A framework to assess the resilience of farming systems

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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 supply chain actors are embedded in local environments and functions of agriculture. 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. 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 a 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-

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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. More specifically, analysis along the framework explores multiple nested levels of farming systems (e.g. 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 richness of the framework is illustrated for the arable farming system in Veenkoloniën, the Netherlands. The analysis reveals a relatively low capacity of this farming system to transform and farmers feeling distressed about transformation, while other members of their households have experienced many examples of transformation.

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 (Guyton 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). Frameworks to analyze resilience therefore go beyond frameworks assessing sustainability, as the latter are comprehensive with regard to environmental, economic, and social performance (see e.g. the Sustainable Intensification Assessment Framework by Musumba et al., 2017), but generally do not focus in detail on the occurrence of challenges or changes in the sustainable outputs desired. 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 which have faced a variety of challenges (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 (i) to develop a framework to assess the resilience of farming systems, and (ii) to 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 this output, i.e. 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

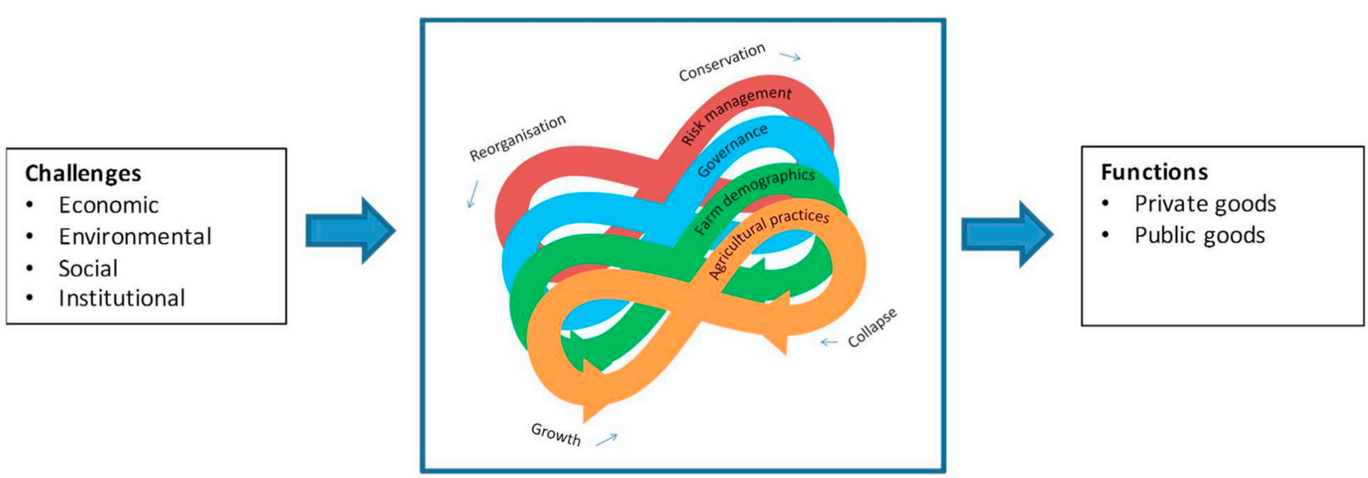

Fig. 1. Adaptive cycles in agriculture.

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, including an illustration of findings for an arable farming system in the Netherlands. The discussion and conclusions are presented in Section 5 and 6 respectively.

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 production purpose and 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 Fig. 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, shocks and stresses may also induce the adoption of new practices (reorganization) or lead to the breakdown and abandonment of an agricultural system (collapse). Such changes may be limited to field plots, but may extend to a whole farm or region.

In farming systems, influences on system change, cycles, stages and impacts are less systematic and automatic than Fig. 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 in energy and fertilizer prices, 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 supply chain to reorganize their price risk management (Assefa et al., 2017), e.g. towards upstream and downstream integration along the chain. 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. At farm level, major changes are often linked to intergenerational transfer in family farms, or to management or shareholder turnover in corporate farms. 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). Especially at the point of generational and ownership transfer, decisions are made whether to continue and how to adapt the organization of the farm to changing needs and abilities. The consequences of eventual discontinuation for the farm, the people affected and the farming system depend on factors such as alternative job opportunities and whether others take over the farm operation or its functions.

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 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 Fig. 2, whereby the 'top-down' steps 1 to 5 address specified resilience, while 'bottom-up' step 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

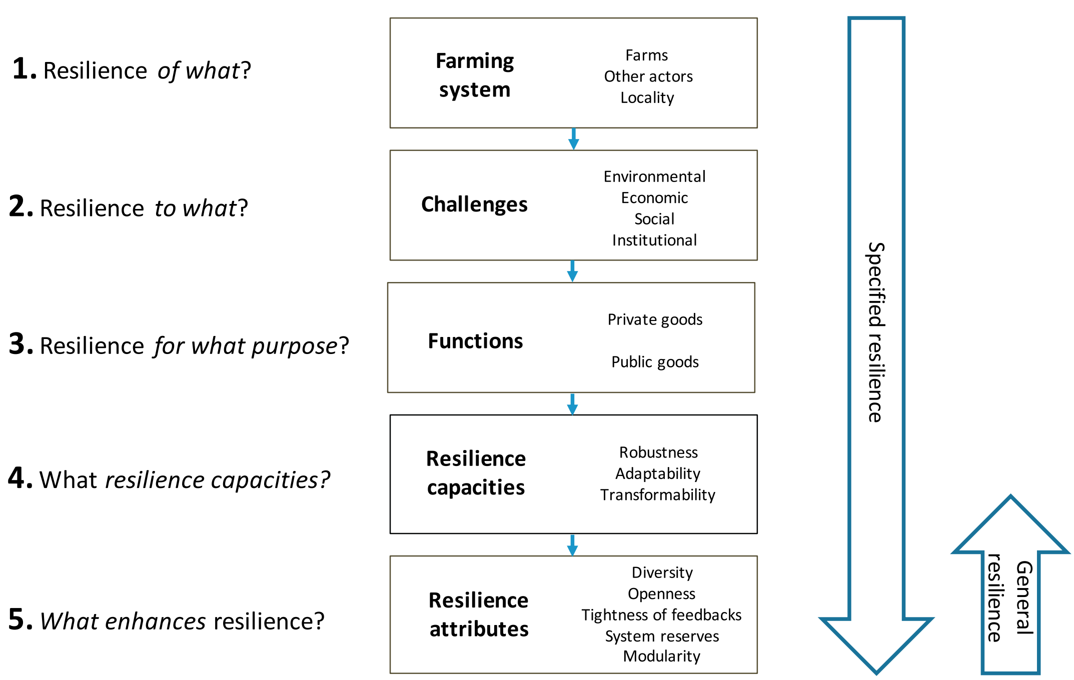

Fig. 2. Framework to assess resilience of farming systems.

'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, although the distribution of benefits matters, not least for resilience itself.

3.1. Step 1: Resilience of what? – Characterizing the farming system

The characterization of a farming system starts with the main product(s) of interest, e.g. starch potatoes, and the regional context, e.g. Veenkoloniën in the Netherlands. The core of the system are the farms that produce the main product(s). Consequently, not all farms in a region are necessarily part of the same farming system. Non-farm 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 (Fig. 3). Because farming systems work in open agro-ecological systems and are linked to various social networks and economic processes, their activities can have multiple 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. Neither farms nor other actors in the farming system are homogenous and tensions between their interests and identities are likely. 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 farm households and supply chain actors.

3.2. 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 and 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 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 steady diffusion 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.

3.3. Step 3: Resilience for what purpose? – Identifying desired functions of the farming system

Farming systems' functions can be divided into the provision of private 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, animal welfare and ensuring that rural areas are attractive places for residence and tourism. Farming systems generally provide multiple functions. This can create synergies or trade-offs (e.g., Reidsma et al., 2015a). 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.

3.4. 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 Fig. 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 (Fig. 4b). *Transformability* is the

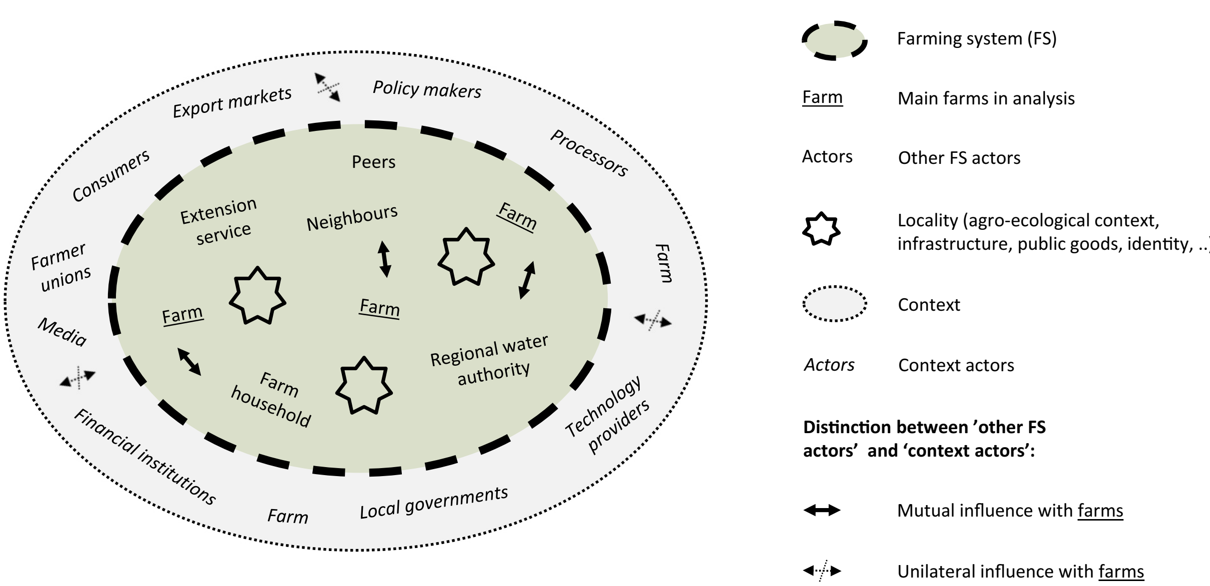

Fig. 3. Characterization of a farming system including example actors.

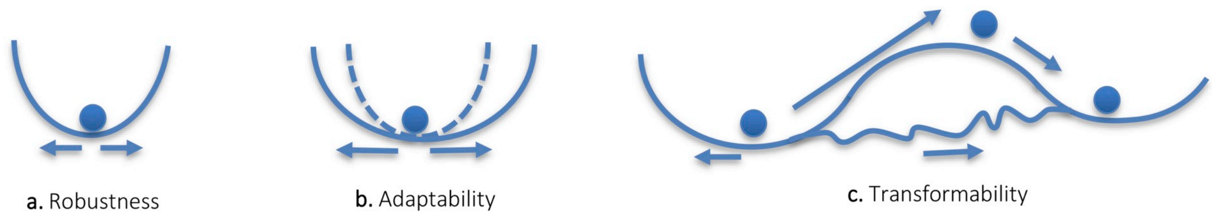

Fig. 4. Illustration of the three resilience capacities of farming systems (based on Holling et al., 2002).

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 (Fig. 4c). Such transformations may also entail changes in the functions of the farming system. Fig. 4c illustrates that transformation can occur after tipping points and collapse, but may also result from a sequence of small and incremental changes (Termeer et al., 2017).

3.5. 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 (Fig. 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 and Scott, 2014) and response diversity, whereby the latter refers to the different responses to disturbance (Reidsma and Ewert, 2008; Carpenter et al., 2012); (ii) modularity, i.e. internal division of the system in independent but connected modules (Carpenter et al., 2012) with potentially different functions; (iii) openness, which refers to connectivity between systems (Carpenter et al., 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 (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 and Scott, 2014. System reserves provide redundancy and serve as buffer that allows to compensate for the loss or failure of system functions (Biggs et al., 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. (2012), 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 framework, we developed a detailed sequence of methodological steps 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 as case studies 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 (steps 2 to 5), whereby findings of earlier steps feed into later assessments. Overall, the methodology consists of a mixed-methods approach (cf. Creswell and Clark, 2017): 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).

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, crop protection and relatively poor economic performance (Diogo et al., 2017). The farming system's boundaries are mainly determined by an ecological factor, namely soil type. The peat soils dominant in the region shape the arable farmers' planting plans which mainly consist of starch potatoes, sugar beet and winter wheat. Given these area and cultivation characteristics, the local potato processing cooperative is also considered a part of the farming system. Stakeholder discussions led to include a range of additional actors into the farming system, e.g. the local water authority which is responsible for water transports from the distant Lake IJssel to the area in case of drought, a regional study club aiming to enhance sustainability, and a regional nature organization stimulating dialogue between citizens and farmers. Furthermore, 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 system actors. The same holds for other household members due to their important role in relation to farm-level decision making. Fig. 5 shows a snapshot of findings at three analytical levels, i.e. the farming system, arable farmers, and other members of the household, to illustrate how findings feed into a meta-analysis across methods applied. Findings are selected from a range of qualitative and quantitative methods, i.e. a stakeholder workshop, a structured assessment of national and regional policy documents, in-depth interviews with arable farmers, interviews with other household members, a focus group on labour issues and a structured farmer survey.

For instance, Fig. 5 shows that at system level the capacity to keep the current status quo was perceived as relatively high. Hence, we could conclude that the system is resilient. However, at the level of the arable farmers, resilience is more doubtful. Farmers assessed the performance of public goods such as soil quality and biodiversity as relatively poor, implying that the system might be robust but does not provide the right functions. Furthermore, farmers expressed feelings of shame for actually being a farmer. This indicates the lack of an enabling environment at farm level which may over time impair the resilience of the Veenkoloniën farming system as a whole, considering that the system's main functions are to produce agricultural products in a sustainable manner, not to become an abandoned area with natural succession vegetation. Pathways to induce changes at system level also emerge from the figure, such as reducing the mutual dependence between farmers and the cooperative and the introduction of policies that dismantle the status quo. More consideration of gender issues may also enhance resilience. Such changes are complex processes and further analysis in the Veenkoloniën is needed to assess whether transformation at system level is possible or whether resilience is more enhanced by leaning on the relatively high adaptive capacity of arable farmers and (or) the other members of the household, which together lend robustness to the

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 characterized 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)[a].
	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); (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); (ii) *farm demographics*, e.g. engagement among young generation and women in agricultural activities (diversity), attraction of skilled labor (modularity); (iii) *governance*, e.g. policies stimulating the three capacities of resilience (diversity), stimulating initiative and polycentricity (modularity); and (iv) *risk management*, e.g. organizing societal feedbacks on the role of farming (tightness of feedbacks), 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 step 4b we infer resilience enhancing attributes (e.g. which collective competences enhance transformation), 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 value chain by forcing costly transformation upon its members).

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Table 1 (*continued*)

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

farming system.

5. Discussion

This paper presented a conceptual and methodological framework to assess the resilience of farming systems. The framework allows to identify and assess resilience-enhancing and -constraining competences and enabling environments with a view to farming systems' multiple functions, challenges, actors and temporal developments. When applying the framework, the comprehensive approach proved fruitful. For instance, by linking resilience to sustainability (Tendall et al., 2015) the approach disallows positive resilience assessments of a system configuration that is unsustainable. However, the empirical application of the framework also faces a number of difficulties. For instance, while the focus on the level of the farming system proved relevant and close to actors' perceived reality, collecting data on indicators at system level, such as migration or the number of mental-health related visits to doctors, can be cumbersome because farming systems do not necessarily converge with administrative areas. The Veenkoloniën farming system in our example stretches over three provinces. Furthermore, policy recommendations at system level have to consider governance arrangements at multiple levels and across the public and private sector and might therefore affect actors far beyond the farming system under consideration. The application also shows that assessing the resilience of farming systems needs to include the whole range of challenges rather than focusing on one specific challenge as is often the case in risk management studies (e.g. Meuwissen et al., 2003). In our example, the arable farmers perceived a range of external challenges to be highly important, such as negative media attention, stricter regulation of pesticides and 'politics turning against agriculture' (Spiegel et al., 2019). This implies that 'specified resilience' in farming systems typically refers to a broader set of specific challenges. Thus, investigating resilience to one challenge only, e.g. climate change, would provide only a partial picture (see also Reidsma et al., 2015b). Caution has to be applied when resilience capacities are assigned by the researchers; data analysis in the qualitative methods used, such as in-depth interviews, implies abductive reasoning (Tavory and Timmermans, 2014) to infer which resilience capacities were revealed e.g. in past recovery from catastrophic events or in current plans to respond to today's challenges. While respondents might not necessarily use the terminology of robustness, adaptability and transformability, the researchers attribute these capacities when reconstructing the narrative. The validity and reliability of the analysis can be enhanced through iterative and dialogical interpretation, both among multiple researchers and with stakeholders (cf. Wagenaar, 2013). Furthermore, the use of multiple methods (both qualitative and quantitative) aims to enhance the robustness of the findings (Creswell and Clark, 2017). Finally, the application of the framework shows that the five generic principles of resilience are defined in a highly generic way. Although this was done on purpose, i.e. to allow relevance across a wide variety of farming systems and to give room for context-specific variation and surprise, it needs to be avoided that the principles become empty shells. Researchers therefore have to acknowledge that each of the principles can materialize in many different ways in different contexts and practices. For instance, in the Veenkoloniën farming system the resilience principle of 'diversity' appeared as multifunctional farming and cooperation

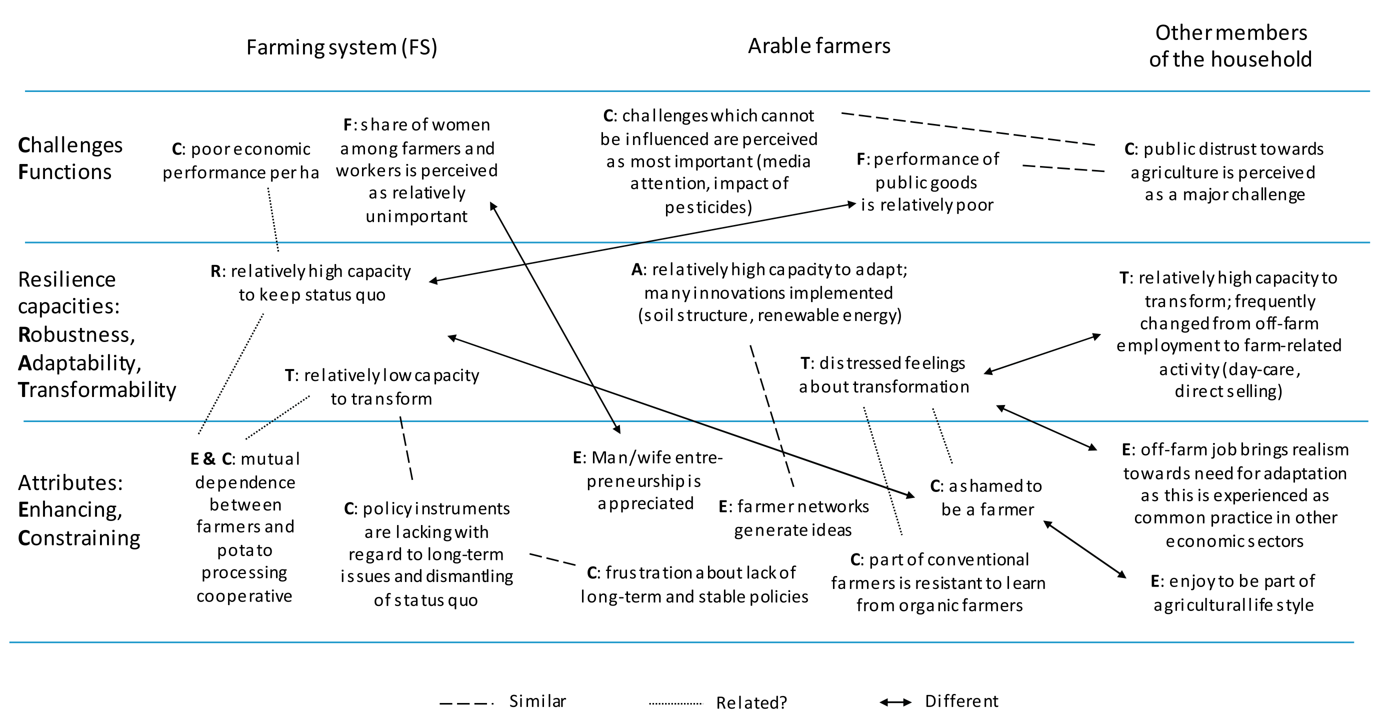

Fig. 5. Snapshot of meta-analysis across findings from multiple methods at three levels of Dutch arable farming system in Veenkoloniën.

between arable and dairy farmers, but also as husband/wife co-entrepreneurship. Therefore, to fully exploit the resilience framework researchers must use it as a heuristic that allows them to find unexpected forms and factors of resilience and to develop theory through the encounter with the empirical practices, instead of applying a fixed-set of variables to shoe-horned cases.

6. Conclusions

The conceptual and methodological framework presented in this paper provides the foundation for an integrated assessment of the resilience of farming systems in Europe and beyond. It transcends previous frameworks in three regards:

- The concept of resilience is multi-faceted and cannot be captured by a single indicator or by looking only at the attributes of a farming system or the capacities of selected actors. Our framework therefore requires and enables an elaborate diagnosis of the resilience of a farming system by considering its multiple and changeable functions, its internal and external interdependencies and the full range of potential shocks and stresses. This allows for a nuanced assessment, e.g. the analysis might find an environment that constrains resilience to social and economic challenges and enhances resilience to ecological challenges, or vice versa.
- The differentiation of three resilience capacities (robustness, adaptability, transformability) can help to assess the range of possible resilience strategies and allows for the investigation of trade-offs and synergies between them.
- The consideration of attributes grounded in multiple adaptive cycle processes enables a reflection on trade-offs across resilience attributes (e.g. enhancing robustness attributes at the expense of transformability attributes) and (intended or unintended) externalities across levels (e.g. enhancing the robustness of a value chain by forcing adaptation/transformation upon its members).

The framework can be used for *ex-post* analysis of farming system dynamics and responses to challenges; and for *ex-ante* assessment and creation of resilience-enhancing strategies and attributes of farming systems. Moreover, due to its focus on farming systems the framework fits well with current EU agricultural policy trends which are expected to provide more flexibility at the (sub)national level to address context-specific challenges, as illustrated by regional specifications in the Rural Development Plans (EC (European Commission), 2018). Early applications of the framework in the SURE-Farm project indicate that further research is needed to develop methods and tools to assess transformability, while suitable tools are available to assess robustness and adaptability (Herrera et al., 2018). This might reflect a deeper structural bias towards status-quo oriented resilience, since current policies appear to enhance robustness rather than adaptability or 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 farming systems in Europe and beyond.

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Appendix A

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

	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	- New competitors in internationalized and liberalized markets - Competition on resources - High (start-up) costs - Resource fixity leading to ‘locked-in situation’ - Increased cost of hired labor - Reduced access to bank loans - Fake news *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)

[a] Source: elaboration by authors.

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

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	Protect biodiversity of habitats, genes and species	Ensure that rural areas are attractive places for residence and tourism with a balanced social structure	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

[a] Source: elaboration by authors based on EC (European Commission) (2018), SAFA guidelines (FAO (The Food and Agriculture Organization of the United Nations), 2013), Paracchini et al. (2008), and Gil et al. (2018).

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