A framework to assess the resilience of farming systems

Miranda MEUWISSEN[1]*, Peter H. FEINDT[2,3], Alisa SPIEGEL[1], Katrien TERMEER[4], Erik MATHIJS[5], Yann DE MEY[1], Robert FINGER[6], Alfons BALMANN[7], Erwin WAUTERS[8], Julie URQUHART[9], Mauro VIGANI[9], Katarzyna ZAWALIŃSKA[10], Hugo HERRERA[11], Phillipa NICHOLAS-DAVIES[12], Helena HANSSON[13], Wim PAAS[1,14], Thomas SLIJPER[1], Isabeau COOPMANS[5], Willemijn VROEGE[6], Anna CIECHOMSKA[10], Francesco ACCATINO[15], Birgit KOPAINSKY[11], P. Marijn POORTVLIET[2], Jeroen CANDEL[4], Damian MAYE[9], Simone SEVERINI[16], Saverio SENNI[16], Bárbara SORIANO[17], Carl-Johan LAGERKVIST[13], Mariya PENEVA[18], Camelia GAVRILESCU[19], Pytrik REIDSMA[14]

[1]Business Economics, Wageningen University, P.O. Box 8130, 6700 EW Wageningen, the Netherlands; [2]Strategic Communication, Wageningen University, the Netherlands; [3]Albrecht Daniel Thaer Institute, Humboldt University at Berlin, Germany; [4]Public Administration and Policy, Wageningen University, the Netherlands; [5]Division of Bioeconomics, KU Leuven, Belgium; [6]Agricultural Economics and Policy Group, ETH Zurich, Switzerland; [7]Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Germany; [8]Agricultural and Farm Development, Institute for Agricultural and Fisheries Research (ILVO), Belgium; [9]Countryside and Community Research Institute, University of Gloucestershire, UK; [10]Institute of Rural and Agricultural Development, Polish Academy of Sciences, Poland; [11]System Dynamics Group, University of Bergen, Norway; [12]Aberystwyth Business School, Aberystwyth University, UK; [13]Department of Economics, Sveriges Lantbruksuniversitet, Sweden; [14]Plant Production Systems, Wageningen University, the Netherlands; [15]INRA, AgroParisTech, Université Paris Saclay, 75005, Paris, France; [16]Department of Agricultural and Forestry Sciences, Università degli Studi della Tuscia, Italy; [17]Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), Universidad Politecnica de Madrid, Spain; [18]Department of Natural Resources Economics, University of National and World Economy, Bulgaria; [19]Institute of Agricultural Economics, Romania

** Corresponding author (miranda.meuwissen@wur.nl)*

Abstract

Agricultural systems in Europe face accumulating economic, ecological and societal challenges, raising concerns about their resilience to shocks and stresses. These resilience issues need to be addressed with a focus on the regional context in which farming systems operate because farms, farmers' organizations, service suppliers and many supply chain actors are embedded in local environments and functions of agriculture. In this paper 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. Using this definition, we (i) develop a framework to assess the resilience of farming systems, and (ii) present a methodology to operationalize the framework with a view to Europe's diverse farming systems. The framework is designed to assess resilience to specific challenges (specified resilience) as well as farming system's capacity to deal with the unknown, uncertainty and surprise (general resilience). The framework provides a heuristic to analyze system properties, challenges (shocks, long-term stresses), indicators to measure the performance of system functions, resilience capacities and resilience-enhancing attributes. Capacities and attributes refer to adaptive cycle processes of agricultural practices, farm demographics, governance, and risk management. The novelty of the framework pertains to the focal scale of analysis, i.e. the farming system level, the consideration of accumulating challenges and various agricultural processes, and the consideration that farming systems provide multiple functions that can change over time. Furthermore, the distinction between three resilience capacities (robustness, adaptability, transformability) ensures that the framework goes beyond narrow definitions that limit resilience to robustness. The methodology deploys a mixed-methods approach: quantitative methods, such as statistics, econometrics and modelling, are used to identify underlying patterns, causal explanations and likely contributing factors; while qualitative methods, such as interviews, participatory approaches and stakeholder workshops, access experiential and contextual knowledge and provide more nuanced insights. Furthermore, the framework allows to generate better understanding of resilience-constraining and enabling attributes. More specifically, analysis along the framework explores multiple nested levels of farming systems (e.g. farmer, farm, farm household, supply chain, farming system) over a time horizon of 1-2 generations, thereby enabling reflection on potential temporal and scalar trade-offs across resilience attributes. The framework will be of interest for *ex-post* analysis of farming system dynamics and responses to challenges; and *ex-ante* assessment and creation of resilience-enhancing strategies and attributes across farming systems.

Graphical abstract. Separate file.

Keywords*:* farming systems; resilience capacities; enabling environment; shocks; long-term stresses; private and public goods.

Highlights

- Resilient farming systems are robust, adaptable and transformable
- Resilience capacities and attributes are sensitive to local context
- Integrated resilience assessment of farming systems needs mixed methods
- Current resilience assessment tools often neglect transformability

1. Introduction

Today's farming systems face a broad range of environmental, economic, social and institutional challenges. Economic and social challenges include more volatile prices in liberalized markets, sudden changes in access to markets, e.g. due to trade wars, political boycotts or Brexit (Maye et al., 2018), the shift towards less stable and less protective policy environments (Daugbjerg and Feindt, 2017) and increasing controversy about agricultural practices (Guiton et al., 2015; Myers et al., 2016) such as novel breeding techniques (Purnhagen et al., 2018) and animal welfare (Bos et al., 2018). These uncertainties exacerbate demographic issues such as a lack of successors to enable generational renewal at farm level (Lobley et al. 2010; Burton and Fischer 2015; Zagata and Sutherland 2015) and insufficient availability of seasonal, permanent and skilled labor (McGuinness and Grimwood 2017). Although such challenges affect food systems at large scales, regional contextual characteristics often buffer or exacerbate their effects (Saifi and Drake, 2008). Response options to challenges also depend on local circumstances. For instance, the economic impact of droughts depends on local factors such as soil quality, cropping patterns, irrigation infrastructure, the flexibility of credit providers, uptake of crop insurance and the flexibility of supply chain partners to retrieve produce from elsewhere (e.g. Diogo et al., 2017). The local network of farms and other actors formally and informally interacting in a specific agro-ecological context is well described by the concept of 'farming systems' (Giller, 2013).

The ability of farming systems to cope with challenges can be conceptualized as resilience (Folke et al., 2010; Folke, 2016; Bullock et al., 2017). Resilience theory emphasizes change, uncertainty, and the capacity of systems to adapt (Holling et al., 2002). Several resilience frameworks have already been developed and applied to components of farming systems, such as farms (e.g., Darnhofer, 2014; Herman et al., 2018), people (Coutu, 2002), businesses (Reeves et al., 2012), food supply chains (Leat and Revoredo-Giha, 2013; Stone and Rahimifard, 2018) and socio-ecological systems (e.g., Walker et al., 2004; Folke et al., 2010; Stockholm Resilience Centre, 2015). Grounded in extensive literature reviews (e.g. Stone and Rahimifard, 2018) and systematic analysis of long-lasting systems (e.g. Reeves et al., 2012), these frameworks provide useful insights into capacities and attributes that enhance or constrain resilience. For instance, Darnhofer (2014) stresses the importance of diversity in farm activities, Stone and Rahimifard (2018) illustrate that redundancy is a characteristic of resilient food supply chains, and Coutu (2002) states that resilient people have an "uncanny ability to improvise". However, it is still unclear how these and other attributes are to be assessed at the level of farming systems, where farms might cooperate across sectors, non-farm populations are neighbors with farmers, farmers contribute to multiple value chains, and where required functions change in response to changing consumer and societal preferences.

Against this background, this paper aims to (i) develop a framework to assess the resilience of farming systems, and (ii) present a methodology to operationalize the framework with a view to Europe's diverse farming systems. We define the 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. This definition deviates from much of the social-ecological resilience literature in its focus on output (i.e., production functions, see Ge et al., 2016) and in considering a socially determined flexibility in the set of desired functions. The three capacities are grounded in literature on adaptive cycles and adaptive governance. Section 2 therefore discusses the main adaptive cycle processes in agriculture, i.e. adaptive cycles inherent in agricultural practices, farm demographics, governance, and risk management. Section 3 presents the key steps of the framework. Section 4 describes the methodology to operationalize the framework in the context of EU farming systems. The discussion and conclusions are presented in Section 5.

2. Adaptive cycles in agriculture

The concept of adaptive cycles originates in ecological systems thinking, where they represent different stages (growth, conservation, collapse, reorganization) through which systems might pass in response to changing environments and internal dynamics (Holling et al., 2002). Farming systems differ from ecological systems in their deliberate attempts to control their environment and to escape environmentally induced disruption. When applied to farming systems, the concept of adaptive cycles therefore serves not as a model but as a heuristic that guides the attention to system change as illustrated in Figure 1. For instance, when farming systems face potentially disruptive challenges, risk management may be utilized to ensure that the system remains in or swiftly returns to status quo (conservation). However, the figure also illustrates that other responses are possible such as spread of well-functioning practices (growth), adoption of new practices (reorganization) or breakdown and abandonment of an agricultural system (collapse). Such changes may relate to specific tools or field plots, but may as well refer to e.g. a whole farm or region. At farm level, major changes are often linked to intergenerational transfer in family farms, or to management or shareholder turnover in corporate farms. In particular at the point of generational turnover, decisions are made whether to continue and how to adapt the organization of the farm to changing needs and abilities. Both succession in family farms and skillful management of corporate farms are constrained by perceptions of farming as a relatively low income occupation with long working hours, remote locations, reduced social life and often high financial challenges (Huber et al., 2015). The consequences of eventual discontinuation for the farm, affected people and the farming system depend on factors such as alternative job opportunities and whether others take over the farm operation or its functions.

[FIGURE 1]

In farming systems, influences on system change, cycles, stages and impacts are less systematic and automatic than Figure 1 suggests; a specific farming system might not go through all stages of the adaptive cycle (Van Apeldoorn et al., 2011). Yet, indications of some influences, stages and impacts can be distinguished. For instance, the agricultural commodity price spikes in 2008 and 2011/12, accompanied by substantial fluctuations of prices of energy and fertilizers, led to increasing concerns that agricultural production practices might no longer keep pace with demand (e.g., von Witzke, 2008). Price spikes induced farmers and other actors along the chain to reorganize their price risk management (Assefa et al., 2017), e.g. towards temporarily cutting production as a response to high input prices, and instruments such as backward and forward integration. Another example of system change relates to the EU enlargements in 2004 and 2007 that facilitated migration of new EU citizens as seasonal and permanent workers to old EU member states. In the Baltic countries, for example, this led to structural deficits of skilled farm labor (Hazans and Philips, 2010). In response, labor markets in the new member states reorganized by adjusting hiring standards and increasing wages, thereby attracting non-EU workers from Ukraine, Russia, Belarus, Moldova and Uzbekistan.

3. Framework to assess resilience of farming systems

Building on the adaptive cycle concept, the framework transcends narrow definitions of resilience that focus on maintaining a current system's equilibrium (conservation). Instead, we include three system capacities as crucial capacities to understand the resilience of farming systems: robustness, adaptability and transformability. These capacities were previously distinguished by Walker et al. (2004), Folke et al. (2010) and Anderies et al. (2013) in the context of social-ecological systems with a focus on the provision of eco-system services. Furthermore, the framework distinguishes resilience to specific challenges (specified resilience) from a farming system's capacity to deal with the unknown, uncertainty and surprise (general resilience). We therefore developed the framework along five steps, as shown in Figure 2, whereby the 'top-down' steps 1 to 5 address specified resilience, while 'bottom-up' question 5 addresses general resilience. With regard to specified resilience, the analytical steps follow the questions posed by Carpenter et al. (2001) and Herrera (2017), i.e. 'resilience of what', 'resilience to what', and 'resilience for what purpose' – to which we added two further questions, i.e. 'what resilience capacities', and 'what enhances resilience'. Some authors also distinguish the 'resilience for whom?' question (see e.g. Quinlan et al., 2016). Our focus on functions provided to society implies that resilience is primarily in the interest of the wider society.

[FIGURE 2]

Step 1: Resilience of what? – Characterizing the farming system. The characterization of a farming system starts with the main product of interest, e.g. potatoes, and the regional context, e.g. Veenkoloniën in the Netherlands. The core of the system are the farms that produce the main product. Consequently, not all farms in a region are necessarily included in the same farming system. Other actors (an umbrella term for people and organizations) are divided into farming system actors and context actors, depending on patterns of influence. Farms and other farming system actors mutually influence each other, while context actors either influence farms or are influenced by farms unilaterally (Figure 3). Because farming systems work in open agro-ecological systems and are linked to various social networks and economic processes, their activities can have significant effects, e.g. through job and income creation, network effects, resource use, landscape impacts and emissions. These external effects and public goods also characterize the farming system. The structures and feedback mechanisms or identity (Cumming and Peterson, 2017) of the farming system are determined by historically shaped paradigms (Hall, 1993) and sense of belonging (Hofstede et al. 2010), which typically change slowly. However, farming systems are open systems with open informational, material and financial flows (Termeer et al., 2018), e.g. through the import of technology, seeds and feed ingredients. Neither farms nor other actors in the farming system are homogenous and tensions between their interests and identities are likely (e.g., farmers want to experiment with new practices to enhance resilience while processors perceive these as risky and decide to buy produce elsewhere). Hence, while the focal scale of the framework is the farming system, other nested levels of the system need to be considered as well, including the farmers, the farms, the farm households, supply chain actors, and other system actors.

[FIGURE 3]

Step 2: Resilience to what? - Identifying key challenges. We consider economic, environmental, social and institutional challenges that could impede the ability of the farming system to deliver the desired public and private goods. We distinguish shocks from long-term stresses. Examples of challenges for EU farming systems are included in Annex I. Whether shocks have irreversible effects on farming system functions (e.g., when excessive precipitation leads to landslides) or have only temporary effects (e.g., production levels readjust after a disease outbreak has been contained) depends on the system's resilience. Long-term stresses develop as gradual change of the system's environment, such as the gradual settlement of invasive plants, ageing of rural populations, or changing consumer preferences. An accumulation of stresses and (potential) shocks is likely to increase the farming system's vulnerability in nonlinear ways, leading to tipping points when critical thresholds are crossed.

Step 3: Resilience for what purpose? - Identifying desired functions of the farming system. Farming systems' functions can be divided into the provision of private goods and public goods. Private goods include the production of food and other bio-based resources but also ensuring a reasonable livelihood for people involved in farming (Annex II). Public goods include maintaining natural resources in good condition, ensuring that rural areas are attractive places for residence and tourism and animal welfare. Farming systems generally provide multiple functions. This can create synergies or trade-offs (e.g., Reidsma et al., 2015). Where trade-offs across functions occur, stakeholders are likely to have different priorities, e.g. for landscape diversity or production maximization, which will also depend on the distribution of costs and benefits. Furthermore, desired functions can change over time, e.g. due to changing societal preferences. This implies that, when interpreting the performance of functions, both dynamics and levels need to be considered. Stable functions are not necessarily good; if the system is not sustainable, i.e. a balanced provision of public and private goods cannot be maintained at desired levels, transformation may be required.

Step 4: What resilience capacities? – Assessing resilience capacities. We distinguish three resilience capacities. *Robustness* is the farming system's capacity to withstand stresses and (un)anticipated shocks (compare Figure 4a). *Adaptability* is the capacity to change the composition of inputs, production, marketing and risk management in response to shocks and stresses but without changing the structures and feedback mechanisms of the farming system (Figure 4b). *Transformability* is the capacity to significantly change the internal structure and feedback mechanisms of the farming system in response to either severe shocks or enduring stress that make business as usual impossible (Figure 4c). Such transformations may also entail changes in the functions of the farming system. Furthermore, although Figure 4c suggests that transformation occurs after tipping points and collapse, it may also result from a sequence of small and incremental changes (Termeer et al., 2017).

[FIGURE 4]

Step 5: What enhances resilience? – Assessing resilience enhancing attributes. Resilience attributes are the individual and collective competences and the enabling (or constraining) environment that enhance one or more resilience capacities, and, more broadly, general resilience. Attributes are grounded in the adaptive cycle processes of agricultural practices, farm demographics, governance, and risk management (Figure 1). We assess these attributes in the context of the five generic principles of resilience as proposed by the Resilience Alliance (2010): (i) diversity, including both functional diversity (Kerner, 2014) and response diversity, whereby the latter refers to the different responses to disturbance (Reidsma and Ewert, 2008; Carpenter, 2012); (ii) modularity, i.e. internal division of the system in independent but connected modules (Carpenter, 2012) with potentially different functions; (iii) openness, which refers to connectivity between systems (Carpenter, 2012); (iv) tightness of feedbacks, i.e. the response of one part of the system to changes in other parts of the system (Walker and Salt, 2006), whereby institutions and social networks shape the informational and material flows and thereby determine the tightness of feedbacks and the likelihood that feedback is delayed until severe consequences occur; and (v) system reserves, i.e. resource stocks (i.e. natural, economic, social capital) to which a system has access when responding to stress and shocks (Kerner, 2014). System reserves provide redundancy and serve as "insurance" that allows to compensate for the loss or failure of system functions (Biggs, 2012). Larger and more diverse reserves generally enable greater resilience (Resilience Alliance, 2010). These five encompassing principles converge with other lists such as the one designed for ecosystem services (e.g., Biggs et al. (2015), also used by the Stockholm Resilience Centre) and agricultural practices (Cabell and Oelofse, 2012). Yet, the five principles of the Resilience Alliance are more generic, thereby allowing to include the complexity of the farming systems' multiple processes and actors.

4. Methodology to operationalize the framework

Building on the heuristic of the framework, a detailed sequence of methodological steps has been developed to guide case inquiry and to enable comparative analysis across cases. Methodological steps deployed in the SURE-

Farm project (surefarmproject.eu) are elaborated in Table 1. The project selected multiple farming systems to account for variety along five dimensions relevant in the context of resilience, including types of challenges and public goods affected (step 1a). The following steps analyze challenges, functions, resilience capacities and resilience attributes, whereby findings of earlier steps feed into later assessments. Overall, the methodology consists of a mixed-methods approach: quantitative methods, such as statistics, econometrics and modelling, are used to identify underlying patterns, causal explanations and likely contributing factors; while qualitative methods, such as interviews, participatory approaches and stakeholder workshops, access experiential and contextual knowledge and provide more nuanced insights. Building on the findings of multiple cases, step 5 aims at theory development and practical learning, in particular when implementation roadmaps are identified (step 5d).

[TABLE 1]

To illustrate how the approach works, we draw on the Dutch case study from the SURE-Farm project. The 'arable farming system with family farms in Veenkoloniën' was selected due to challenges related to, among others, wind erosion and relatively low economic performance (Diogo et al., 2017). The farming system's boundaries are mainly determined by an ecological factor, soil type. The peat soils dominant in the region are shaping the arable farmers' cropping plans which mainly consist of starch potatoes, sugar beet and winter wheat. Given these area and cropping characteristics, the potato processing cooperative and the local water authority, which is responsible for water transports from the distant IJssel Lake to the area in case of drought, are strong players. Both are part of the farming system, reflecting mutual dependence between them and the farms (step 1b). Due to local initiatives to intensify cooperation between arable and dairy farms, inter alia for joint crop rotation, dairy farmers in the region are also considered as system actors. Regarding the time horizon, most farmers find it difficult to look 20 years ahead, given the various current challenges they are facing (step 1c). Other household members are included in in-depth interviews to reflect their important role in relation to off-farm income opportunities (step 1d). With regard to challenges (step 2), SURE-Farm considers standard categories such as price fluctuations and financial risks, which are augmented by farming system-specific challenges which emerged from in-depth interviews. In the Veenkoloniën farming system, the farmer survey therefore includes soil quality and crop protection challenges. With regard to the importance of functions (step 3a), tensions are found between farmers' preference to achieve an adequate income and other stakeholders' preference to maintain natural resources in good condition, which reflect current concerns about among others soil quality. Desired functions towards the future (20 years) are elicited through a participatory workshop with system actors and other stakeholders. When collecting indicators to measure the performance of current functions (step 3b), proxies are mostly needed for indicators at the farming system level for aggregate information such as net migration and tourist activities (Annex II) as the farming system area does not converge with administrative areas such as provinces. In addition, for some indicators objective information is lacking. We therefore use subjective proxies. For instance, during one of the participatory workshops, one of the indicators reflecting quality of life in rural areas, 'share of registered psychological disorders among farmers (e.g., suicides, doctor visits due to psychological issues)' (Annex II), is replaced with 'degree of unhealthy stress among farmers'. Performance of functions (step 3c) is investigated inter alia through analyzing stability of and down-side risks to each function. With regard to the assessment of resilience capacities (step 4), structured surveys are used to elicit farmers' perceptions about their own capacities, while stakeholder workshops reveal perceived capacities at farming system level. The analysis also evaluates how actual and potential policies and strategies of system actors such as the local water authority and the potato processor contribute or constrain capacities of robustness, adaptability and transformability. In addition, the technique of abductive reasoning is used to infer, e.g. from in-depth interviews, which resilience capacities were revealed in the past after catastrophic events, or in current plans to respond to today's challenges. While the respondents might not necessarily use the terms of robustness, adaptability and transformability, the researcher attributes these capacities in reconstructing the narrative. Veenkoloniën farmers for instance seem to regard most of their current strategies as adaptation, ranging from including unions in their cropping plans to experimenting with various measures to improve soil quality. The multiple insights into (perceived) resilience capacities then lead to the core of the framework, i.e. linking the capacities 'back' to step 3 and 2, i.e. the functional performance as affected by a range of challenges, and assessing which attributes enhance the resilience capacities, i.e. linking to the next step of the framework (step 5). With regard to 'linking back', statistical analysis (inter alia) is carried out to assess e.g. associations between variables of farm structural change (reflecting adaptability and transformability) and functional performance, such as gross margin per hectare and diversity of ecosystem services. Econometrics are used (among others) to link to step 5. For instance, building on the theory and hypotheses of the five generic principles of resilience, econometric analysis can provide insights into factors (e.g. diversity of risk management tools) contributing to the stated resilience capacities of farmers. Detailed interpretations of in-depth interviews will add to these insights as e.g. annual statistics 'may not tell the whole story', or policy instruments might have unanticipated consequences in specific regional contexts. With regard to the resilience-enhancing attributes (step 5), in-depth interviews and stakeholder workshops are used to identify a range of attributes which could potentially be relevant for the Veenkoloniën, such as stimulating farmers' learning about soil improvements and cooperation with dairy farmers, leadership of local (water) authorities to rapidly act in case of crisis, and policies stimulating such developments, thereby building on the generic principles of resilience (step 5a). Next, their current state, enhancing or constraining effect on the resilience capacities and potential improvements of such attributes are assessed (step 5b/5c). Due to the gradual and complex nature of resilience there will not be a single 'yes/no diagnosis' for the Veenkoloniën farming system. Instead, the joint consideration of the multiple analyses at various levels and for multiple challenges will provide 'an elaborated diagnosis', e.g. eventually finding a robustness-enhancing, adaptability-constraining environment for economic challenges, and a resilience-constraining environment for social and environmental challenges. Lessons learned from the Veenkoloniën farming system feed into the roadmap design across EU farming systems (step 5d).

5. Discussion and conclusions

This paper presented a conceptual and methodological framework to assess the resilience of farming systems. The framework allows to identify and assess resilience-enhancing competences and enabling environments in the context of farming systems' multiple functions, challenges, actors and temporal developments. The paper also sketches out the methodology for applying the framework in an assessment of farming systems. The novelty of the framework pertains to the focal scale of analysis, i.e. the farming system level, the consideration of various accumulating challenges and agricultural processes, the distinction between robustness, adaptability and transformability as resilience capacities, and the consideration that farming systems provide multiple functions that can change over time. Furthermore, we embed the concept of farming systems in broader notions of 'socio-ecological systems' (Walker et al., 2004) but focus on the productive function in the context of other social and ecological functions.

While the framework revolves around challenges affecting farming systems, it does not treat farming systems as passive or static but includes the multiple innovations and opportunities in key agricultural processes as these can enhance or constrain resilience capacities and attributes. Moreover, the framework fits well with current EU agricultural policy trends which are poised to provide more flexibility at the (sub)national level to account for context-specificity, as illustrated by regional specifications in the Rural Development Plans (EC, 2018). Furthermore, the framework links resilience to sustainability (Tendall et al., 2015) by determining 'resilience for what purpose', thereby preventing that outcomes positively assess the resilience of a system configuration that might be unsustainable.

The conceptual and methodological framework presented in this paper provides the foundation for an integrated assessment of the resilience of European farming systems (Herrera et al., 2018). The framework will be of interest for *ex-post* analysis of farming system dynamics and responses to challenges; and *ex-ante* assessment and creation of resilience-enhancing strategies and attributes across farming systems. Moreover, due to providing insights in resilience at multiple nested levels of farming systems in the context of a range of challenges, the framework enables to provide an 'elaborated diagnosis' of the resilience of a farming system, e.g. eventually simultaneously finding a resilience-contraining environment for social and economic challenges and a resilience-enhancing environment for environmental challenges, or vice versa. Moreover, the inclusion of three resilience capacities (robustness, adaptability, transformability) reflects different possible resilience strategies. In addition, the consideration of attributes grounded in multiple adaptive cycle processes enables to reflect on trade-offs across resilience attributes (e.g. enhancing robustness at the expense of transformability) and (intended or unintended) externalities across levels (e.g. enhancing the robustness of a value chain by forcing adaptation/transformation upon its members). Further research is needed towards tools to assess transformation and transformability; tools are available to assess robustness and adaptability, but less for transformability (Herrera et al., 2018). The same is true for policies and strategies: current policies mostly contribute to robustness and adaptability, but less to transformability (Feindt et al., 2018; SURE-Farm policy brief, 2018). By enabling us to ask these questions, the framework contributes to a broader and more nuanced understanding of the (conditions for) resilience of European farming systems.

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Table 1: Methodology to operationalize the resilience framework in the SURE-Farm project

	Steps	Methodology
1. Farming system (FS)	**1a.** Compare diverse set of FS to explore variety of FS' constellations, challenges, functions and responses	We selected 11 EU FS to include variety along five dimensions: (i) challenges (economic, social, environmental, institutional); (ii) agro-ecological zoning; (iii) type (sector, intensity, farm size, organizational form); (iv) produce (high-value products, commodities); and (v) affected public goods (landscape, water quality, biodiversity).
	1b. Characterize farming system	A FS is characterised by its actors (farms and other actors with mutual influence) and locality. Naming FS by referring to farm type and region, e.g. 'large-scale arable farming in East Anglia (UK)', is a short-hand. While the farm type highlights the marketable goods (e.g. arable crops), the region is a short-hand for the related public goods that are mostly bound to landscape and location, and for the farm and non-farm actors, many of which will be located in the region.
	1c. Analyze developments over time	We consider the current situation +/- 20 years, and five explorative scenarios (>20 years)[1].
	1d. Explore multiple, nested levels of the FS to deal with FS' soft boundaries	Analyses are carried out at level of farmer, farm household, farm, supply chain, and FS.
2. Challenges	Identify relevant challenges per FS	We elicit the perceived importance of about 20 inductive challenges per FS, consisting of shocks with reversible and irreversible effects on FS functions, and long-term stresses. Secondary data are collected for challenges such as extreme weather and price and subsidy changes. Also a variety of qualitative approaches is used to identify challenges, including participatory workshops and in-depth interviews.
3. Functions	**3a.** Understand desired functions in each FS	Functions are understood through (i) elicitation of importance among farmers and other stakeholders; and (ii) evaluating which topics are apparent in policy documents. Importance of functions can vary across FS.
	3b. Identify indicators to reflect functions	Multiple types of indicators are used at the various levels, such as monetary indicators (e.g. gross margin per hectare), technical parameters (e.g. total amount of major food products), age-related parameters (e.g. average age of farmers and contract workers), and proportions (e.g. share of registered psychological disorders). If indicators are not available at the proper level, proxies are used.
	3c. Assess performance of indicators	We use a variety of methods: (i) multivariate statistical analysis; (ii) econometrics; (iii) modelling; (iv) visualization (drawing/plotting); (v) system dynamics; (vi) eliciting perceived performance in structured surveys and during stakeholder workshops; and (vii) conducting qualitative interviews with a range of stakeholders.
4. Resilience capacities	**4a.** Define three capacities, i.e. robustness, adaptability, and transformability, in context of FS	Application of the capacities to FS will elicit a broad range of strategies as well as contested interpretations of the boundaries between adaptation and transformation.
	4b. Assess three capacities	We use two approaches: (i) after providing the *definition* and an example for each capacity we elicit perceived capacities; and (ii) building on step 3c we *infer* the prevailing capacities by investigating 'the story behind the performance' (e.g. why is there hardly any effect of a shock; why does a function not recover for a long time after a shock; why do some functions decline gradually while other are maintained or even enhanced). Through statistics, econometrics and modelling we learn about underlying patterns, causal explanations and likely contributing factors; through the

		qualitative approaches we expect more contextualized and nuanced insights in resilience capacities.
5. Resilience attributes	**5a.** Identify attributes in context of the generic principles of resilience, i.e. diversity, openness, tightness of feedbacks, system reserves, and modularity (Resilience Alliance, 2010)	Attributes are identified with regard to (i) *agricultural practices*, e.g. learning from others about novel agricultural practices (openness), loose coupling with natural capital to create buffers (system reserves), stimulating horizontal and vertical cooperation (modularity); (ii) *farm demographics*, e.g. engagement among young generation and women in agricultural activities (diversity), organizing societal feedbacks on the role of farming (tightness of feedbacks), attraction of skilled labor (modularity); (iii) *governance*, e.g. policies stimulating the three capacities of resilience (diversity), infrastructure facilitating knowledge and adoption of cutting-edge technologies (openness), stimulating initiative and polycentricity (modularity); and (iv) *risk management*, e.g. exploring novel approaches including big data analytics and smart contracts to reduce risks (openness), enabling leadership to deal with catastrophic events (system reserves), encouraging learning, flexibility and openness to new ideas (modularity). Attributes are expected to vary across FS.
	5b. Assess resilience-enhancing attributes	Two approaches are used: (i) after defining *specific* attributes we explore their current state, contribution to resilience capacities, and potential improvements; and (ii) building on steps 3c and 4b we *infer* resilience enhancing attributes, their current state and potential improvements. Through statistics, econometrics and modelling we learn about patterns, underlying causal explanations and likely contributing factors; through expert and stakeholder assessment we expect more contextualized insights in resilience attributes including synergy and trade-offs.
	5c. Identify resilience-constraining attributes	Evidence is collected 'along the way' through (i) identifying 'what is not working' (steps 4b, 5b); and (ii) reflecting on trade-offs across resilience attributes (e.g. enhancing robustness at the expense of transformability) and (intended or unintended) externalities across levels (e.g. enhancing the robustness of a farm/value chain by forcing adaptation/transformation upon its members).
	5d. Identify implementation roadmaps	Building on the generic principles of resilience and lessons learned from steps 5b and 5c we use back-casting in 11 FS to identify implementation roadmaps (who? what? when?).

[1]Mathijs et al. (2018): 1: Sustainability; 2: Middle of the road; 3: Regional rivalry; 4: Inequality; 5: Fossil-fueled development.

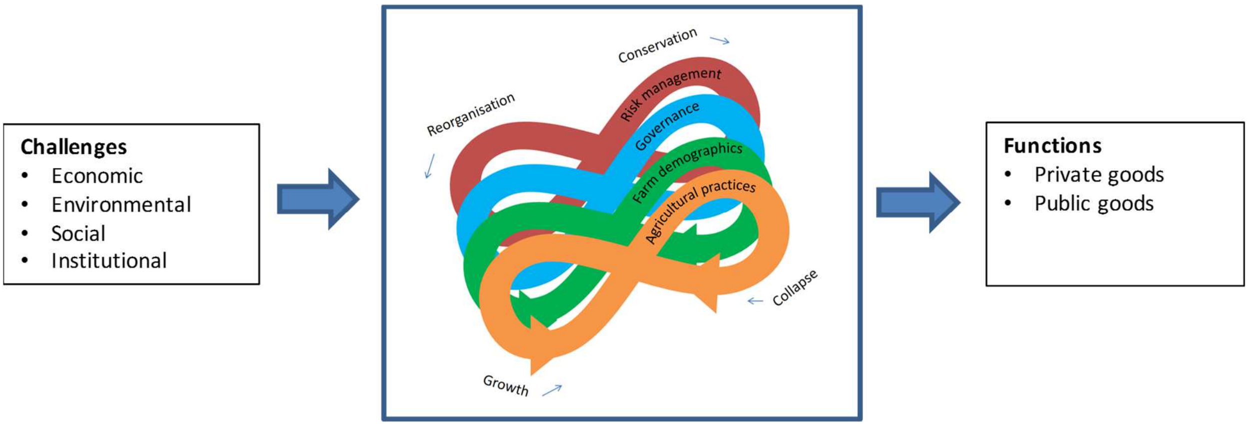

Figure 1: Adaptive cycles in agriculture.

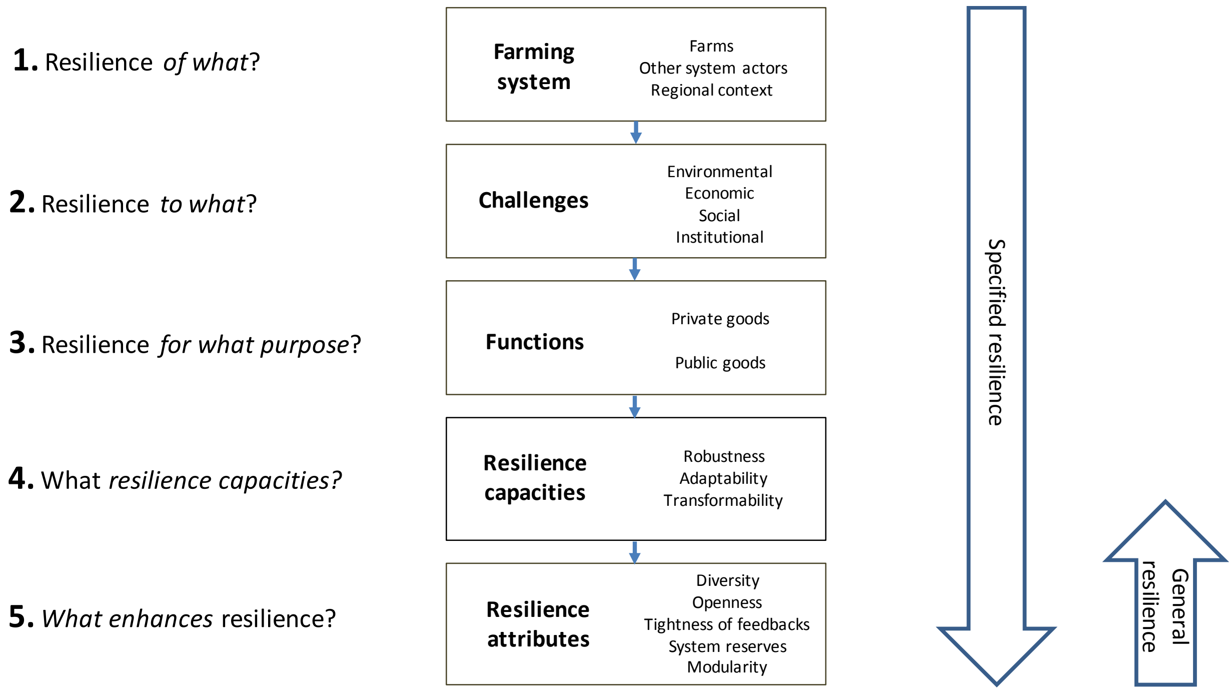

Figure 2: Framework to assess resilience of farming systems.

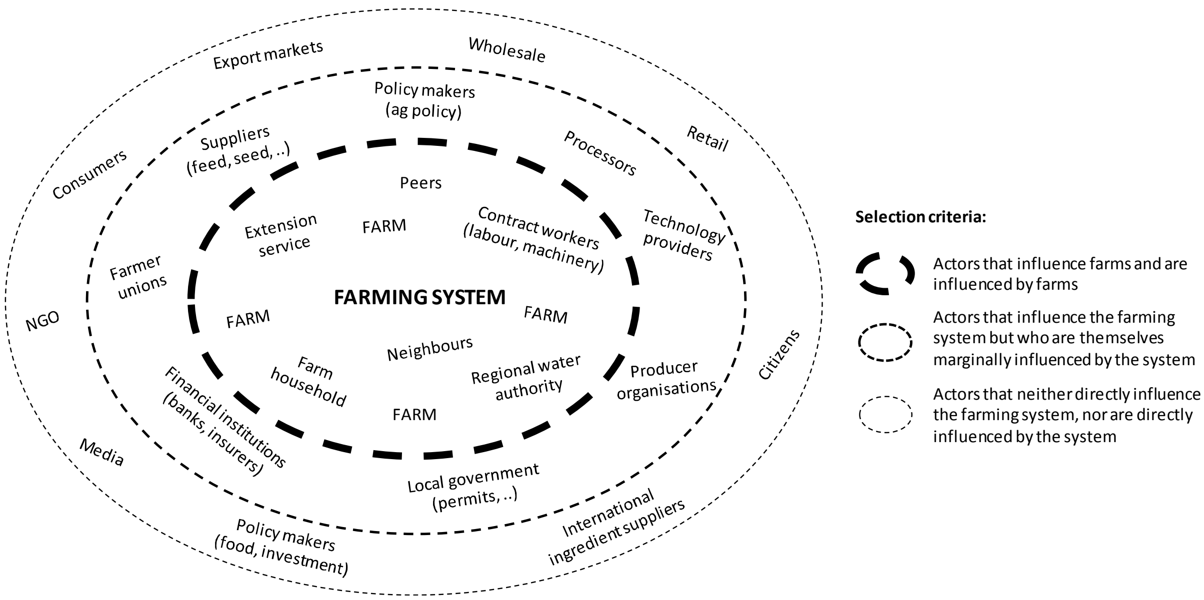

Figure 3: Selection criteria to identify system actors, including example actors. Dotted lines reflect that farming systems are open systems with so-called soft boundaries.

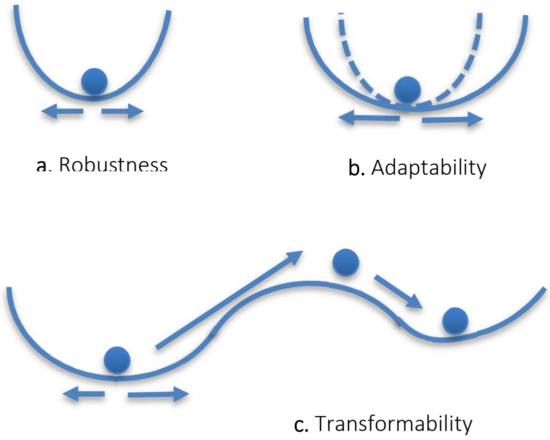

Figure 4: Illustration of the three resilience capacities of farming systems (based on Holling et al., 2002).

Annex I: Examples of environmental, economic, social and institutional challenges potentially affecting farming systems, subdivided into shocks and long-term stresses[1].

	Environmental	Economic	Social	Institutional
Reversible and irreversible shocks	- Extreme weather events (droughts, excessive precipitation, hail storms, frost, floods) - (Epidemic) pest, weed or disease outbreaks	- Price drops for outputs and price spikes for inputs - Food or feed safety crisis - Changes in interest rates	- Peaks in (social) media reporting on food safety or pest/disease issues (food scares) - Sudden changes to on-farm social capital (illness, death, divorce) - Insufficient availability of seasonal labor	- Sudden changes in access to markets (e.g. Brexit, Russian embargo) - Bans (e.g. pesticide use)
Long-term stresses	- Soil erosion - Climate change - Pollution by heavy metals - Hydro-geological disturbance - Decline of pollinators - Antimicrobial resistance - Loss of habitats - Gradual settlement of invasive species	- Reduced access to bank loans - Fake news - Increased cost of hired labor - New competitors in internationalized and liberalized markets - Competition on resources - High (start-up) costs - Resource fixity leading to 'locked-in situation' *Changes in*: - Quality of interactions between farmers and other actors - Upstream and downstream market power along the value chain	- Stress regarding ownership and the succession of the farm - Remoteness, reduced access to social services (education, health), less developed infrastructure - Reduced access to advisory services and skills training - Public distrust towards agriculture (safety, animal welfare, anti 'factory farming', ..) - Ageing of rural populations (lack of generational renewal, rural outmigration) *Changes in*: - Commitment towards cooperatives - Consumer preferences	- Wars, conflicts, international instability - Intellectual property ('biopatents') *Changes in*: - Government support for agriculture (national, EU) - Regulations (land tenure, environment, ..) - Restrictive standards (e.g. GM-free standards) - Production control policies (quota) - Regulations in destination markets - Agricultural policies elsewhere (US Farm Bill, ASEAN policies, BRICS policies)

[1]Source: elaboration by authors.

Annex II: Functions of farming systems subdivided into private goods and public goods, including example indicators to measure each function[1].

Private goods	Deliver healthy and affordable food products	Deliver other bio-based resources for the processing sector	Ensure a reasonable livelihood for people involved in farming	Improve quality of life in farming areas by providing employment and decent working conditions
Indicators	- Total amount (tons, liters) of major food products - Yield (tons/ha, liters/livestock unit) of major food products - Real price of food products for consumers - Share of fruits and vegetables in total production	- Total amount (tons, liters) of major non-food products - Yield (tons/ha, liters/livestock unit) of major non-food products	- Gross margin per hectare (for arable farms), gross margin per livestock unit (for livestock farms) - Share of farm income coming from agricultural production (excluding subsidies and direct payments) - Share of forced exists among farms due to economic reasons	- Number of workers employed on farms and related businesses including contract and part-time workers - Share of registered psychological disorders (e.g., suicides; doctor visits due to psychological issues) - Number of farm associations and learning platforms - Feeling proud to be a farmer in the region
Public goods	Maintain natural resources in good condition (water, soil, air)	Protect biodiversity of habitats, genes and species	Ensure that rural areas are attractive places for residence and tourism (countryside, social structures)	Ensure animal health and welfare
Indicators	- GHG emission intensity (per ha or per product) - Water withdrawal by agriculture as % of total withdrawal - Water retention - Nutrient surplus - Capacity to avoid soil erosion - Soil compaction - Frequency/number of social debates about water/air issues related to agriculture	- Share of ecological focus and protected area, including forest, set-aside land, national parks - Crop diversity - Diversity of ecosystem services provision - Number of birds - Number of insects - Pollination - Habitat quality based on common birds	- Net migration - Number of tourists visiting the area per year, excluding big cities if any - Share of villages having at least one supermarket and a school - Rate of pluri-active farms - Share of women among farmers and contract and part-time workers - Average age of farmers and part-time workers - Extent of public access (e.g. footpaths, bridleways) - Broadband coverage - House prices relative to urban areas	- Use of antibiotics - Share of farms enrolled in certification scheme for animal welfare - % of animals free from stress/discomfort (e.g. based on behavioral indicators) - Longevity of animals

[1]Source: elaboration by authors based on EC (2001), SAFA guidelines (FAO, 2013), Paracchini et al. (2008), and Gil et al. (2018).