenges, function indicators and attributes when critical thresholds were exceeded. Once participants reflected on this, they discussed their ideas in a plenary session. NL-Arable: Critical thresholds of resilience attributes were not discussed plenary due to time constraints. PL-Horticulture: Modified (aggregated) function indicators were used compared to the outcome of the previous workshop to achieve more structured and focused responses. Therefore four indicators were outlined based on the previous results, some consisting of several indicators of relatively high importance defined within the previous approach. SE-Poultry: Separate workshops were conducted for the egg and broiler production.

Table 6.1. Number of times challenges were assessed being in a certain position relative to the perceived critical threshold (aggregated results across 9 case studies; only main challenges were discussed in each farming system).

		Position relative to perceived critical threshold				**No threshold defined**	**Not discussed**	**Total† (n)**
Challenge	**Domain**	**Not close**	**Some-what close**	**Close**	**At 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		1	1				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 of rural areas	Social				1			1
Low labour availability	Social		1	1	1			3
Changes in consumer preferences	Social				1		1	2
Total (n)		**4**	**11**	**12**	**10**	**-**	**1**	**38**

†For BE-Dairy and FR-Beef desk studies were conducted instead of workshops. Results from these case studies are hence not included in this table.

Participants could define critical thresholds for most system *function indicators* (Table 6.2); for instance, critical thresholds for the yield per hectare, an indicator related to the function "Food production", e.g. in BG-Arable, RO-Mixed and NL-Arable. Systems were perceived to be "close" to critical thresholds for "Food production" and "Economic viability" and "somewhat close" to those for "Natural resources" and "Attractiveness of the area". In IT-Hazelnut, for instance, the threshold for "Gross margin" relating to the function "Economic viability" was assessed to be 5,000 Euros per hectare, but was expected to differ from farm to farm. Based on current variability of markets and climate, it is likely that the value will someday drop below the indicated threshold, which makes that the system may be close to this critical threshold. For the seemingly low performing systems PL-Horticulture and ES-Sheep, some indicator levels were perceived to be at or beyond the threshold. In these systems, immediate action seems required, e.g. with regard to product prices and availability of labour in the area. Reaching critical thresholds for soil quality, an indicator representing "Natural Resources", was a concern in UK-Arable and NL-Arable. In those systems, participants mentioned that continuous adaptation is needed to prevent further degradation. In NL-Arable, a participant from the regional water board indicated that in the long-term water availability would decline, thus the system would approach a threshold. Most other participants took a more medium-term stance and therefore proximity to this threshold was considered somewhat close. Overall, there was rarely a disagreement between participants about threshold levels. In BE-Dairy, where a desk-study was performed, water quality and greenhouse gas emissions were perceived to be beyond acceptable levels set by European and regional policy makers. Farmers in BE-Dairy are likely to disagree with these externally determined thresholds. In SE-Poultry, DE-Arable&Mixed, ES-Sheep and NL-Arable, participants indicated that critical thresholds for economic viability differ from farm to farm. Hence, exceeding critical thresholds in these case studies may foremost imply the disappearance of economically less competitive farms from the farming system, rather than an immediate decline of the entire farming system performance.

Table 6.2. Number of times function indicators were assessed being in a certain position relative to the perceived critical threshold (aggregated results across nine farming systems; only main function indicators were discussed in each farming system).

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

†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.

For *resilience attributes*, relatively fewer critical thresholds were defined than for *function indicators* (Table 6.3; 22 out of 37 vs. 35 out of 42). Thresholds of *resilience attributes* were mostly (semi-) qualitatively determined. For instance, in DE-Arable& Mixed "Supports rural life" was assessed to be on the lower end of a 1 to 5 scale where 1 implied very low and 5 implied a very high support. Participants indicated that a further decline in support would imply crossing a critical threshold. Overall, when defined, *resilience attributes* seem less close to critical thresholds than *function indicators*. From a methodological point of view, *resilience attributes* might be harder to grasp, and therefore more difficult to define and also perceived to be less close to critical thresholds than *function indicators.* From a theoretical point of view, the distance to critical thresholds could suggest that under the current *challenges*, resilience capacities are still sufficient to, for instance, start an adaptation or transformation process that steers away from critical thresholds of system *challenges* and *indicators*. However, the presence of some attributes e.g. "Reasonably profitable", when discussed and when a critical threshold was defined, was perceived to be close to a critical threshold, similar to the function "Economic viability" in most case studies (previous section). For the resilience attribute "Diverse policies", i.e. policies that equally support robustness, adaptability and transformability (Chapter 2), the systems in ES-Sheep and IT-Hazelnut were perceived to be at or beyond a critical threshold. In IT-Hazelnut the system was perceived to be close to a critical threshold regarding "Infrastructure for innovation". In IT-Hazelnut, current innovation levels were perceived already high, but would benefit from more to ensure further adaptation and improvement. For most other *resilience attributes* the system was perceived to be (somewhat) close to critical thresholds.

Table 6.3. Number of times resilience attributes were assessed being in a certain position relative to the perceived critical threshold (aggregated results across 9 farming systems; only main resilience attributes were discussed in each farming system).

Resilience attribute	Position relative to perceived critical threshold: Not close	Some-what close	Close	At or beyond	No threshold defined	Not discussed	Total† (n)
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
Supports rural life		2	1				3
Socially self-organized	1	2	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**

†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.

While noting down and discussing critical thresholds, participants often mentioned enabling conditions that help avoiding the exceedance of critical thresholds, rather than precise values for critical thresholds. Enabling conditions can be seen as general notions of how system specific problems can be solved for the current system. Enabling conditions in the agronomic domain were mentioned only in BG-Arable, NL-Arable and ES-Sheep; e.g. improving productivity levels (BG-Arable) and availability of geo-localization technologies (ES-Sheep). Enabling conditions in the economic domain were e.g. creating access to new markets (ES-Sheep, IT-Hazelnut, NL-Arable), environmental payments (NL-Arable, ES-Sheep) and improving input/output price ratios (SE-Poultry, RO-Mixed, PL-Horticulture, NL-Arable, IT-Hazelnut). Enabling conditions in the environmental domain were e.g. low occurrence of extreme weather events (BG-Arable, IT-Hazelnut, NL-Arable, PL-Horticulture, RO-Mixed), improved soil quality (NL-Arable, UK-Arable) and ecological and resource management regulations (IT-Hazelnut, RO-Mixed, ES-Sheep). Specifically in UK-Arable, emphasis was put on enabling conditions in the environmental domain. Enabling conditions in the institutional domain included good governance practices of authorities (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). Enabling conditions in the social domain were e.g. related to rural demographics and/or availability of labour (BG-Arable, IT-Hazelnut, PL-Horticulture, RO-Mixed, SE-Poultry, ES-Sheep, DE-Arable&Mixed) and more horizontal and vertical cooperation and social self-organization (BG-Arable, ES-Sheep, PL-Horticulture, RO-Mixed, UK-Arable). Specifically, in BG-Arable and RO-Mixed emphasis was put on enabling conditions in the institutional and social domain.

6.4.2 Interacting thresholds and impact of exceeding these

In all case studies, interacting thresholds across level and/or domain were observed (Figure 6.1; SM6.3). More details on the interacting thresholds are presented in the SM6.3. Common interactions between critical thresholds occur between field-environmental and 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 (Figure 6.1). 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 so much of a shock or stress that it leads to yields that are too low to sustain an adequate level of farm income (see SM6.3). In a majority of the farming systems, high input prices and decreasing output prices and sales further diminish the farm income. Too low incomes at farm level were in all case studies resulting in reduced attractiveness of farming, farmers quitting 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 quitting a farm. Farmers quitting their farm without having a successor was in multiple farming systems also considered to contribute to a smaller rural population at farming system level (FR-Beef, ES-Sheep, RO-Mixed, BG-Arable, IT-Hazelnut, PL-Horticulture; Figure 6.1). Interestingly, although socially oriented *function indicators* and *resilience attributes* were less often formally included in the discussions, they eventually appeared when explaining how challenges impact the farming system. Having less farms in the farming system was also associated with a lower maintenance of natural resources and a less attractive countryside (ES-Sheep, FR-Beef; SM6.3). Interactions with critical thresholds in the environmental domain at farm and farming system level were mentioned in a few other case studies. In NL-Arable, at farm level in the environmental domain a narrow rotation in which starch potato is grown every second year was expected to lead to increased pressure of plant parasitic nematodes (SM6.3). In UK-Arable, low income at farm level was expected to lead to declining soil health at field level (SM6.3). In IT-Hazelnut and SE-Poultry, environmental regulations were expected to improve the maintenance of natural resources at farming system level, but also to push farm income levels below a threshold through increased costs (SM6.3). Overall we observed that environmental thresholds certainly feature, but differ in the level at which they play a role and in what direction they evolve. In farming systems for which access to land is an issue (e.g. BE-Dairy, PL-Horticulture), quitting of farmers may also be an opportunity, provided land becomes available on the market for sale or to be leased. In ES-Sheep, quitting of farmers was experienced as a serious issue. In IT-Hazelnut, the retention of young people on the farms was specifically mentioned as something that could support the rural life and vice versa (SM6.3). Both low economic viability at farm level and low attractiveness of farming and a smaller rural population were considered to reduce the access to labour at farm level in BG-Arable, SE-Poultry, PL-Horticulture, DE-Arable&Mixed, RO-Mixed, and ES-Sheep. Access to labour in BG-Arable, PL-Horticulture and RO-Mixed was important for the continuation of activities on farms, as lack of labour was expected to push yields below acceptable levels (Figure 6.1). In BG-Arable lack of labour could be overcome by implementing new technologies, but this would require a labour force with higher levels of education and qualification which is even harder to find. Lack of labour was also expected to push production costs beyond critical thresholds in SE-Poultry and RO-Mixed. Hence, in multiple systems, low economic viability, attractiveness of farming, rural depopulation and low level of services at farming system level, and low access to labour seem to be part of a vicious cycle.

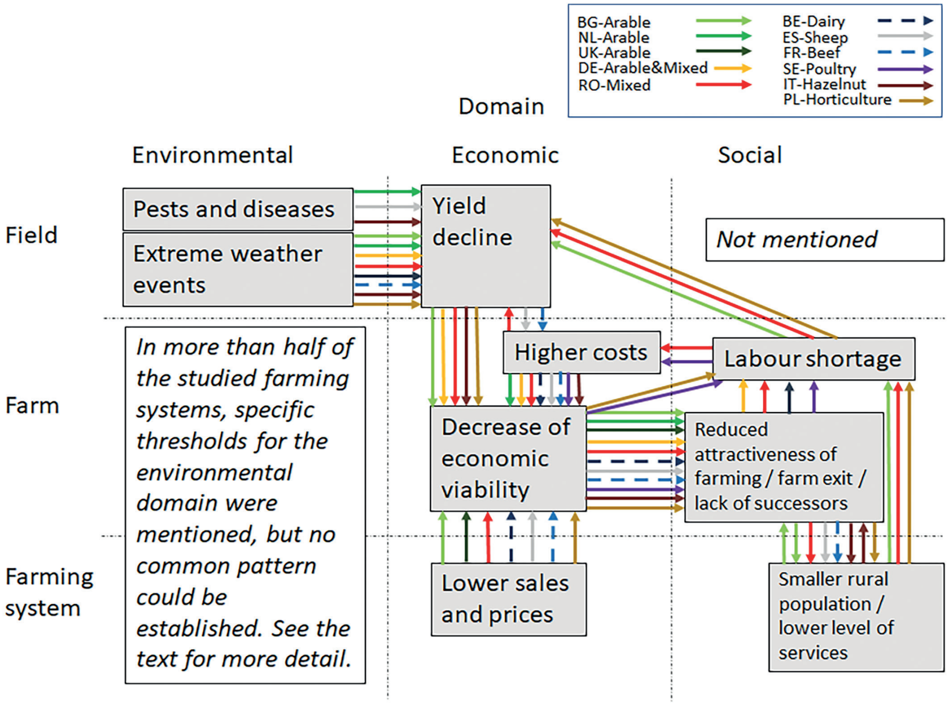

Figure 6.1. A synthesis of main interactions across scales and domains for 11 European farming systems (based on the framework of Kinzig et al., 2006).

Following from Figure 6.1, it can be made plausible that after exceeding critical thresholds of *challenges*, a decline in performance of system's main *function indicators* and *resilience attributes* was expected by workshop participants in most case studies (see SM6.1 for details). Across farming systems, the functions "Food production", "Economic viability", and the "Natural resources" were in most cases expected to decline moderately or strongly (SM6.1). Especially system functions in arable systems were perceived to be moderately to strongly affected. In ES-Sheep, ongoing decline of function performance was expected to be aggravated. When discussed in case studies, "Biodiversity & habitat" and "Animal health & welfare" were on average expected to be less impacted compared to other functions.

When exceeding critical thresholds of challenges, also a decline in *resilience attributes* was expected in most case studies, mainly because of a decline in profitability, production being less coupled with local and natural capital, a declining support of rural life and lower levels of self-organization (SM6.1). By contrast, participants in BG-Arable and SE-Poultry generally expected improvements in *resilience attributes* after critical thresholds are exceeded (SM6.1). For instance, infrastructure for innovation was expected to develop positively in BG-Arable and SE-Poultry, while it was expected to develop negatively in other case studies (DE-Arable&Mixed, ES-Sheep, NL-Arable, UK-Arable). In the case of BG-Arable, participants expected increased collaboration, leading to innovation, in case the system would collapse. In the case of ES-Sheep, participants expected that the current low profitability of farmers will not allow investment in new infrastructures for innovation.

6.5 Discussion

6.5.1 Closeness to critical thresholds

All studied farming systems were perceived to be "close" or "at or beyond" at least one critical threshold for *challenges*, *function indicators* or *resilience attributes* (Tables 6.1-3). The actual state of the system may be more or less close to a threshold than the participant's perception. Obviously, for case studies that are perceived to be "at or beyond" critical thresholds while still continuing business as usual, the actual state must be at a different position than perceived. Still, perceived closeness can be seen as a clear stress signal, indicating that change is needed, expected or even already experienced. An example refers to the ban of crop protection products before alternatives are available. This stress signal could instigate a study about a reasonable time to phase in/out regulations regarding the use of crop protection products before actually implementing them. Perceptions of being close to or at critical thresholds also indicate that, from the perspective of farming system actors, immediate action is needed to preserve the farming system or guide it in its transition, thus avoiding a situation where sustainability is even lower. Looking at multiple *challenges* puts individual *challenges* into perspective. To give an example, climate change may be a problem causing regime shifts in many socio-ecological systems (Biggs et al., 2018), but for the studied farming systems this is not the only *challenge* and often also not perceived to be the most urgent, except for some arable systems (Table 6.1). This supports the notion that climate change should be studied in the context of other drivers (Hermans et al., 2010; Mandryk et al., 2012; Reidsma et al., 2015). At a global level, reducing anthropogenically induced climate change is, of course, urgent and agricultural systems' contribution to it must be reduced. Some challenges experienced by FS actors, especially farmers, may also be implicitly caused by climate change; for instance changing legislation and high input costs. For most of the farming systems in our study, climate awareness of some stakeholders, such as conventional farmers, is however not likely triggered due to the impact of climate change on their system per se. When deliberated in an appropriate manner with those stakeholders, new legislation in the context of fighting climate change may however have considerably more effect regarding changing stakeholder perceptions.

Function indicators for food production and economic viability were often perceived to be close to critical thresholds. This confirms the need to closely monitor economic indicators as is done in the CMEF of the CAP (European Commission, 2015). When discussed, social *function indicators* were generally perceived to be "not close" or "somewhat close" to a critical threshold, except for ES-sheep where participants experienced that a critical threshold was exceeded (e.g., quality of life through number of farms, which lead to work generation) (Table 6.2). Environmental *function indicators* were in most cases perceived to be "not close" or "somewhat close" to critical thresholds (Table 6.2). Only in arable systems, environmental functions were experienced "close" or "at or beyond" critical thresholds. This was mainly related to the capacity of soils (at farm or field level) to deal with an excess or lack of water, often due to climate change. Participants in workshops of arable systems indicated that a lot of effort was already required to maintain rather than to improve the current soil quality. Arable systems, in need for soil improvement to avoid critical thresholds, would benefit from enabling conditions at national and EU level that foster the maintenance of natural resources. Mitter et al. (2020), based on a mechanistic scenario development approach for European agriculture, expect improved attention for natural resources only in a scenario following a "sustainability pathway" out of five possible future scenarios. Current conditions and their future development hence do not seem to support a resilient future of arable systems. Overall, perceived closeness to critical economic thresholds could explain the perceived lower importance of social and environmental functions compared to economic and production functions (Chapter 3).

Defining critical thresholds seemed most difficult for *resilience attributes* (Table 6.3). According to Walker and Salt (2012) it is actually impossible to determine critical thresholds for *resilience attributes* because they all interact. However, *function indicators* also interact, but were easier to assess for participants. We argue that difficulties in determining critical thresholds are probably more an indication of the perceived redundancy of *resilience attributes* for system functioning: presence and contribution to resilience was low to moderate according to stakeholders' perceptions (Chapters 2 & 3). This could be related to a control rationale (Hoekstra et al., 2018), in which keeping a relatively stable environment and improving efficiency is more important than increasing the presence of *resilience attributes*. It should be noted, however, that participants often could indicate enabling conditions that improve the *resilience attributes*. This could be an indication that participants are aware of the importance of *resilience attributes*, but are in need for more concrete, locally adapted indicators that represent the *resilience attributes*. In any case, suggesting improvements for *resilience attributes* could be seen as an implicit acknowledgment by participants that building capacities for adaptation or transformation is required.

Perceived thresholds may be different than the real threshold. For the systems that are perceived to be "at or beyond" critical thresholds, it is not necessarily too late to adapt in case the real threshold is actually at a different level than the perceived one. The extensive sheep system in Spain was judged to be close to a collapse, but alternative systems and strategies to reach those have been proposed (Chapter 5). In IT-Hazelnut, introduction of new machinery in the past has made farming more attractive for the younger generation, thus avoiding depopulation (Nera et al., 2020). Further developments in IT-Hazelnut regarding local value chain activities at farming system level rather than farm scale enlargement, are aimed to further stimulate economic viability and the retention of young people in the area (Nera et al., 2020; Paas et al., 2020). In PL-Horticulture, the case study is relatively close to Poland's capital where access to land is limited, system actors aim at increasing the economic viability via vertical and horizontal cooperation at farming system level, which keeps re-attracting seasonal laborers from nearby Ukraine, where wages are lower, to the region. The common factor in these examples of adaptation is that resources are needed to implement them. Be it financial, human, social or other forms of resources. The examples above also suggest that coming back to a desired state, even after exceeding a critical threshold, is possible, provided the disturbance causing the exceedance does not last too long (e.g. Van Der Bolt et al. 2018), and adaptation strategies are available (e.g. Schuetz, 2020). The notion of a critical threshold being a combination of magnitude (level) and duration was not discussed much in the workshops but could help to further define critical thresholds. For instance with regard to the number of years the farming system can deal with extreme weather events as was done in NL-Arable.

It is worth noting that *challenges* are perceived to be more often "at or beyond" perceived critical thresholds than *function indicators* and *resilience attributes*. From a system dynamic perspective this could suggest that the studied farming systems have some buffering capacity to deal with disturbances (Meadows, 2008). An example of this is the farm expansion in area and number of animals in many farming systems that compensates for the loss of farms from the system. From a methodological perspective, it could be argued that the participatory assessment of critical thresholds of *challenges* is easier than for *system functions* and *resilience attributes*. Critical thresholds of *challenges* are linked to important *function indicators* and *resilience attributes* and, therefore, may serve as warnings in the mental models of farming system stakeholders.

6.5.2 Interaction of critical thresholds

Based on workshop results and further reflections, interactions between critical thresholds are expected to (in)directly affect the economic viability at farm level, a central critical threshold observed in all farming systems (Figure 6.1). Economic viability at farm level is a relatively fast and measurable indicator. This gives another argument for monitoring income and other economic indicators in the monitoring frameworks such as the CMEF. The lack of a consistent pattern with regard to environmental thresholds indicates the importance of the local context.

In all farming systems, exceeding the critical threshold for economic viability at farm level affects the attractiveness of the sector, the number of farm closures and the availability of farm successors, which in turn in about half of the case studies contribute to lower availability of (qualified) labour and/or depopulation, which finally can reinforce low economic viability. Hence, a vicious cycle is initiated. This suggests that processes related to the economic and social domain can be driving dynamics of farming systems as well as being reinforced by those dynamics. This potentially can turn a relatively slow social process into a fast process. Social processes are therefore indeed important to monitor (Walker and Salt, 2012). This is already acknowledged in, for instance, in DE-Arable&Mixed, where participants emphasized the attractiveness of the area, specifically regarding the development of infrastructure.

Through its interactions with processes in other domains and levels, economic performance can be seen as an indirect driver as well as a warning signal for approaching critical thresholds in other domains and levels. In all farming systems food production was perceived to directly impact economic viability. Therefore, from the perspective of many farming system actors participating in our workshops, focus on food production and economic viability (FoPIA-SURE-Farm 1), which are based on relatively fast and measurable processes (Walker & Salt, 2012), seems often more justified than focusing on the more slowly developing social functions such as providing an attractive countryside. However, this may be due to the fact that (conventional) farmers were in most case studies the best represented stakeholder group, thus possibly masking the voices of other stakeholder groups that were represented less. In any case, social and environmental functions should not be overlooked as a focus on one domain will likely lead to missing important interactions with critical thresholds in other domains (Kinzig et al., 2006). For example, improving economic viability through scale enlargement and intensification, meaning fewer farms and often replacing labour by technology, often leads to a less attractive countryside. Regarding the environmental domain, focus on economic farm performance can even be dangerous as it could ignore externalized risk. For instance in UK-Arable and NL-Arable soil quality, the base of crop production and hence economic performance, was considered close to critical thresholds, while prohibition of certain crop protection products was seen as a challenge for the farming system, rather than the damage these products cause to surrounding ecosystems. Another example of externalized risk in one of our case studies is the pollution of water bodies in IT-Hazelnut. On their own, farmers may initially not have the willingness or capacity to look beyond the farm level. In IT-Hazelnut, farmers, through interaction with environmental actors, are now addressing these environmental issues. Building on this example, we argue that for instance societal dialogues and policy deliberations on improving sustainability and resilience need input from specific social and environmental actors, possibly even from outside the farming system. This seems necessary to counter-balance the bias towards economic performance at farm level by most of the participating farming system actors in most of our workshops.

In the more remote case studies, e.g. DE-Arable&Mixed and BG-Arable, attractiveness of the area seems low anyway. Consequently, improving prices alone, for instance, may not improve the availability of the necessary labour, thus reducing the emphasis on economic performance. Extensive rural development seems necessary to maintain the functioning of these farming systems. Mitter and et al. (2020), based on their mechanistic scenario development approach, expected no or negative developments regarding rural development in all future scenarios of European agriculture. The notion that both mechanisms at European and farming system level are not wired to address rural development, shows how the low attractiveness of an area can persist once it has come about.

Avoiding exceedance of critical thresholds without further adaptation or transformation, implies a performance at or below the current low to moderate levels for most system *function indicators* and *resilience attributes* (Chapter 3). A potential exceedance of a critical (and interacting) threshold in the coming ten years is expected to lead to negative developments for most system *function indicators* and *resilience attributes*. Negative developments of *function indicators* are expected in the economic, social as well as the environmental domain. On average, across all farming systems, we did not observe any differences in the magnitude of the effect between domains for *function indicators*. This consistent development confirms the idea that the different domains are interacting.

The consistent expected developments for *function indicators* and *resilience attributes* after exceeding critical thresholds suggest a perceived interaction between them. One could argue that a system needs resources to react to shocks and stresses (Meadows, 2008; Walker and Salt, 2012), especially for adaptation and transformation. These resources can only be adequately realized when there is an enabling environment and when system functions are performing well. The other way around, *resilience attributes* can be seen as "resources" to support system functions on the way to more sustainability. For instance, 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 to improve system functioning (Table 2.5).

6.5.3 Farm level responses to reaching critical thresholds of challenges

Impact 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 critical thresholds would be perceived differently among farmers. As mentioned before, farm closure generally leads to a less attractive countryside, a long-term process that is currently not perceived the most important issue in most studied farming systems, according to stakeholder input. Increasing farm size could be seen as a solution to compensate for the loss of farms and farmers in the farming system. 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, ES-Sheep), production margins are low, which could further stimulate this thinking. However, from the farm level perspective, beyond a certain size, further economies of scale are not realized in some of the studied farming systems, i.e. there are limits to growth dependent on the rural context. In BE-Dairy, for instance, increasing farm size seems to be limited due to environmental standards. In ES-Sheep, 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 initiatives, etc., but also hospitals, schools, etc. Besides, to further increase farm size, farmers in ES-Sheep depend on extra labour that is not available because of low attractiveness of the countryside, while investment in labour saving technology does not pay off with the current market prices. This is an example of the reflection of Kinzig et al. (2006) that a seemingly reversible threshold (no hysteresis effect) becomes irreversible because a certain management option to reverse processes is not available anymore. Based on Figure 6.1, we argue that this specific example may be true for more farming systems where a lack of labour force is experienced and investment in labour saving technology are not likely to pay off (e.g. RO-Mixed).

6.5.4 Implications for monitoring resilience

Social indicators

The importance of the social domain of farming systems makes us argue that indicators in this domain should be monitored. The option for countries in CAP2021-27 to shift 25% of the budget from income support (Pillar I) to rural development (Pillar II) provides the opportunity to adapt policies and investments to rural development needs. For instance for the more remote farming systems such as DE-Arable&Mixed and BG-Arable. We argue that a large shift of budget across the two pillars is already an indication of the perceived need to improve rural living conditions and can thus be used for monitoring. Although relating to economic values, the allocation of budget to rural development can thus be seen as the importance that is attributed to support processes in the social domain. Caution is needed however, as Pillar II also supports processes related to the environmental domain. Surveys among (agricultural) experts at national and regional level that record how much of the budget should be shifted from pillar I to II is a further step in assessing the performance of farming systems in the social domain. This implies introducing subjectivity in the CMEF on the evaluation side, while the choice of the parameter (shift of budget) is defined objectively, i.e. externally. Jones (2019) remarks that objectively defined and subjectively evaluated resilience assessments are relatively robust, easy and quick, while the limitations lay mainly in having to deal with bias, priming and social desirability. Other possibilities for objectively defined and subjectively evaluated indicators may lie in including indicators on living conditions and quality of life in rural areas based on Eurofound studies (Eurofound, 2021, 2019). These type of indicators also have the advantage of being entirely in the social domain, i.e. they don't indirectly refer to economic values such as the shift in budget from Pillar I to Pillar II as discussed above.

Monitoring resources

A common reflection in the discussion section so far is that having adequate system resources seems essential for stimulating system *resilience attributes* and dealing with challenges. In cases of low farming system resilience, building system resources may initially depend largely on external resources. This implies a role for regional, national and EU government bodies, i.e. a pro-active role for actors in the institutional domain outside the farming system. Given the tendency to focus on economic performance at farm level, external resources in the form of economic subsidies should be increasingly conditional regarding environmental and social functioning of the farming system. The emphasis on (accessible) resources for building resilience is also acknowledged in several recent resilience frameworks (Duchek, 2020; Mathijs and Wauters, 2020), for instance with regard to knowledge and innovation systems (AKIS; Mathijs and Wauters, 2020). To elaborate on the example of AKIS, we argue that, rather than only monitoring and evaluating the amount of budget and the number of people that benefit from improved AKIS (as is currently done in for instance the CMEF), also the amount of this resource and stakeholders` access to it should be known and evaluated regularly. Similarly, other social and institutional resources need to be monitored next to economic and environmental resources.

6.5.5 Reflection on methodology

Given the challenges regarding assessing and discussing critical thresholds in workshops (stakeholder participation, differing stakeholder opinions, differing metrics, farm-specificity of thresholds, expert judgments of case study researchers on proximity to those thresholds), all identified critical thresholds could be seen as "Thresholds of potential concern" (TPCs; Walker and Salt 2012 citing Biggs and Rogers, 2003). In our case these TPCs would express the concerns of a selection of farming system stakeholders. TPCs can be seen as a set of evolving management goals that are aimed at avoiding critical thresholds that are expected, e.g. from experiences in other systems, but are not known. In case thresholds are considered beforehand as TPC's, Q-methodology (McKeown and Thomas, 2013) may be an interesting participatory method to define which TPC deserves most priority. Estimating main functions of a system by assessing critical thresholds as TPCs, reduces the presence of clear sustainability goals. This makes the threshold assessment less dependent on externally determined values and criteria than most sustainability assessments (see e.g. Binder et al. 2010). Implicitly, the goal is to avoid a decline in sustainability and resilience levels of the current system, which may give the participating system actors the trust to provide details, expose interrelatedness between sustainability domains, and also come up with solutions. Regarding the latter, it should be noted that avoiding exceedance of critical thresholds does not automatically imply that a system is steering away from mediocre performance. This is why after assessing critical thresholds, participants should also be stimulated to think about adaptations to improve their system to desired sustainability and resilience levels (Chapter 5). Be it by steering away or actual exceeding critical thresholds to arrive at higher sustainability levels. Chapter 5 suggests a back-casting approach, but other solution-oriented methods such as participatory multi-criteria decision analysis may also be appropriate (Belton and Stewart, 2002). In any case, starting with a threshold assessment before solution-oriented participatory methods may create path-dependency, resulting in adaptations that lead to a reconfirmation of the current system where a transformation might actually be more appropriate. This path-dependency is likely to be reinforced by only inviting participants from within the farming system. Farming system actors are for instance probably biased regarding depopulation and a loss of attractiveness of the rural area, as it is related to farm closure. Considering the possibility that the closure of individual farms could be good for the farming system as a whole might go beyond the mental models of some farming system actors. Participatory methods involving so-called "critical friends" that have no direct stake in the system might help to overcome this obstacle (Enfors-Kautsky et al., 2018). Involving external actors is especially required in unsustainable systems that persist through the agency of only a subset of stakeholders.

It should be noted that critical thresholds are never static as they depend on the context (Kinzig et al., 2006; Resilience Alliance, 2010). The need for labour, for instance, depends on the level of automatization in agriculture. Critical thresholds may change because of slowly changing variables (Kinzig et al. 2006 citing Carpenter et al. 2003), which is also acknowledged in this study by presenting interacting thresholds across levels and domains in multiple case studies. Different domains could be addressed by including a variety of social, economic, institutional and environmental *challenges*, *function indicators* and *resilience attributes*. Using the framework of Kinzig et al. (2006) forced in particular researchers in some case studies to reflect on critical thresholds in the social domain, while focus of participants was more on economic and environmental processes. The framework of Kinzig et al. (2006) can hence show where knowledge of stakeholders is limited. This is an asset as exposing the limits of local knowledge is often lacking in participatory settings (Mosse, 1994). Explicitly adding the institutional domain and a level beyond the farming system to the framework of Kinzig et al. (2006) may further reveal the limits of knowledge and improve the understanding of farming system dynamics. To further stimulate co-production of knowledge, the figures with interacting thresholds (e.g. Figure 6.1) could be fed back to farming system stakeholders in a follow-up workshop. In addition, farming system actors could be stimulated to think about representative indicators for resilience attributes. These representative indicators could add local meaning and thus improve stakeholders' understanding and assessment of the resilience attributes and resilience mechanisms (see also Chapter 5).

Becoming aware about a threshold can help reducing the likelihood of exceeding one (Resilience Alliance, 2010). Indeed, assessing critical thresholds may bring the awareness that is needed to move away from the conditions that have caused them. Participatory methods that are more specifically aimed at social processes could bring about awareness of system actors. However, interrelatedness with processes in other domains are consequently likely to be lost out of sight. Still, specific attention for social processes in the conducted workshops can improve the integrated nature of the assessments, for instance by pre-selecting at least one indicator related to a social function and a resilience attribute related to social conditions. For some case studies in this study, this would imply a suggestion that new functions and system goals are needed. Although top-down, this could initiate the process of system actors picking up this signal as being valuable (belief formation) and the process of redirecting the system as a whole to an alternative state (conversion; Biesbroek et al. 2017).

The study presented in this paper is a resilience assessment that is partly objectively and partly subjectively defined: we worked with a set of *function indicators* and *resilience attributes* selected in a previous workshop by stakeholders based on lists prepared by researchers (Chapters 2 & 3). Such an approach may not be feasible at European scale, but has proven effective for postulating candidate indicators for monitoring frameworks such as the CMEF. More participatory workshops in a diverse range of European farming systems are advised to find more of these indicators that can enrich those monitoring frameworks. It should be noted however, that assessments inclining towards a subjective definition and evaluation of resilience are poorly researched and that translation issues and cultural biases can limit these kind of assessments (Jones, 2019). Further elaboration and study of participatory methodologies is therefore necessary to improve its use for evaluating sustainability and resilience at farming system, national and European level. Specifically the desired or acceptable degree of objectivity vs. subjectivity in assessments across different levels (field, farm, farming system) and domains (economic, environmental, social) should be discussed.

6.6 Conclusion

In our participatory approach, all 11 studied systems in the European Union were perceived to be "close to", "at or beyond" at least one identified critical threshold (Tables 6.1-3). In particular, critical thresholds in the economic domain were considered to be (almost) reached. This could explain the economic orientation of farming system stakeholders and the current CMEF of the CAP. Overall, a strong decline in system performance was expected if critical thresholds would be exceeded. We conclude that concern for exceeding critical thresholds is justified, even though precise determination of a threshold position based on a participatory approach is difficult. Stakeholder perceptions on critical thresholds provide useful information as they serve as a stress signal and can be used as a starting point for a dialogue with farming system actors. We suggest that critical thresholds could be seen as a "thresholds of potential concern" for which management and policy goals may be developed. For instance, policies to attract more agricultural workers to an area to avoid a shortage of labour. Those policy and management goals should include the development of metrics that provide rigorous information on that specific threshold. The analysis of critical thresholds provides a basis for early thinking about possible alternative configurations of the systems. In this regard, the results can be used to reflect collectively about farming system trajectories, as to system functions and the often-competing goals of the different stakeholders. Therefore, the results of the analysis can be used to develop a contextualized, shared vision and to identify, within each farming system of interest, where to focus regarding increasing the resilience and sustainability of the farming system.

Critical thresholds were perceived to interact across levels of integration (field, farm, farming system) and domains (social, economic, environmental) in all case studies (Figure 6.1). Common across case studies was the central role of economic performance at farm level, which was mainly affected by price levels and yield levels. This is another confirmation of the importance of economic indicators in the CMEF. However, in all case studies, exceeding the critical threshold of economic performance at farm level was associated with social issues such as lower attractiveness of farming, lower availability of successors or farm exit. In some farming systems, these social consequences were also experienced as critical thresholds contributing to lower labour availability reinforcing the low economic performance or contributing to depopulation, which encourages the loss of attractiveness of farming. This reinforcing effect may speed up the erosion of resources in the social domain. Social indicators are therefore important to consider when assessing the sustainability and resilience of farming systems.

A recurrent theme in our discussion section is the importance of system resources for stimulating sustainability and resilience of farming systems. For instance with regard to creating buffering capacities, building *resilience attributes* or finding the means to implement resilience enhancing strategies. We therefore stress the need to include system resource indicators such as soil quality, habitat quality, knowledge levels, attractiveness of rural areas and general well-being of rural residents when monitoring and evaluating the sustainability and resilience of European farming systems. In cases of low farming system resilience, building system resources may initially depend on actors in the institutional domain outside the farming system. In case of economic subsidies, these should be increasingly conditional on the environmental and social functioning of farming systems.

Supplementary Materials

Supplementary Materials 6.1: https://ars.els-cdn.com/content/image/1-s2.0-S0743016721003223-mmc1.docx

Supplementary Materials 6.2: https://ars.els-cdn.com/content/image/1-s2.0-S0743016721003223-mmc2.xlsx

Supplementary Materials 6.3: https://ars.els-cdn.com/content/image/1-s2.0-S0743016721003223-mmc3.docx

General discussion

7.1 Objectives and design of the study

The aim of this thesis is to operationalize the SURE-Farm resilience framework (Meuwissen et al., 2019) with new and (semi-)quantitative methods and to assess the sustainability and resilience of current and future European farming systems. The following research questions are central in this thesis:

- Is there a balance between social, economic and environmental functions in European farming systems in terms of importance and performance?
- Are European farming systems approaching critical thresholds?
- What resilience capacities do and should European farming systems have?
- What strategies enhance sustainability and resilience of European farming systems?

In this chapter I first discuss the research findings. I start with outcomes in relation to the research questions that are common across case studies and subsequently zoom in on specific case studies. This part of the discussion is largely based on SURE-Farm deliverable 5.7, which concerns a policy brief that I co-authored as second author (Reidsma et al., 2021). Based on the integrated work presented in this thesis I can provide a plausible narrative about current and future sustainability and resilience of European farming systems. This plausibility is primarily based on, and hence limited by, the case studies and the level of detail involved.

In the second section I reflect on the strengths and limitations of the resilience framework and methodology used in this thesis. In the third section I discuss the relevance and implications of my work in a wider context. In the fourth section, I provide recommendations for assessing sustainability and resilience of European farming systems. I end with the main conclusions of my work.

7.2 Sustainability and resilience of European farming systems

7.2.1 Sustainability and critical thresholds

In the studied farming systems there was generally an emphasis on food production and economic viability, where the maintenance of natural resources was often perceived to come third in terms of importance (all chapters). The sustainability of the farming systems was generally perceived to be moderate (Chapter 3). Moreover, most farming systems were perceived to be close to economic, environmental and/or social critical thresholds (Chapter 6). A variety of challenges, such as extreme weather events, low prices, price volatility, high production costs and continuous change of laws and regulations, pushed many farming systems to the limits. In addition, critical thresholds were perceived to interact across system levels (field, farm, farming system) and domains (social, economic, environmental), with low economic viability leading to lower attractiveness of the farming system, and in some farming systems making it hard to maintain natural resources and biodiversity.

Economic viability is perceived to be a central function of farming systems (Chapters 2, 3, 5 & 6), but in many systems it is perceived to be close to its critical threshold (Chapter 6). Food production needs to be high to ensure economic viability. Moreover, past strategies (e.g., increasing farm size and intensity) often focused on improving production and economic viability (e.g. Chapter 2). In Chapter 6 I argued that these functions are part of fast system processes and that concerns about more immediate stress-signals from these processes result in trade-offs with slower processes related to public goods (e.g., improvement of soil quality and social well-being in the farming system). These trade-offs could reinforce the already strong emphasis put on food production and economic functions by stakeholders (Chapters 2 & 3).

Accumulating challenges cause some systems to be close to an undesired decline, such as in the case of the extensive sheep production in Huesca, Spain, where a vicious circle leads to low economic returns, low attractiveness of the sector and abandonment of pasture lands (Chapter 5). In other systems, such as the starch potato system in the Veenkoloniën, the Netherlands, innovation and self-organisation have, so far, prevented the system from an undesired decline, but nematode pressure, droughts, high production costs and stricter regulations keep the system close to critical thresholds (Chapter 6; Herrera et al., 2022).

7.2.2 Current resilience and strategies

Based on an assessment of the presence of resilience attributes and strategies implemented in the past in 11 European farming systems, resilience was judged to be low to moderate (Chapters 2 & 3). Arable systems and horticultural systems scored relatively low, while the high-value egg and broiler system in southern Sweden, and the small-scale hazelnut system in Viterbo, Italy, scored higher. In Sweden, this was mainly because of production and legislation being well-coupled to local and natural capital, while in Italy, the system was reasonably profitable and socially self-organized (Nera et al., 2020). In most farming systems, presence of resilience attributes and historical dynamics of main functions suggest a certain robustness, which prevails over transformability (Chapters 2 & 3). In this context, adaptability is mostly employed for keeping stability and realizing (slow) incremental improvements. The focus on robustness is reflected in the policies in place for the studied farming systems (Buitenhuis et al., 2020b, 2020a; Feindt et al., 2019), while farmers in the studied farming systems perceived themselves as having slightly more adaptability than robustness (Spiegel et al., 2021, 2020). In Chapter 2 I argue that the focus on robustness fits well with a control-rationale that is focussed on efficient production in a stable context (Hoekstra et al., 2018). However, the economic and environmental context is not stable and expected to become increasingly instable. Moreover, given the perceived low to moderate sustainability and resilience of current farming systems, in particular regarding their closeness to critical thresholds, adaptation or even transformation seems necessary. A shift towards a resilience rationale seems, therefore, required for most of the farming systems studied in this thesis. The self-reported adaptability of farmers (Spiegel et al., 2021) is an essential capacity at farm level that may induce a shift in thinking at farming system level, provided the adaptability is not primarily employed for increased robustness.

Past strategies to cope with challenges were often geared towards maintaining profitability, such as intensification and scale enlargement (Chapter 3). Such past strategies were to a lesser extent geared towards building the important resilience attributes related to social self-organization, infrastructure for innovation, response and functional diversity, and coupling production to local and natural capital (Chapter 3). These strategies kept farming systems robust, but there are limits to the success with regards to increasing farm size and intensity (Chapters 3 & 5). In the extensive sheep production system in Huesca, Spain, for instance, further expansion of farms was not feasible due to labour shortage (Chapter 5). Systems focused on production and economic functions may seem to enhance resilience in the short-term, but they negatively affect other resilience attributes and deteriorate resilience in the long-term (Chapters 3 & 6). In the hazelnut production system in Viterbo, Italy, for instance, this is acknowledged and new strategies to improve sustainability and resilience are directed towards self-organization at the farming system level (Chapter 2; Nera et al., 2020). Strategies aiming for long-term sustainability and resilience thus need to consider how to nurture environmental and social dynamics that are needed to sustain and enhance economic viability of farming systems (e.g., natural resources and labour are needed to maintain profitable yields). Hence, there is a clear need for alternative systems with a balanced attention for economic, social and environmental dimensions.

7.2.3 Future sustainability, resilience and strategies

Assessments on alternative systems are in this thesis only elaborated for the extensive sheep production system in Huesca, Spain (ES-Sheep; Chapter 5). Many of the observations for ES-Sheep are similar to the observations done in other farming systems, using the same participatory approach (Accatino et al., 2020). For instance, the balance between social, economic and environmental functions was not always kept by stakeholders when envisaging alternative systems (Chapter 5; Accatino et al., 2020). Envisaged alternative systems in ES-Sheep included a focus on intensification, specialization, technology, product valorisation, collaboration and an attractive countryside (Chapter 5). In other farming systems, alternative systems also included a focus on diversification and organic and/or nature-friendly farming (Accatino et al., 2020). Each type of these alternative systems may enhance the performance of some system functions, but, in the end, all functions need to perform at adequate levels. Keeping in mind the interactive nature of system indicators and their corresponding thresholds, (a combination of) strategies should address multiple system functions and attributes simultaneously. Technological innovation is required, but should be accompanied with structural, social, agro-ecological and institutional changes (Chapter 5; Accatino et al., 2020). In ES-Sheep and other studied farming systems, stakeholders indicated that particularly enabling conditions in the social and institutional domains were lacking to make change happen (Chapter 5; Accatino et al., 2020). Enabling conditions that should be addressed in ES-Sheep and other systems are the access to knowledge, more effective bureaucracy, improving the consistency and transparency of policies and regulations, and providing compensation for the delivery of public goods (Chapter 5; Accatino et al., 2020). From the above it becomes clear that all actors inside as well as outside the farming system need to be involved to realize more sustainable and resilience farming systems.

Obviously, not all farming systems can implement all changes as presented in the previous paragraphs. In particular the stability of the farming system itself and its context should play a role in implementing changes. Depending on the stability of the context, I assume in Chapter 2 that agricultural systems are/move somewhere on the gradient between having a technological control rationale in a stable context and an ecological resilience rational to deal with contexts of uncertainty (Hoekstra et al., 2018)[4]. Many contemporary, intensive and specialized systems seem to be too much on the "control" side, i.e. the degree of technology use has improved production, but social and environmental sustainability limits are approached (Chapter 6), while the economic and environmental context is increasingly variable. In these systems, for instance, supporting nature-based pest management through diversification is likely to reduce pesticide use, but a trade-off with (control over) yield may occur (van der Werf and Bianchi, 2022). On the other hand, very extensive systems may benefit from more technologization and control as it can help to do "better than nature" (Ford Denison and McGuire, 2015) or help the co-existence of agriculture with wild-life (e.g. placing electric fences to avoid wolf attacks on sheep; Chapter 5).

The capacity of farming systems to move along the control-resilience continuum is important for a broader discussion on agricultural sustainability. From a sustainability perspective, literature suggests that agricultural performance at national or continental level can be improved when different types of farming systems, including more technology-based intensive as well as more ecological-based extensive systems, are spatially divided (Accatino et al., 2019; Bakker et al., 2021; Schulte et al., 2019). However, from a resilience perspective, concentration of specific farm types in one region would also reduce the farm heterogeneity, which is considered an important resilience attribute (Chapters 2 & 3; Cabell and Oelofse, 2012). The costly process of spatial planning and re-allocation, therefore, should explicitly consider the sustainability *and* resilience of farming systems in combination with the stability of the economic, social and environmental context.

7.3. Methodological strengths and limitations

7.3.1 Framework

Farming system

The flexible definition of a farming system regarding the geographical delineation allowed for study cases that were different in size and number and types of actors. Yet, during the cross-case study comparison, differences in culture, size of the farming system etc. made it difficult to compare case studies directly (Chapter 2). Instead, I compared common patterns across case studies, e.g. regarding important resilience attributes in Chapter 2 and critical thresholds in Chapter 6. The definition of a farming system that was used also provides flexibility when looking at a single case study: the system can be defined at any level at which emergent properties are expected regarding a topic of interest. As such, (farming) system research should not be presented as a particular study domain, but rather as a way of thinking that supports defining a problem in a multi-stakeholder setting or support the scaling of innovations. Parts of the framework, for instance, already shaped researchers' thoughts, beyond the SURE-Farm project, on studying the link between financial assistance for drought-affected agriculture and resilience in tropical Asia (Goodwin et al., 2022) and on studying the response and resilience of agri-food systems in twenty-five Asian countries (Dixon et al., 2021).

[4] This also relates to the concept of adaptive cycles: in a growth/conservation phase (in a relatively stable environment), a control strategy (focussed on robustness and efficiency) works, but in a decline/reorganization phase a resilience rationale (focussed on adaptability and transformability) is needed.

Farming systems research emphasizes the production aspect of agriculture, rather than on the consumption aspect. Work on agricultural resilience is often embedded in the notion of food systems (e.g. Ericksen, 2008; Prosperi et al., 2016; Tendall et al., 2015), which addresses both the production and consumption aspects related to agriculture. Food systems include, beside farming systems, the whole value chain of agricultural produce, including, amongst others, food processors, super markets and consumers (Berkum et al., 2018; von Braun et al., 2021). Within SURE-Farm work, it became clear that these actors are indeed important to improve farming system sustainability and resilience (Chapters 2 & 5; Meuwissen et al., 2020). Consumers, for instance, are important actors that determine the demand for food. By implicitly placing food demand outside the farming system boundary it could be perceived as a factor that cannot, or even should not, be influenced or controlled. However, to stay within planetary or regional boundaries for the environment and human well-being, changing food demand through changing consumption patterns is part of the solution space (Springmann et al., 2018).

Challenges

In the framework, there is a focus on challenges affecting the system negatively, rather than as an opportunity for positive system change. In the resilience literature, a pending system change is often seen as an opportunity (e.g. Westley et al., 2011) for which preparations can be taken (Enfors-Kautsky et al., 2018). Challenges as an opportunity originate in the metaphor of the adaptive cycle that has been shortly discussed in the discussion of Chapter 6. The idea of seeing challenges as an opportunity is that after a crisis, in which part of the system resources have been released, actors could use their agency to influence the re-organization phase for the benefit of sustainability and resilience. Walker et al. (2020), for instance, identified opportunities for improved social and environmental sustainability at global level after the COVID-19 crisis. In agricultural research the notion of opportunities after unexpected events has also appeared (Darnhofer, 2021).

Realizing desired change through a crisis requires a thorough understanding of the system regarding its main values, variables and drivers (Walker et al., 2020) as well as an understanding of the agency of individual actors in social-ecological systems (Westley et al., 2013). Based on the work presented in this thesis, such a claim cannot be made. In contrast, in Chapter 6, it is pointed out that critical thresholds whose exceedance precede a release of a system are very difficult to assess. Moreover, the exceedance is expected to greatly negatively impact the sustainability and resilience of farming systems (Chapter 6). It should also be noted that the adaptive cycle, which provides the origin of seeing challenges as opportunities, is a metaphor, i.e. so far there is very little empirical evidence that could support a working model for the adaptive cycle in socio-ecological systems in general (Cumming and Collier, 2005; Cumming and Peterson, 2017), or in agricultural systems in specific (e.g. van Apeldoorn et al., 2011). After all, considering the uncertainties and stakes, a risk avoiding strategy relating to challenges seems the best option in order to avoid a forced system transformation. However, unexpected events are increasingly common in a globalized world (Darnhofer, 2021). These events may push farming systems beyond critical thresholds. In such situations, adaptability is needed. Based on the findings in this thesis, farm heterogeneity and experimentation at levels below the farming system are recommended (Chapters 2 & 3). These resilience attributes could help to have production technologies available in case critical thresholds are exceeded, i.e. improve adaptability and transformability at farm and farming system level. To benefit from unexpected change at farming system level, further elaboration of theories, conceptual frameworks and methods seems necessary (Darnhofer, 2021).

Functions

The list of eight functions proofed practical: they were easily recognized and acknowledged by participants and representative indicators were relatively easy to determine. This provided a good base for discussion with farming system stakeholders. However, when it came to evaluating the importance and performance of functions, participants sometimes argued that all functions were connected and therefore that an evaluation was difficult (e.g. Chapter 2).

In the context of this thesis, functions were primarily categorized in the economic, environmental or social domain. Alternatively, a categorization according to ecosystem services (Table 7.1) could have been interesting: existing resilience theories are mainly based on resilience studies that are primarily focussing on the ecological functioning of socio-ecological systems (e.g. Bennett and Peterson, 2005; Carpenter et al., 2005) and, more importantly, can be strongly embedded in the ecosystem services framework (e.g. Biggs et al., 2012; Schlüter et al., 2015). However, some of the proposed functions by Meuwissen et al. (2019) are difficult to categorize according to ecosystem services (Table 7.1). Moreover, apart from providing ecosystem services, farming system functioning can also be associated with **dis**services provided **to** ecosystems (Huang et al., 2015). Indeed, the categorization in economic, social and environmental domains, can, without confusing stakeholders, include notions of agricultural disservices by means of addressing trade-offs between different domains, e.g. between food production (economic) and biodiversity & habitat (environmental)(e.g. Chapters 5 & 6)[5].

Table 7.1. System functions considered in the resilience framework of Meuwissen et al. (2019) and linkage to the eco-system services (ES) framework that distinguishes provisioning, regulating, supporting and cultural ES.

Function	Description	Domain	Type of ES
	Private goods		
Food production	Deliver healthy and affordable food products	Economic	Provisioning
Bio-based resources	Deliver other bio-based resources for the processing sector	Economic	Provisioning
Economic viability	Ensure economic viability (viable farms help to strengthen the economy and contribute to balanced territorial development)	Economic	Cultural?
Quality of life	Improve quality of life in farming areas by providing employment and offering decent working conditions	Social	Cultural?
	Public goods		
Natural resources	Maintain natural resources in good condition (water, soil, air)	Environmental	Supporting
Biodiversity & habitat	Protect biodiversity of habitats, genes, and species	Environmental	Regulating
Attractiveness of the area	Ensure that rural areas are attractive places for residence and tourism (countryside, social structures)	Social	Cultural
Animal health & welfare	Ensure animal health & welfare	Environmental	Regulating? Cultural?

Robustness, adaptability and transformability

Resilience thinking needs metaphors in the absence of complete understanding of a system's potential behaviour. Robustness, adaptability and transformability and their accompanying metaphors of balls in stability landscapes (Figure 1.2) proved useful for farming systems. Using these three resilience capacities may suit the thinking process of farming systems actors better than the more complicated metaphor of

[5] The categorization in terms of domains instead of ecosystem services is an important adaptation for studies on the resilience of farming systems (having a strong technological component) compared to studying resilience studies on ecosystems.

(interacting) adaptive cycles (See also the discussion under the sub-section "Challenges" in this section). The metaphor of adaptive cycles is best used by researchers in the evaluation phase. For instance to determine the position in the adaptive cycle (Reidsma et al., 2019b) and the capacities present in the system to deal with the different phases in the adaptive cycle (Cabell and Oelofse, 2012; Le Goff et al., 2022; Tittonell, 2020).

Yet, it should be noted that the distinction between adaptability and transformability was sometimes difficult to make in participatory settings (Chapter 2). Although the concepts of adaptability and transformability could be merged for the sake of convenience (Chapter 2), I think this should not be done so easily. Addressing all three capacities in the studied systems really pointed at something that was lacking: transformative capacity. Considering this lack, notions of a system's identity (Cumming and Collier, 2005; Cumming and Peterson, 2017) should be used with care in farming systems research. Marshall et al. (2012), for instance, mention that identity, in the form of attachment to an area or occupation, may be positive for adaptation to incremental change, but reduce transformational capacity. Identity, when based on history, may also result in the exclusion of much needed new actors that can help transforming the system, as they don't belong in the original picture (Enfors-Kautsky et al., 2018).

In this thesis, some farming systems seem rather unsustainable and therefore in need of transformation (e.g. ES-Sheep; Chapter 5). In Chapters 2 & 6 it is already mentioned that mere adaptations sometimes do not seem enough, but that lock-in interests of farming system actors can impede possible transformations. Indeed, power issues play an important role, while they have been scarcely addressed in this thesis. I already mentioned the "critical friends" approach to break the lock-in (Chapter 6). Critical friends are important to question and reframe dominant agendas for change, but complementary actors may be needed (Chambers et al., 2022). For instance, actors that can navigate conflicting agendas or elevate marginalized agendas for change (Chambers et al., 2022).

Resilience attributes

In this thesis I adapted an existing list of resilience attributes. This resulted in 22 attributes from which 13 were selected and discussed in participatory workshops (Chapters 2, 3, 5 & 6). The 13 resilience attributes were initially categorized according to five resilience principles selected by Meuwissen et al. (2019) based on previous resilience research on socio-ecological systems (e.g. Walker and Salt, 2012). During the analyses and interpretation of workshop results, a categorization according to system resources in the form of different kind of capitals (e.g. financial, social) turned out to be more intuitive for farming systems.

It is challenging to determine what would be the right set of resilience attributes for farming systems: the importance of resilience attributes turned out to be context and stakeholder dependent (Chapters 2 & 3). One could also think of additional resilience attributes related, for instance, to the remoteness of the area (Chapter 6), foresight capacities (e.g. relating to policy changes) and the type of product (e.g. fresh or long lasting, seasonal or available throughout the year). From a practical point of view, discussing 13 resilience attributes in a participatory workshop is already challenging. In such a setting, including more attributes is not recommended, so selection becomes important.

A generic advice is to make sure that all different forms of capital are represented by the resilience attributes that will be evaluated for a farming system. That way it resonates with the balanced attention for system functions in the economic, social and environmental domain. Another generic advice is to make sure that all resilience attributes relate to the same level of analysis. In the case of European farming systems, it is recommended to include the resilience attributes related to being reasonable profitable, production being coupled with local and natural resources, farm heterogeneity, social-self organization and infrastructure for innovation, as these were perceived important in most case studies (Chapters 2 & 3). In particular, being reasonably profitable and having infrastructure for innovation were perceived important for transformability (Chapters 2 & 3). Further research is necessary to identify the much-needed resilience attributes for improved transformability. In the case of farming systems, experimentation could be such an attribute (Chapter 2).

7.3.2 Participatory methods

The participatory methods that were developed and used in this thesis were supported by the resilience framework. This yielded a very structured and rather exhaustive, but still flexible, approach regarding the presentation of functions and resilience attributes covering the economic, social and environmental domain. As discussed in Chapters 2 & 5, this resulted in knowledge exchange from researchers to participants. The structure provided by the framework also stimulated the knowledge exchange from participants to researchers regarding the farming system-specific actors, challenges, function indicators, and, in the case of ES-Sheep, local indicators for resilience attributes (Chapter 5).

The participatory methods had multiple limitations. I see the stakeholder selection and participation reducing the representativeness and reproducibility of the research as the main limitation for getting an objective and comprehensive picture of a farming system (Chapters 2, 5 & 6). As a consequence of the selection process, radical thinkers were largely absent, which limits the likelihood of transformative change in cases where current sustainability and resilience is low (Chapter 5). As mentioned before, multiple actors with different skill sets or personality traits may be needed to guide transformation (Chambers et al., 2022). In addition, researchers themselves could play an active role in guiding transformations, i.e. move beyond the more or less neutral role of the "honest broker" (Wittmayer and Schäpke, 2014). This implies that researchers become politically involved and explicitly advocate for values important for society in addition to scientific values and standards (Pielke, 2007). In general this leads to a vague distinction between knowledge and ethics and between (scientific) quality and (societal) truth, i.e. a post-normal understanding of science (Ravetz, 2002). In particular the combination of (scientific) uncertainty and (societal) urgency surrounding the topic of sustainability and resilience of agricultural systems justifies such a development. It should be noted, however, that a post-normal understanding of science in trans-disciplinary research requires researchers to navigate important and urgent, but potentially conflicting, demands from science, society and the self (Sellberg et al., 2021). In particular young scientists in trans-disciplinary studies should be aware of this in order to engage sustainably at a professional, political and personal level (Sellberg et al., 2021).

Overall, the methodology can be regarded as relatively quick, interactive and interdisciplinary, providing ample information on critical thresholds, current system dynamics and future possibilities. The participatory workshops supported the construction of joined visions for the farming systems, at least regarding relevant strategies and enabling conditions for change. Altogether, the participatory approach used in this thesis leans towards the descriptive and explanatory, while exploration and (re-)design are hardly addressed (see e.g. Giller et al., 2008). Related to this, the approach is more leaning towards information extraction rather than rapport building with local stakeholders (Mosse, 1994). To become more complete as a participatory approach, additional activities and tools need to be developed that direct towards a joint vision and action plan for change. For such a vision and plan, the right set of goals, strategies, resources and actors involved need to be determined (Mathijs and Wauters, 2020). Existing approaches, such as the Wayfinder approach (Enfors-Kautsky et al., 2018), could be used for inspiration, provided it is first adapted to the context of farming systems.

7.3.3 Quantitative methods

The quantitative method to assess farm resilience in Chapter 4 was functional for filtering high-dimensional data but was limited for empirically confirming the resilience attributes in agricultural systems. Empirical evidence based on quantitative data remains important to check the assumptions of generic resilience theory in an agricultural context, e.g. to assess the role of diversity (Dardonville et al., 2020) and intensity (Dardonville et al., 2022a). Fortunately, there are multiple methods available for quantitative resilience assessments based on empirical data (see e.g. Dardonville et al., 2021; Gil et al., 2017). Within the SURE-Farm consortium, for instance, Slijper et al. (2021) studied the effect of different forms of payments on the resilience capacities of European farms. They found negative and positive effects of payments on robustness, while no effect was observed for adaptability or transformability (Thomas Slijper et al., 2021).

Gil et al. (2017) point out that, when using statistical methods, the real cause-effect relation is often not found. In addition, these methods are ill-equipped to deal with social risks as these are difficult to quantify.

Hence, a statistical method integrating economic and environmental farming system functions, let alone integrating social functions, is still not available (Chapter 4). Based on my experiences with the analyses in Chapter 4, I have come to the conclusion that multiple statistical analyses with a single response variable are recommended over integrating multiple response variables in one analysis. Quantitative trade-off analyses should, therefore, be conducted with other types of methods such as dynamic simulation models (e.g. Herrera et al., 2022; Pinsard et al., 2021) and optimization models (e.g. Shi et al., 2021). It should be noted, however, that these alternative methods are often not empirical and therefore their practical relevance is questioned (Klapwijk et al., 2014). Complementary participatory approaches, such as the methods presented in this thesis (Chapters 2 & 5), have the potential to improve the practical relevance of models in trade-off analyses (Klapwijk et al., 2014).

Models representing system behaviour over time are important in the context of resilience (Herrera et al., 2022). In particular systems thinking theory and subsequent system dynamics modelling could provide the right context to integrate different kinds of quantitative and qualitative knowledge (Sterman, 2000). Based on these knowledge sources, system dynamic models can be used for simulating different scenarios regarding, for instance, the implementation of new technologies and policies, but also changing values of system actors. In some first attempts to apply system dynamics modelling in a qualitative way, I noticed that by including different, interacting framework indicators (e.g. functions indicators, resilience attributes), sustainability and resilience get mixed up (Accatino et al., 2020). On the one hand this operationalizes sustainability and resilience as complementary concepts. On the other hand, it may prevent researchers and stakeholders to get a quick overview of important system variables, resulting in a reduced interest in the subject. Systems dynamics modelling should, therefore, always be conducted within the context of a framework, such as the one used in this thesis, that filters and categorizes the most important system variables.

7.4 Relevance in a wider context

In Chapter 1 I argued that the global/European production system has low sustainability and decreasing resilience, which, as I argue, is intrinsically linked with the design of the global Economic system. This image has been confirmed by the research chapters in this thesis. An important finding for the studied farming systems was the importance of a balanced attention for the social, economic and environmental domain. This balanced attention stretches beyond the boundaries of the farming system. In this thesis we have already seen the focus on economic performance at individual farm level (Chapter 2) and the tendency to forget about social indicators and sometimes environmental indicators when there is a plenitude of economic indicators (Chapter 5). At a global level, something similar is happening due to the dominant role of markets in guiding human activity (Raworth, 2017). For instance with regard to an overemphasis on economic growth in the form of gross domestic product.

Raworth (2017) points out that, besides markets, the three other pillars supporting human well-being and welfare should be considered equally: the households, the government and the collaborative management of the commons, i.e. a large share of the formal and informal institutions that operate mainly in the social and environmental domain. In the context of sustainability and resilience of farming systems, farm households are indeed very important regarding supplying an unpaid or cheap, yet motivated, knowledgeable, responsive and flexible labour force that is willing to work long hours in order to stay economically viable (van Vliet et al., 2015), being a source for generational renewal (Coopmans et al., 2021; van Vliet et al., 2015), influencing decision making (Urquhart et al., 2019) and providing quality of life to farmers, farm workers and rural communities (van Vliet et al., 2015). Without trying to idealize the concept of family farming, it can be concluded that the family farm household is of particular importance for the current functioning of farming systems and the wider food system. In this context, he decline of family farms and the rise of large scale farm corporations (e.g. Giller et al., 2021; Nyström et al., 2019) seem developments that could remove crucial actors for making farming systems more sustainable and resilient.

In general, the national government is an actor that can take risks that no other actor can take, which makes it an important actor for creating welfare and change, in particular through innovation (Mazzucato, 2018). Although the role of government is not exactly clear yet regarding farming systems (and probably never will be), it has become clear in this thesis (e.g. Chapters 3 & 5) that farming system actors cannot make the necessary changes alone (lack of agency). There is a need for actors outside the farming system to change the economic and institutional context (changing the structure) in order to allow for change. Unified, collaborating national governments at European level could partly realize this. Hopefully, the full implementation of the EU's new green deal and it's Farm to Fork strategy will be an example of this. Especially when realized under the current and, to a large extent, unexpected global challenges: a persistent pandemic, rising geo-political tensions and unprecedented market dynamics.

When thinking about the commons as important for farming system functioning, I still sometimes believe that this is a bit farfetched, as farms mostly operate individually and are to a considerable extent detached from their local biophysical environment (while in most cases actually being considered as land-based systems). This, from a resilience and sustainability perspective, seems exactly the issue: a low degree of self-organization and a low degree of production coupled to local and natural capital, i.e. low degrees of two important resilience attributes. The commons, i.e. that what we share and manage together for our welfare and well-being, comprise mainly the social and environmental environment. These are the domains that are most easily neglected as has become clear in this thesis. Fortunately, previous research on the use of commons has provided an overview of boundary conditions and rules to prevent the erosion of common resources (Ostrom, 1990). Apart from ecological commons, other types of commons could be considered, such as knowledge, digital and cultural commons. In fact, the understanding of what commons really are, how to manage them and how important they are for human well-being could be interpreted as a cultural common. Doubting the important role of commons in European agriculture, as I did at the start of this paragraph, could even be seen as an indication that this common is actually eroded. A boundary condition for its comeback is a less dominant role of markets and their main actors in economies. Identifying and monitoring environmental and social commons would be an important first step towards a more prominent role and recognition of commons for the creation of welfare and well-being. In the "Further research" section below, I, therefore, put forward a basic structure of a policy monitoring and evaluation framework, for instance for the Common Agricultural Policy (CAP) of the European Commission, that can help stakeholders and governments realize what their commons actually are and how to monitor them.

7.5 Further research

7.5.1 Attention for resources in future resilience research and policies

As discussed in Chapter 6, having adequate resources in all domains seems essential for improving system resilience attributes and dealing with challenges. Overall, in (agricultural) economics there is a large emphasis on inputs, throughputs and outputs, i.e. on system flows or system performance (Sterman, 2000). This is for instance very visible in the CAPs Common Monitoring and Evaluation Framework (CMEF) whose indicators primarily describe money flows, even regarding environmental objectives, while the status of relevant resources is hardly addressed. Emphasizing system flows leads to event-oriented cause-effect analyses that neglect crucial feedback loops in a system as the flows are hardly associated with the resources that they affect and are affected by (Meadows, 2008; Sterman, 2000). Elaborating further on this, Meadows (2008) emphasizes the buffering capacity of system resources and their importance as leverage points to realize change and resilience in systems. Further sustainability and resilience research on farming systems should, therefore, explicitly have attention for environmental, economic and social resources.

The resilience attributes used in this thesis provide a good base for including resources in the analyses and monitoring of farming systems (see also section 7.3.1). While applying systems thinking to the resilience framework used in this study, it can be argued that functions of a system relate more to its flows, where attributes relate more to its stocks/resources (Chapters 2 & 6). In that sense, attributes are a source of resilience, but also a manifestation of system flows over time, i.e. system sustainability. This is in fact the operationalization of sustainability and resilience as complementary concepts as proposed in the resilience framework (Chapter 6).

Taking this system's perspective of interacting functions and attributes, I elaborate why and how resources can be included in existing monitoring frameworks on sustainability and resilience. As an example I take the CMEF, the monitoring framework of EU's agricultural policy instrument, the CAP. The CMEF has been developed to measure the implementation and impact of the CAP while considering contextual factors (European Commission, 2015). The CMEF was primarily developed based on a sustainability perspective regarding economic growth, management of natural resources and socio-economic development of rural areas (European Commission, 2015). Although the previous editions of the CAP and also the new CAP (CAP 2021-27) aim to address environmental, economic as well as social aspects of European agriculture, the indicators in the current CMEF mainly cover monetary investments in the environmental and economic domain. Regarding the impact indicators, i.e. the main indicators to evaluate the effectiveness of the CAP, social indicators are completely absent. In addition, when addressed elsewhere in the CMEF, the indicators in the social domain are often expressed in economic terms, for instance as investment in rural facilities.

Fortunately, there are already a few examples of resource indicators in the current CMEF. For instance, the percentage of organic matter in top soils could be explicitly regarded as an environmental resource. Based on the work in this thesis, the resilience attribute describing the degree to which production is coupled with local and natural capital should be added as an environmental impact variable (Chapters 2 & 3). This will not be an easy task. Ongoing work of e.g. Dardonville et al. (2022b) is a starting point for (quantitative) indicators related to this resilience attribute. Current CMEF contextual indicators that may be distinguished as social resource indicators are the number of farms and agricultural training of farm managers. Based on the work in this thesis, the resilience attribute that describes the degree to which farming system actors are capable of self-organization should be considered as a resource and added as a social impact variable (Chapters 2 & 3). Asking farming stakeholders about perceived self-organization is a good start, but more objective metrics adapted to farming systems may be needed as well. Also the resilience attribute related to the level of infrastructure for innovation is an important resource that should be included (Chapters 2, 3 & 6). Work regarding Agricultural Knowledge and Information Systems could provide useful indicators for this resilience attribute (e.g. EIP-Agri, 2018). Other current CMEF indicators (Pillar I result indicators) that could be regarded as resource indicators are, for instance, structural diversity and crop diversity (currently still measured as amount of subsidies and area under subsidy). Based on the results presented in this thesis alone, I cannot confirm the importance of these indicators. Existing literature on the role of diversity in agriculture shows ambivalent results (Dardonville et al., 2020). Given the lack of diversity in multiple contemporary EU farming systems geared towards operating under a control rationale (Chapter 2), different forms of diversity should still be regarded as a potential solution for improving resilience. For instance crop diversity regarding economic buffering capacity for when a crop fails (Abson et al., 2013).

7.5.2 The complementary role of subjective and objective resilience assessments

A final observation regarding the indicators in the CMEF is that they are objectively defined and objectively assessed, i.e. they are defined and measured by actors outside the farming systems under study (Jones, 2019). Moreover, they are based on available quantitative data. This may be one of the reasons why social indicators are less covered in the framework, as they are generally hard to measure. Including local data and perceptions could overcome this shortcoming, provided that explicit attention is given to social indicators (Chapters 2 & 3).

Participatory approaches have the potential to include local data and perceptions and thus complement existing monitoring frameworks, such as the CMEF. This thesis has, for instance, shown that participatory methods can provide resource indicators in the economic, environmental and social domain that are relevant across a diverse set of farming systems in Europe (previous section; 7.4.1.). A subsequent question that arises is: what degree of influence of local actors should be sought when assessing farming system resilience? The objectivity-subjectivity continuum for assessing resilience as presented in Jones (2019) helps to reflect on this question (Figure 7.1). Jones (2019) distinguishes between *defining* and *evaluating* resilience. Both activities can be done subjectively, i.e. by actors inside, and objectively, i.e. by actors outside the farming system (Jones and d'Errico, 2019). *Defining* resilience relates to the choice of methods and indicators that are used to measure resilience. *Evaluating* resilience relates to the actual assessment of resilience according to the defined methods and indicators.

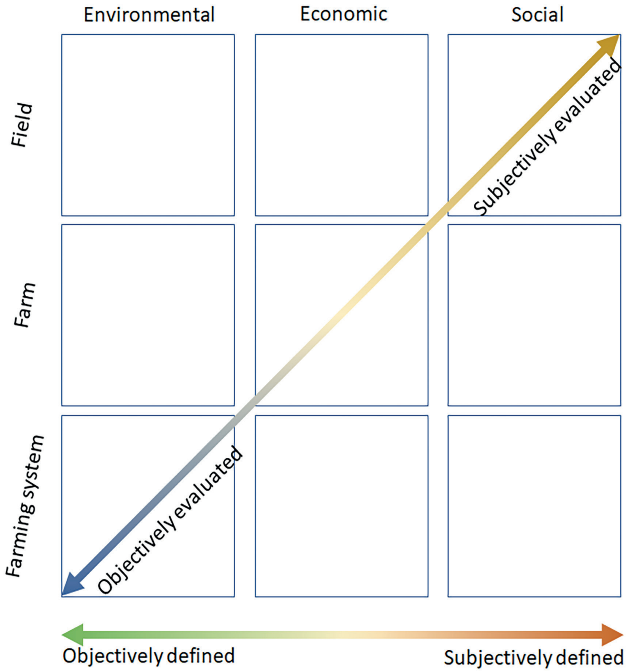

Figure 7.1. Suggested emphasis on objectively or subjectively defining and evaluating resilience indicators per domain and level of analysis. Source: combined from Kinzig et al. (2006) and Jones (2019).

I suggest, based on the reflections in the previous paragraphs, that from the environmental to the economic to the social domain, the desired degree of subjectivity in *defining* resilience should increase. This is in line with Van Calker et al. (2005) who, in the context of a sustainability assessment, suggest an increasing role for experts regarding ecological dimensions and an increasing role for stakeholders regarding social dimensions of farming systems. As mentioned in Chapter 6, farming system actors may not have the capacities or willingness to evaluate resilience at farming system level. For *evaluating* resilience, the degree of objectivity needs, therefore, to be higher at the farming system level, compared to farm and field level where most farming system actors operate (Figure 7.1). The emphasis on subjectivity or objectivity for *evaluating* resilience should also be dependent on the domain, with an increasing degree of subjectivity towards the social domain. This is partly a practical choice to improve the availability of data on the social domain. Overall, a diagonal arrow for *evaluating* resilience is presented in Figure 7.1. A good yield at field level, for instance, depends on the goals a farmer has, but can also be compared with potential and water-limited yields (Van Ittersum et al., 2013). At farm level, objectively *evaluated* farm income is justified as much as the subjective appreciation of a farmer for his current income: both actual income and personal appreciation of that income is important for a farmer's potential desire to quit or continue the farm. Also in the environmental domain, thresholds of soil organic matter at farm level, for instance, could be *evaluated* subjectively as well as objectively (Hijbeek et al., 2017). At farm level, it is also important to compare and consider objective (e.g. Slijper et al., 2021) and subjective (Spiegel et al., 2021) *evaluations* of resilience: large differences imply differences in perceptions of farming system actors and actors outside the farming system that need to be bridged. An emphasis on objectively *evaluating* resilience at farming system level in the environmental domain is required as feedbacks of agricultural practices may not be experienced at farm and field level because they are too slow or because the feedback is transferred to actors beyond the farming system (see e.g. Chapter 6), e.g. citizens or wildlife populations.

7.6 Conclusions

Based on the application of new and (semi-)quantitative methods developed in this thesis the following conclusions on the sustainability and resilience of European farming systems – and the methods to assess sustainability and resilience - can be drawn:

Current sustainability and resilience:

- European farming systems were perceived to have low to moderate sustainability and resilience (Chapters 2 & 3) and operate close to critical thresholds (Chapters 5 & 6).
- In the studied farming systems there was an overemphasis on (short-term) economic viability and a lack of attention for (long-term) social variables, while robustness was perceived to prevail over adaptability and transformability (Chapters 2 & 3).
- According to stakeholders, main building blocks for current resilience in most case studies were the resilience attributes related to having production coupled with local and natural resources, heterogeneity of farm types, social self-organization, reasonable profitability, and infrastructure for innovation. The latter two were perceived as particularly important for transformability (Chapters 2 & 3).
- Past strategies of farming systems were often geared towards making the system more profitable, and to a lesser extent towards the other important resilience attributes (Chapter 3).

Future sustainability and resilience:

- For improving sustainability and resilience, future farming systems need a more balanced attention for economic, social and environmental domains, and an enabling environment. (Chapters 5 & 6).
- In terms of strategies, technological innovation is often required, provided it is implemented simultaneously with social, agro-ecological and institutional strategies that consider the long-term (Chapters 3 & 5).
- To implement such strategies, all involved actors inside and outside the farming system need to collaborate (Chapters 3 & 5).

Understanding and assessing farming system sustainability and resilience:

- Sustainability *and* resilience of farming systems remains a challenging topic, regarding its complexity in terms of detail (different domains, many concepts and variables) and dynamics (non-linearity, thresholds, interactions).
- The research presented in this thesis confirms the usefulness of the resilience framework in reducing this complexity through a step-wise approach tailored to farming systems.
- The participatory approaches presented in this thesis (Chapters 2 & 5) contribute mainly to describing and explaining sustainability and resilience of farming systems.
- These methods provide, therefore, a good basis for exploring future farming systems (Chapter 5).
- The quantitative approach (presented in Chapter 4) confirmed the impact of weather extremes on economic and environmental farm performance, but was limited in explaining resilience, and raised awareness about the influence researchers have on the results through the selection of response variables.
- Based on the work and reflections presented in this thesis I see scope for better understanding and assessing farming system sustainability and resilience through:
    - system thinking theory that explicitly includes the notion of common pool resources and the power and agency of all actors, i.e. including the household, government and market actors, inside and outside the (open) system boundaries; and
    - use of participatory integrated assessments including different levels and domains, complemented by objective and/or subjective approaches that are applied to a single domain and/or level of analysis. The level of subjectiveness of these complementary approaches should be dependent on the level and domain of analysis.
- System thinking theory and participatory integrated assessments should, therefore, be implemented in existing monitoring and evaluation frameworks, such as the Common Monitoring and Evaluation Framework of the Common Agricultural Policy.

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Summary

An increasing variety of stresses and shocks provides challenges for farming systems in Europe. As a consequence, the sustainability and resilience of Europe's diverse farming systems is at stake. In particular the possible presence of economic, social or environmental thresholds in farming systems is worrying, as beyond those thresholds permanent and undesired system change may happen.

Sustainability of a system is in this thesis defined as an adequate performance of all system functions across the environmental, economic and social domains. Sustainability of agricultural systems has been studied extensively, but existing frameworks and tools are not designed to study resilience which is much more about the different capacities of systems to deal with disturbances. Moreover, in agricultural sustainability assessments, the social aspects are often least integrated, compared to the economic and environmental. Of particular importance are participatory, integrated assessments that focus on improving sustainability *and* resilience as they are designed to come up with adaptation options and action-oriented approaches together with relevant stakeholders.

Resilience can be defined as the capacity to resist change without changing its feedback system and functionality, i.e. robustness, while acknowledging the possibility of alternative stable states. The acknowledgement of possible stable alternative states of a system has led scholars to argue that ecological resilience thinking should also encompass, besides robustness, the system's capacity to adapt or to organize structural and functional change. Resilience of agricultural systems has been studied at a conceptual level and resilience indicators have been proposed. The actual operationalization has taken place only to a limited extent. In particular, quantitative assessments of agricultural systems are lacking in literature. Lack of good data may be one of the reasons for this. Much resilience work on agricultural systems is therefore qualitative in nature, for instance involving assessments based on system parameters that supposedly bring resilience to the system. The examples in which the resilience concept of agricultural systems is operationalized, are not guided by an integrated resilience framework that was applied to many different agricultural systems.

The work presented in this thesis was part of the EU Horizon 2020 project SURE-Farm to assess the sustainability and resilience of European farming systems. Within SURE-Farm, a resilience framework was developed that considers the need for combining approaches, having a local focus and stimulating participation of relevant (local) actors. The SURE-Farm framework proposed five steps to assess farming system sustainability and resilience (Meuwissen et al., 2019; Figure 1.1). From Step 1 to 5 specific resilience is addressed, i.e. resilience to a specific type disturbance. Step 1 to 3 relate, therefore, to the questions resilience "of what?", "to what?" and "for what purpose?". Step 4 addresses the farming system specific resilience capacities that need to be developed. Based on the previous steps, system characteristics are identified that convey general resilience to the system, regardless the type of disturbance (Step 5).

The aim of this thesis is to operationalize the above introduced resilience framework with new and integrated methods and to assess the sustainability and resilience of current and future European farming systems. The following research questions are central in this thesis: 1) Is there a balance between social, economic and environmental functions in European farming systems in terms of importance and performance? 2) Are European farming systems approaching critical thresholds? 3) What resilience capacities do and should European farming systems have? 4) What strategies enhance sustainability and resilience of European farming systems? The methods applied in this thesis follow the five steps of the resilience framework as much as possible. From a methodological point of view, the methods aim to operationalise the framework by using locally adapted indicators and different sources and types of data.

Chapter 2 presents the Framework of Participatory Impact Assessment for Sustainable and Resilient FARMing systems (FoPIA-SURE-Farm I). FoPIA-SURE-Farm I investigates current farming system functioning, dynamics of main indicators, and specifies resilience for the different resilience capacities, i.e., robustness, adaptability, and transformability. Three case studies with specialized farming systems serve as an example for the used methodology: starch potato production in Veenkoloniën, The Netherlands; dairy production in Flanders, Belgium; and hazelnut production in Lazio, Italy. Chapter 3 presents the

synthesis of the application of FoPIA-SURE-Farm I to 11 European farming systems. Results from Chapters 2 & 3 overlap. In most farming systems, functions that related to food production, economic viability, and maintaining natural resources were perceived as most important. Perceived overall performance of system functions suggests moderate sustainability of the studied farming systems. Overall, the resilience of the studied farming systems was perceived as low to moderate, with robustness and adaptability often dominant over transformability. This indicates that finding pathways to more sustainability, which requires adaptability and transformability, will be a challenging process. General characteristics of farming systems that supposedly convey general resilience, the so-called resilience attributes, were indeed perceived to contribute positively to resilience. Profitability, having production coupled with local and natural resources, heterogeneity of farm types, social self-organization, and infrastructure for innovation were assessed as being important resilience attributes. To allow for transformability, being reasonably profitable and having access to infrastructure for innovation were viewed as essential. Past strategies were often geared towards making the system more profitable, and to a lesser extent towards the other important resilience attributes. To improve sustainability and resilience of European farming systems, responses to short-term processes should better consider long-term processes. Technological innovation is required, but it must be accompanied with structural, social, agro-ecological and institutional changes. The relative importance of some resilience attributes in the studied systems differed from case to case. This indicates that the local context in general, and stakeholder perspectives in particular, are important when evaluating general resilience and policy options based on resilience attributes. Overall, FoPIA-SURE-Farm I results seem a good starting point for raising awareness, further assessments, and eventually for developing a shared vision and action plan for improving sustainability *and* resilience of farming systems.

While Chapters 2 & 3 presented the development and applications of a participatory semi-quantitative method, Chapter 4 aimed to complement the results regarding sustainability and resilience of current farming systems with a quantitative method. A statistical method using longitudinal data was applied to study farm performance (food production, profitability, nitrogen surplus) under different conditions regarding weather, market and farm structure. A case study for potato production in three regions in the Netherlands was employed, using data from 2006-2019. Statistical model performance was at best moderate. Model results were easily influenced by the selection of response variables. Food production, economic and environmental performance levels and gradual dynamics were primarily determined by input intensity levels. How these levels are determined by intensity of cropping, i.e. positively or negatively, differed per case study. Year-to-year variability was determined by average yearly weather conditions and weather extremes. We did not find evidence of moderating effects of farm structure on the impact of weather conditions and weather extremes. Overall, the conclusion is that results do only provide insights that can confirm existing knowledge at case study level. In the context of resilience of farms, while using a relatively small dataset, the application seems limited to a rather homogeneous farm population in a stable economic environment. Researchers intending to apply this method in (arable) farming systems should be well aware of the influence they can have over the results through the selection of response variables.

Following up on the sustainability and resilience assessment of current systems, Chapter 5 aims to find pathways to more sustainable and resilient farming systems, while identifying and avoiding critical thresholds. To serve this purpose, a participatory, integrated and indicator-based methodology is presented that leads researchers and farming system actors in six steps to a multi-dimensional understanding of sustainability and resilience of farming systems in the future (FoPIA-SURE-Farm II). The method is presented for the case study of extensive sheep production farming system in Huesca, Spain. Participants in the participatory workshop indicated that their farming system is very close to a decline or even a collapse. Approaching and exceeding critical thresholds in the social, economic and environmental domain is currently causing a vicious circle that includes low economic returns, low attractiveness of the farming system and abandonment of pasture lands. More sustainable and resilient alternative systems to counteract the current negative system dynamics were proposed by participants: a semi-intensive system primarily aimed at improving production and a high-tech extensive system primarily aimed at providing public goods. Both alternatives place a strong emphasis on the role of technology, but differ in their approach towards grazing, which is reflected in the different strategies that are foreseen to realize those alternatives. Although the high-tech extensive system seems most compatible with a future in which sustainable food production is very important, the semi-intensive system seems a less risky bet as it has on average the best compatibility with multiple future scenarios. Overall, the methodology can be regarded as relatively quick, interactive and transdisciplinary, providing ample information on critical thresholds, current system dynamics and future possibilities. As such, the method enables stakeholders to think and talk about the future of their system, paving the way for improved sustainability and resilience.

In Chapter 6, FoPIA-SURE-Farm II is applied to assess the presence of critical thresholds in 11 European farming systems. All studied systems were perceived to be close, at or beyond at least one identified critical threshold, i.e. these systems are (very likely) exceeding thresholds within the next 10 years. Stakeholders were particularly worried about economic viability and food production levels. Moreover, critical thresholds were perceived to interact across system levels (field, farm, farming system) and domains (social, economic, environmental), with low economic viability leading to lower attractiveness of the farming system, and in some farming systems making it hard to maintain natural resources and biodiversity. Overall, a decline in performance of all key system variables was expected by workshop participants in case critical thresholds would be exceeded. For instance, a decline in the attractiveness of the area and a lower maintenance of natural resources and biodiversity. Chapter 6 shows that concern for exceeding critical thresholds is justified and that thresholds need to be studied while considering system variables at field, farm and farming system level across the social, economic and environmental domains. For instance, economic variables at farm level (e.g. income) seem important to detect whether a system is approaching critical thresholds of social variables at farming system level (e.g. attractiveness of the area), while in multiple case studies there are also indications that approaching thresholds of social variables (e.g. labour availability) are indicative for approaching economic thresholds (e.g. farm income). Based on the results, reflections follow on the importance of considering system resources, such as knowledge levels, when monitoring and evaluating the sustainability and resilience of Europe's farming systems.

Chapter 7 provides a synthesis of the research presented in this thesis. Based on the synthesis, policy recommendations are made for improved sustainability and resilience. Subsequently, the framework and methods used in this thesis are evaluated. After that, the relevance of the work is discussed. Based on that discussion, reflections follow on improving the evaluation and monitoring of sustainability and resilience of farming systems in Europe. I conclude that sustainability and resilience of farming systems remains a challenging subject due to its complexity in terms of detail (different domains, many concepts and variables) and dynamics (non-linearity, thresholds, interactions). The research presented in this thesis confirmed the usefulness of the resilience framework in reducing this complexity through a step-wise approach tailored to farming systems. The participatory approaches presented in this thesis contributed mainly to describing and explaining sustainability and resilience of current farming systems. These methods provide, therefore, a good basis for exploring future farming systems. The quantitative approach (presented in Chapter 4) confirmed the impact of weather extremes on economic and environmental farm performance, but was limited in explaining resilience, and raised awareness about the influence researchers have on the results through the selection of response variables. Based on the work and reflections presented in this thesis I see scope for better understanding and assessing farming system sustainability and resilience through system thinking theory and the use of participatory integrated assessment

Samenvatting

Een toenemende diversiteit aan stressfactoren en schokken treft de landbouw in Europa. Als gevolg daarvan komen de duurzaamheid en veerkracht van Europa's diverse agrarische systemen in gevaar. De mogelijke aanwezigheid van economische, sociale of milieukundige kantelpunten zijn in het bijzonder reden tot zorg, omdat voorbij deze kantelpunten permanente en ongewenste systeemveranderingen plaats kunnen vinden.

De duurzaamheid van een systeem is in dit proefschrift gedefinieerd als een adequate prestatie van alle systeemfuncties in de milieukundige, economische en sociale domeinen. Duurzaamheid van agrarische systemen is uitgebreid bestudeerd, maar de bestaande raamwerken en methoden zijn niet ontworpen om veerkracht te bestuderen, wat veel meer gaat over de verschillende capaciteiten van een systeem om om te gaan met verstoringen. Bovendien zijn sociale aspecten in duurzaamheidsbeoordelingen in de landbouw vaak in geringe mate meegenomen ten opzichte van economische en milieukundige aspecten. Om duurzaamheid en veerkracht te beoordelen zijn participatieve en integrale beoordelingen van bijzonder belang omdat ze ontworpen zijn om ook met adaptatie-opties en actie-georiënteerde benaderingen te komen in samenspraak met relevante belanghebbenden.

Veerkracht kan worden gedefinieerd als de capaciteit van een systeem om verandering te weerstaan zonder dat de terugkoppelingsmechanismen en functionaliteit van het systeem veranderen, d.w.z. robuustheid, terwijl de mogelijkheid van alternatieve stabiele toestanden van het systeem ook wordt erkend. Het erkennen van mogelijke alternatieve stabiele toestanden heeft wetenschappers er toe gebracht om te stellen dat ecologische veerkracht, naast robuustheid, ook aanpassingsvermogen en het vermogen om structureel en functioneel te veranderen zou moeten omvatten. Veerkracht van agrarische systemen is bestudeerd op een conceptueel niveau en veerkracht indicatoren zijn geopperd. De toepassing op concrete agrarische systemen is echter in beperkte mate doorgevoerd. In het bijzonder kwantitatieve benaderingen ontbreken in de literatuur. Gebrek aan goede data zou hier een van de redenen voor kunnen zijn. Veel studies naar veerkracht in agrarische systemen zijn daardoor kwalitatief van aard, bijvoorbeeld door inschattingen te maken op basis van systeemkarakteristieken die zogenaamd veerkracht aan het systeem zouden moeten geven. De voorbeelden die er zijn waarin het veerkrachtconcept voor agrarische systemen is geoperationaliseerd volgen bovendien geen integraal raamwerk voor veerkracht dat toegepast is in veel verschillende agrarische systemen.

Het onderzoek dat gepresenteerd wordt in dit proefschrift was onderdeel van het EU Horizon 2020 project SURE-Farm om de duurzaamheid en veerkracht van Europese boerderijsystemen te bepalen. Binnen SURE-Farm werd een veerkrachtraamwerk ontwikkeld dat oog heeft voor het combineren van verschillende benaderingen, een lokale focus en het stimuleren van participatie van relevante (lokale) actoren. Het SURE-Farm veerkrachtraamwerk bestaat uit vijf stappen om de duurzaamheid en veerkracht van Europese boerderijsystemen te bepalen. Van Stap 1 tot 5 wordt specifieke veerkracht bepaald, d.w.z. veerkracht ten opzichte van een specifieke verstoring. Stap 1 tot 3 verhouden zich daarom tot de vragen "de veerkracht waarvan?", "ten opzichte van wat?" en "met welk doel?". Stap 4 gaat over de specifieke capaciteiten van veerkracht van het boerderijsysteem. Gebaseerd op de voorgenoemde stappen, systeemkarakteristieken kunnen worden geïdentificeerd die generieke veerkracht geven aan het systeem, ongeacht het type van verstoring (Stap 5).

Het doel van dit proefschrift is om het hierboven genoemde veerkracht raamwerk te operationaliseren met nieuwe en integrale methoden om de duurzaamheid en veerkracht van huidige en toekomstige Europese boerderijsystemen te kunnen bepalen. De volgende onderzoeksvragen staan centraal in dit proefschrift: 1) Is er een balans tussen sociale, economische en milieukundige functies van Europese boerderijsystemen? 2) Naderen Europese boerderijsystemen kritische drempelwaarden? 3) Welke capaciteiten van veerkracht hebben Europese boerderijsystemen, en welke zouden ze moeten hebben? 4) Welke strategieën verbeteren de duurzaamheid en veerkracht van Europese boerderijsystemen? De methoden die toegepast zijn in dit proefschrift volgen de vijf stappen van het veerkracht raamwerk zo goed als mogelijk. Vanuit een methodologisch perspectief operationaliseren de methoden het raamwerk door lokaal aangepaste indicatoren en verschillende bronnen en soorten van data te gebruiken.

Hoofdstuk 2 presenteert het Framework of "Participatory Impact Assessment for Sustainable and Resilient FARMing systems" (FoPIA-SURE-Farm I). FoPIA-SURE-Farm I onderzoekt huidige boerderijsystemen m.b.t. het functioneren, de dynamiek van belangrijke indicatoren, en de verschillende capaciteiten van veerkracht, d.w.z. robuustheid, adaptatievermogen en het vermogen tot transformatie. Drie gevalstudies met gespecialiseerde boerderijsystemen worden gebruikt als voorbeeld voor de gebruikte methodologie: de productie van zetmeelaardappelen in de Veenkoloniën, Nederland; zuivelproductie in Vlaanderen, België; en de productie van hazelnoten in Lazio, Italië. Hoofdstuk 3 presenteert de synthese van de toepassing van FoPIA-SURE-Farm I in 11 Europese boerderijsystemen. De resultaten van Hoofdstukken 2 & 3 overlappen. In de meeste boerderijsystemen worden functies relaterend aan voedselproductie, economische levensvatbaarheid en het onderhouden van natuurlijke hulpbronnen gezien als het meest belangrijk. De door de deelnemers waargenomen prestaties van systeemfuncties suggereert een middelmatige duurzaamheid van de bestudeerde boerderijsystemen. In het algemeen werd de veerkracht ingeschat als laag tot middelmatig, waar robuustheid en aanpassingsvermogen sterker ingeschat werden dan het vermogen om te transformeren. Dit geeft aan dat het vinden van wegen naar meer duurzaamheid een uitdagend proces is, want daar is immers aanpassingsvermogen en vermogen om te transformeren voor nodig. De karakteristieken van boerderijsystemen die zogezegd generieke veerkracht geven, de zogenaamde attributen van veerkracht, werden inderdaad waargenomen als positief voor de veerkracht. Winstgevendheid, een productie gekoppeld aan lokale en natuurlijke hulpbronnen, heterogeniteit van boerderijtypes, sociale zelforganisatie, en infrastructuur voor innovatie werden ingeschat als belangrijke attributen van veerkracht. Voor het vermogen tot transformatie werden met name winstgevendheid en toegang tot infrastructuur voor innovatie essentieel geacht. Strategieën die toegepast werden in het verleden waren er vooral op gericht om de winstgevendheid te vergroten en minder gericht op de andere belangrijke attributen van veerkracht. Om de duurzaamheid en veerkracht van Europese landbouwsystemen te vergroten zullen reacties op korte termijn processen beter rekening moeten houden met lange termijn processen. Technologische innovatie is nodig, maar het moet gepaard gaan met structurele, sociale, agro-ecologische en institutionele veranderingen. De relatieve belangrijkheid van sommige attributen van veerkracht verschilde tussen boerderijsystemen. Dit geeft aan dat de lokale context in het algemeen, en perspectieven van belanghebbenden in het bijzonder, belangrijk zijn voor het evalueren van generieke veerkracht en beleidsopties op basis van attributen van veerkracht. Alles bij elkaar opgeteld, lijkt FoPIA-SURE-Farm I een goed startpunt voor het creëren van bewustzijn, verder onderzoek en uiteindelijk het ontwikkelen van een gedeelde visie en actieplan voor het verbeteren van duurzaamheid en veerkracht van boerderijsystemen.

Hoofdstuk 4 heeft als doel de kwalitatieve resultaten over huidige duurzaamheid en veerkracht uit Hoofdstukken 2 & 3 aan te vullen met een kwantitatieve benadering. Een statistische methode voor meerjarige datareeksen was toegepast om boerderijprestaties te bestuderen mb.t. voedselproductie, winstgevendheid en stikstofoverschot onder verschillende omstandigheden wat betreft weer, markt en boerderijstructuur. Een gevalstudie voor drie aardappel producerende regio's werd gebruikt met data van 2006 t/m 2019. De prestaties van de statistische modellen waren hoogstens middelmatig. Model resultaten waren gemakkelijk te beïnvloeden door de selectie van responsvariabelen. Het niveau en de graduele verandering van voedselproductie, economische prestaties en milieuprestaties werden voornamelijk beïnvloed door input-intensiteit. Hoe die beïnvloeding door intensiteit werkte, d.w.z. positief of negatief, verschilde per gevalstudie. Jaarlijkse variatie werd hoofdzakelijk bepaald door gemiddelde jaarlijkse weersomstandigheden en weersextremen. Er werd geen bewijs gevonden voor impactreductie van weersomstandigheden en weersextremen door boerderijstructuur. Alles bij elkaar genomen kan de conclusie getrokken worden dat de resultaten in dit hoofdstuk slechts bestaande kennis bevestigen op het niveau van de gevalstudies. In de context van veerkracht van boerderijen in combinatie met een relatieve kleine dataset lijkt de methode zich te beperken tot een vrij homogene boerderijpopulatie in een stabiele economische omgeving. Onderzoekers die de gebruikte methoden willen gebruiken in (akkerbouw) boerderijsystemen zullen goed moeten beseffen dat ze veel invloed kunnen hebben op de resultaten door de selectie van responsvariabelen.

Hoofdstuk 5 heeft als doel om paden naar meer duurzame en veerkrachtige boerderijsystemen te vinden, terwijl kritische drempelwaarden worden geïdentificeerd en ontweken. Voor dit doel werd een participatieve, integrale en indicator-gebaseerde methode gepresenteerd. Deze methode leidt onderzoekers en belanghebbenden in het boerderijsysteem in zes stappen naar een multidimensionaal begrip van duurzaamheid en veerkracht van toekomstige boerderijsystemen (FoPIA-SURE-Farm II). De methode wordt gepresenteerd aan de hand van een gevalstudie met extensieve schapenhouderij in Huesca, Spanje. Deelnemers in de participatieve workshop gaven aan dat hun boerderijsysteem heel dicht bij een neergang of zelfs ineenstorting staat. Het naderen en overschrijden van kritische drempelwaarden in het sociale, economische en milieu domein zorgt op dit moment voor een vicieuze cirkel met onder meer lage winstgevendheid, lage aantrekkingskracht van het boerderijsysteem en de verwaarlozing van weidegronden. Deelnemers stelden twee alternatieve, meer duurzame en veerkrachtige systemen voor: een semi-intensief systeem dat allereerst gericht is op het verhogen van de productie en een hightech extensief systeem dat allereerst gericht is op het aanbieden van publieke diensten. Beide alternatieven leggen een sterke nadruk op de rol van technologie, maar verschillen in hun benadering tot weidegang. Dit verschil wordt gereflecteerd in de verschillende strategieën die voorzien worden om de alternatieve systemen te bewerkstelligen. Alhoewel het hightech extensieve systeem het meest verenigbaar lijkt met een toekomstscenario waarin de productie van duurzaam voedsel erg belangrijk is, lijkt het semi-intensieve systeem minder risicovol omdat het, gemiddeld genomen, het meest verenigbaar is met meerdere andere toekomstscenario's. Alles bij elkaar genomen, kan de gebruikte methode gezien worden als relatief snel, interactief en trans-disciplinair, die veel informatie aanlevert over kritische drempelwaarden, huidige systeemdynamieken en toekomstige mogelijkheden. Zo doende helpt de methode belanghebbenden om na te denken en te praten over de toekomst van hun systeem, en helpt zo in de voorbereiding naar meer duurzaamheid en veerkracht.

In hoofdstuk 6 wordt FoPIA-SURE-Farm II toegepast om de aanwezigheid van kritische drempelwaarden te bepalen in 11 Europese boerderijsystemen. Alle bestudeerde systemen bevinden zich, aldus deelnemers, dichtbij, op of over ten minste één geïdentificeerde kritische drempelwaarde, d.w.z. dat deze systemen (erg waarschijnlijk) kritische drempelwaarden gaan overschrijden binnen de komende 10 jaren. Deelnemers waren in het bijzonder bezorgd over economische levensvatbaarheid en niveaus van voedselproductie. Kritische drempelwaarden werden bovendien waargenomen als interacterend tussen systeemniveaus (veld, boerderij, boerderijsysteem) en domeinen (milieu, economisch, sociaal), waar lage economische levensvatbaarheid leidt tot een lagere aantrekkingskracht van het boerderijsysteem, en, voor sommige boerderijsystemen, een hoge moeilijkheidsgraad om natuurlijke hulpbronnen en biodiversiteit te onderhouden. In het algemeen werd een neergang in prestaties van alle systeemvariabelen verwacht door workshop deelnemers in het geval kritische drempelwaarden zouden worden overschreden. Bijvoorbeeld een neergang in de aantrekkingskracht van een gebied en minder onderhoud aan natuurlijke hulpbronnen en biodiversiteit. Hoofdstuk 6 laat zien dat bezorgdheid over het overschrijden van kritische drempelwaarden terecht is en dat de drempelwaarden van systeemvariabelen onderzocht moeten worden op veld-, boerderij- en boerderijsysteem niveau en in het sociale, economische en milieu domein. Economische variabelen op boerderijniveau (bijvoorbeeld inkomen), lijken belangrijk om te detecteren of een systeem richting kritische waarden van sociale variabelen gaat op het niveau van het boerderijsysteem (bijvoorbeeld aantrekkingskracht van het gebied). Tegelijkertijd zijn er in meerdere gevalstudies indicaties dat het naderen van drempelwaarden van sociale variabelen (bijvoorbeeld beschikbaarheid van arbeid) een aanwijzing zijn voor het naderen van economische drempelwaarden (bijvoorbeeld bedrijfsinkomen). Op basis van de resultaten volgen enkele reflecties op het belang van het in het oog houden van hulpbronnen van het systeem, zoals kennis niveaus, bij het monitoren en evalueren van de duurzaamheid en veerkracht van Europese boerderijsystemen.

Hoofdstuk 7 geeft een synthese van het onderzoek dat weergegeven wordt in dit proefschrift. Gebaseerd op deze synthese worden aanbevelingen gedaan voor het verbeteren van duurzaamheid en veerkracht. Vervolgens worden het theoretische raamwerk en de methodes geëvalueerd die gebruikt zijn in dit proefschrift. Daarna volgt een discussie over de relevantie van het onderzoek. Op basis van de voorgaande discussies worden reflecties gegeven over het verbeteren van het monitoren en evalueren van duurzaamheid en veerkracht van boerderijsystemen in Europa. Ik concludeer dat de duurzaamheid en veerkracht van boerderijsystemen een uitdagend onderwerp blijft door de complexiteit in termen van detail (verschillende domeinen, veel concepten en variabelen) en dynamieken (non-lineariteit, drempelwaarden, interacties). Het onderzoek dat gepresenteerd wordt in dit proefschrift bevestigt het nut van het gebruikte veerkracht raamwerk: de complexiteit rondom veerkracht is gereduceerd middels een stapsgewijze benadering aangepast aan boerderijsystemen. De participatieve benaderingen in dit proefschrift droegen vooral bij aan het beschrijven en uitleggen van duurzaamheid en veerkracht van huidige boerderijsystemen. De resultaten van deze methoden vormen daardoor een goede basis voor het exploreren van toekomstige boerderijsystemen. De kwantitatieve benadering (gepresenteerd in Hoofdstuk 4) bevestigde de impact van weersextremen op economische en milieukundige boerderijprestaties, maar was beperkt wat betreft het verstrekken van inzicht in veerkracht. De kwantitatieve benadering liet ook zien hoe onderzoekers invloed kunnen hebben op de resultaten door de selectie van responsvariabelen. Gebaseerd op resultaten en reflecties in dit proefschrift zie ik ruimte voor verbetering wat betreft het begrijpen en bepalen van duurzaamheid en veerkracht door meer gebruik te maken van systeemdenken en het gebruik van participatieve integrale assessments.

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About the author

Wim Paas was born and raised in Genemuiden, the Netherlands, where he enjoyed the water-rich environment and a hands-on work culture. He completed a BSc study International Land and Water Management at Wageningen University in 2011. During an internship in Ethiopia on small-scale irrigation schemes he became interested in agronomy. He completed a MSc study Plant Sciences with a specialization in Natural Resource Management at Wageningen University in 2013. After graduation, he worked as a junior researcher on tropical farming systems with the Farming Systems Ecology group (2013-2014) and the Plant Production Systems group of Wageningen University (2015-2016). In 2017 he started a PhD on the sustainability and resilience of European farming systems with the Plant Production Systems group and Business Economics group of Wageningen University. The PhD and additional activities were conducted within the context of SURE-Farm, an international consortium funded by the Horizon 2020 program of the European Commission. In his research, Wim is keen on applying quantitative and qualitative research methods in complementary ways to capture the various dimensions of social-ecological systems. Besides doing research and reflecting on existence, he likes to move around by foot and bicycle, take care of trees and gardens, tinker with tools and machines and build constructions that improve everyday life in and around the homestead. In the near future, he envisions to settle with his family on a farm in rural France where he will put his body and mind to work.

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PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Methods (and indicators) to study the sustainability and resilience of farming systems

Writing of project proposal (4.5 ECTS)

- Integrated assessment of the sustainability and resilience of European farming systems

Post-graduate courses (7.6 ECTS)

- Companion modelling; WUR/CIRAD (2014)
- Participatory trials design; ICRAF (2014)
- Bayesian statistics; PE&RC; SENSE (2017)
- Multivariate analysis; PE&RC; SENSE (2019)
- GIS in practice; PE&RC; WIMEK (2019)

Invited review of (unpublished) journal manuscript (8 ECTS)

- 11 verified reviews for 8 individual manuscripts in 7 different journals (https://www.webofscience.com/wos/author/record/1863521)

Competence strengthening / skills courses (2.2 ECTS)

- Effective behaviour in the professional surroundings; WUR (2014)
- Project and time management; WUR (2019)
- Competence assessment; WGS (2020)
- Career assessment; WGS (2022)

Scientific Integrity/Ethics in science activities (0.3 ECTS)

- Ethics in plant and environmental sciences; WGS (2019)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Midterm weekend (2019)
- PE&RC Day (2019)
- PE&RC Last year weekend; (2021)

Discussion groups / local seminars or scientific meetings (11.1 ECTS)

- Sustainable intensification of agricultural systems (SIAS) (2014-2015)
- Tuesdays with resilience (2017)
- SURE-Farm consortium meetings (2017-2021)
- 7th International Symposium for Farming System Design (2021)

International symposia, workshops and conferences (3.5 ECTS)

- 173rd symposium of the European Association of Agricultural Economists; Bucharest (2019)
- XVI European Society for Agronomy Congress; online (2020)

Societally relevant exposure (0.5 ECTS)

- News article in WUR’s magazine Resource (2021)

Lecturing/supervision of practicals/tutorials (6.9 ECTS)

- Quantitative analysis of land use systems (2020-2021)
- Academic advisor for academic consultancy training (2022)

BSc/MSc thesis supervision (26 ECTS)

- The effects of change in extreme climate events on agriculture in the Netherlands
- Assessing the resilience and sustainability of a hazelnut farming system in Central Italy
- An assessment of the sustainability and resilience of two livestock farming systems in Europe using a participatory approach
- Participatory assessment of the functions, sustainability and resilience of large-scale arable farming in the East of England
- Assessing resilience and sustainability in German large-scale corporate arable farms
- Analyzing the resilience of an arable farming system in the Veenkoloniën, NL, using system dynamics modelling
- Exploring the impact of nematode dynamics on starch potato yield in the Veenkoloniën
- The impact and assessment of extreme drought events on arable crop production in the Netherlands
- Synergies and trade-offs between perceptions of sustainability and resilience in two small-scale European farming systems

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