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Report on resilience framework for EU agriculture

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INDEX

1 Introduction 1
2 The resilience concept 2
  2.1 Three main processes 2
  2.2 Stages of adaptive cycle processes 3
  2.3 Processes are interrelated 6
3 The resilience framework and its components 7
  3.1 Characterising the farming system (resilience of what) 8
  3.2 Key challenges (resilience to what) 9
  3.3 Essential functions of the farming system (resilience for what purpose) 10
  3.4 Resilience indicators 11
  3.5 Resilience attributes 13
4 Discussion and conclusions 18
5 References 19

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1 Introduction

Farming systems in Europe face a vast range of environmental, economic, social and institutional challenges. Examples include more volatile producer and input prices, higher probability of extreme weather events, increasing dependence on land owners and financial institutions, organizational change within value chains, competing policy objectives and increasing administrative demands, and new societal concerns and changing consumer preferences (Rosin et al., 2013; Maggio et al., 2014; Gertel and Sippel, 2016). Farming system dynamics determine how systems respond and cope with such risks. Resilience theory provides an integrated framework to investigate the ability of complex social-ecological systems to cope with changing environments (Folke et al., 2010; Bullock et al., 2017). The theory emphasises change, uncertainty, interconnectivity and adaptability of complex systems (Senge, 1990; Holling and Gunderson, 2002). In this paper we define resilience as *maintaining the essential functions of EU farming systems in the face of increasingly complex and volatile economic, social, environmental and institutional challenges.*

A farming system is a system hierarchy level above the farm (Giller, 2013) at which properties emerge as a result of the formal and informal interactions and interrelations among farms, available technologies, stakeholders along the value chain, citizens in rural and urban areas, consumers, policy makers, and the environment (Ge et al., 2016). For instance, many EU farms are particularly vulnerable at the point of intergenerational hand-over due to a decrease in the attractiveness of farming when compared to other employment sources, which can lead to lack of interested successors or new entrants (Happe et al., 2009; Fischer and Burton, 2014; Chiswell and Lobley, 2015; Van Vliet et al., 2015). This is not only affecting the farm, and hence entrepreneurial and employment opportunities in the agricultural sector, but also the landscape. Cultural and environmental implications of farming practices have significant implications for the attractiveness and demographic stability of rural areas (Copus et al., 2006). Furthermore, standard business practices that produce a competitive income for farmers are often based on increasing farm size and on agricultural techniques that contribute to accumulated societal concerns and environmental risks, in particular related to water, soil and biodiversity (Hazell and Wood, 2008). Such business practices are increasingly perceived with reservation by consumers and retailers (Spiller and Nitzko, 2015). As most farming systems in Europe are regional and specialised, these risks and uncertainties therefore differ across regions, subsectors, different types of farms, and different farming systems.

Existing resilience frameworks do not sufficiently capture the regional interplay of the multiple processes and stakeholders apparent in farming systems. For instance, Walker et al. (2004) and Folke et al. (2010) conceptualise resilience in broadly defined socio-ecological systems, Darnhofer (2010) discusses resilience enhancing strategies at farm level, while Tendall et al. (2015) and Waters (2011) focus on the role of value chain actors in regional and global food systems. Also the holistic food security paper by Bullock et al. (2017) mainly stresses field and farm strategies. The same is true for metrics to assess resilience. Although indicators have been defined, a review by Quinlan et al. (2016) shows that indicators mostly focus on a specific issue, such as biophysical measures (Carpenter et al., 2001), a different scale, e.g. watersheds (Carpenter et al., 2001), or do not distinguish between robustness, adaptability and transformability (Cabell and Oelofse, 2012).

In order to capture the described developments in EU agriculture, and in order to proactively address those challenges, we propose a framework to analyse the resilience of EU farming systems. The integrated framework can be applied by public and private decision makers to formulate differentiated strategies across EU farming systems depending on context-specific challenges and available resources.

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2 The resilience concept

The resilience framework explained here builds on the concept of adaptive cycles (Holling et al., 2002) as a heuristic. Adaptive cycles represent different stages (growth, equilibrium, collapse, reorientation) through which systems pass in response to changing environments and internal dynamics (Fath et al., 2015). The sequence, direction and speed with which farming systems proceed through these adaptive cycles are empirical questions. While a system might remain in one stage for a long time, and the sequence of stages is not fixed, transition from one stage to another is always a possibility if circumstances change. Reorientation is generally preceded by so-called ‘tipping points’ which illustrate thresholds beyond which systems may collapse or change drastically (Ge et al., 2016).

Most analyses of agricultural production systems have confined their conceptual vision to the growth and equilibrium phases, and have neglected the possibility of collapse and reorientation phases. A consequent shortcoming of this limited vision is that conditions for system continuation have either been taken for granted, or have been confined to notions of status quo stability or incremental change. Accordingly, the stages of collapse and reorientation have been framed out of consideration and widely ignored. We use the adaptive cycles as a conceptual metaphor to understand change in farming systems. While in practice it may be difficult to observe all phases in farming systems (Van Apeldoorn et al., 2011), understanding adaptive cycles improves understanding of resilience (Carpenter et al., 2001). For instance, while many agricultural sectors seem persistent, drastic system changes (regime shifts) within one generation (Cumming and Peterson, 2017) may be the result of a tipping point.

2.1 Three main processes

Studies assessing the resilience of agricultural systems mostly focus on agricultural production processes (e.g. Porter et al., 2013) and generally find that diverse systems are more resilient to variability (e.g. Reidsma and Ewert, 2008; Gil et al., 2017). However, in practice, changes in among others technology, markets and policy resulted in larger and more specialised farms (Andersen et al., 2007; Mandryk et al., 2012). Hence, developments in agriculture can only be understood if multiple processes are considered simultaneously. We emphasize three main adaptive cycle processes that are essential for EU farming systems: next to agricultural production processes, these are farm demographics, and governance processes (Fig. 1).

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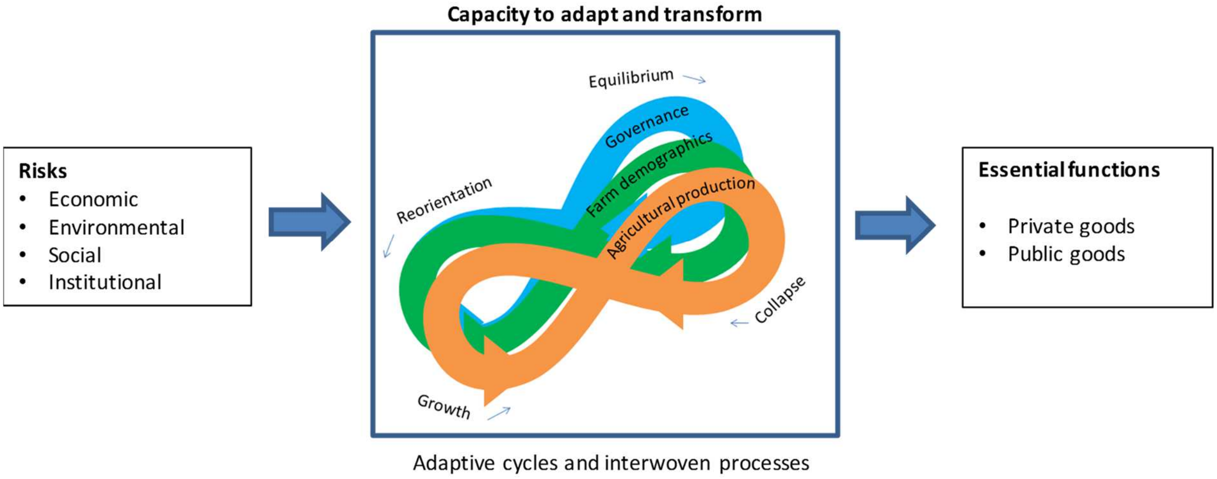

Figure 1: The resilience concept for farming systems.

Agricultural production is defined as the agricultural and multifunctional activities undertaken by farms leading to the provision of private and public goods, such as the provision of food and fibre, regulating services for climate change mitigation and clean water as well as cultural services such as landscapes (e.g. Reidsma et al., 2015). Farm demographics concern the provision of labour to farming systems, capturing both farm populations and hired labour force. Governance is defined as the organization and process of societal steering through a mixture of economic, communicative, and regulatory steering mechanisms, ultimately aimed at the realization of collective goals (Kjaer, 2004). In our framework, governance embraces elements of the Common Agricultural Policy (CAP) and its national transpositions, public and private regulations affecting agricultural production chains, and public and private risk management strategies. Other processes affecting the performance of farming systems, such as local infrastructure and culture, are incorporated as farming system characteristics.

2.2 Stages of adaptive cycle processes

In reality, the processes depicted in Fig. 1 are not as regular as this conceptual representation suggests. However, in the domain of each constituent adaptive cycle, indications of the main stages can be distinguished. Adaptive agricultural production cycles have been analysed since the recognition of the hog cycle and consequent development of the cobweb model (Hanau 1927, Ezekiel 1928). However, the emergence of adaptive cycles goes far beyond these patterns of price and supply responses that are found in farm sectors with delayed supply responses. An illustrative example is the pig production sector in North-Western Europe, which saw enormous *growth* in the past due to increasing connectedness to global input and output markets (Assefa et al., 2017a). However, over recent years conventional pig production lost connectedness with markets and society due to a variety of factors, including a higher valuation of animal welfare, environmental problems and political developments (e.g., the Russian embargo). As a result, many farms quit the market through loss of perspectives or even bankruptcy (*collapse*) or more orderly professional *reorientation* . This phenomenon extends not just to "factory farms", but also to farms which use relatively traditional production techniques. On the other hand, the EU ban on battery cages for laying hens in 2012 and the delisting of eggs from such facilities by major retailers in countries such as the Netherlands and Germany several years before led to the exit of "battery egg" production on a massive scale, whereas many family-based businesses used this opportunity for *reorientation* towards alternative technologies (Spiller et al., 2015). Besides such involuntary developments, farmers in various branches of production, along with value chain actors, have transformed their production systems by endowing their products with credence characteristics (such as organic and local food), thereby finding new ways to connect to markets and society, and new potential for *growth*.

On the global scale, agricultural price spikes in 2008 and 2011/12, led to increasing concerns that the process of the technological treadmill may have slowed down, and agricultural production may no longer grow as fast as demand (e.g., von Witzke, 2008). These price spikes were accompanied by substantial fluctuations of prices of energy and fertilizers . Whilst these increased production costs, they also revealed new potential markets for non-food agricultural products, including bioenergy and other alternative feedstock sources . Equally, recent subsequent declines in energy and food prices show that farmers as well as the up- and downstream sectors need to be aware of and able to respond rapidly to substantial uncertainties. While these uncertainties require appropriate risk management strategies, the price fluctuations may nevertheless indicate that in the medium or long term the bioeconomy may provide particular new *growth* perspectives.

Regarding demographics, the process of the farm population as well as the labour force is also affected by several overlapping cycles at various scales. The most obvious is the generational cycle within the farm family. Employed labour force and the management of corporate farms are also affected by similar processes of generational renewal. In every new generation of a family or turnover of employees (especially managers) of a corporate farm, decisions are necessary on whether to continue and how to adapt the organisation of the farm to changing needs and abilities, especially as farming is often perceived as bound to limiting conditions (or push factors of farm exit), such as low income, long working hours, remote locations and often high personal financial risks (Huber et al., 2015). Farm demography is also affected by technological cycles, both within the sector and outside. Cochrane's (1958) model of the technology treadmill describes how farmers have either to adopt a new technology (*growth*) or suffer from decreasing incomes that might finally lead to market exit that occurs in extreme cases through bankruptcy (*collapse*) while in others through involuntary or consciously planned professional *reorientation* (push factor). A conscious reorientation is more likely when wages outside agriculture are attractive (a pull factor) and farm employees have convertible skills. At the farming system level, technological progress not only reduces total labour input, but also results in an increasing capital to labour ratio, which in turn requires beyond necessary financial resources and more efficient use of labour, specialised operator skills and improved farm management capacities. Such a development can enable *growth* of production and per capita income. However, accumulation of push and pull factors in combination with demands for highly specialised skills may result in a structural deficit of farm successors and skilled farm labour, which could trigger *reorientation* or even *collapse* of regional farming systems. Such a reorientation can include seasonal and permanent migration of farm labour and farmers, such as the establishment of new farms in East Germany and other former socialist countries after 1990 by farmers migrating from other EU regions and countries, such as West Germany, the Netherlands and Denmark. Farm structural change has also led to a decrease in medium-sized and mixed farms towards more large-scale and specialised farms (Mandyk et al., 2012; Van Vliet et al., 2015).

Regarding governance, processes occur and interact at different spatial levels from local/regional to national, EU and international. At the EU level, we can distinguish two adaptive cycles. The first one applies to the European Union's CAP as a system of farm support (see Feindt, 2010; Knudsen, 2009; Termeer et al, 2015). The establishment of the CAP scheme in 1962 enabled a period of *growth*. The mixture of import levies, export subsidies, and guaranteed prices led to a modernisation of production systems, increased production, sufficient farmers' income and enough food at affordable prices. However, the high guaranteed prices also resulted in overproduction, which required ever more extensive market interventions, causing an increasing budget deficit. By the mid-1980s, repeated budget overruns even threatened a *collapse* of the CAP. A sequence of piecemeal adjustments measures of the CAP– milk quotas, budget stabilisers and set-aside – resulted in an *equilibrium* stage, although not one that was self-stabilising. It bought time but did not provide a structural solution for the vicious cycle of overproduction, market intervention and budget deficits. Furthermore the CAP became increasingly criticized for its distorting effects on international markets and its negative side effects such as landscape distortion and environmental pollution. The decreasing public legitimizing of tax money flowing to farmers threatened a collapse of the CAP again. Since 1992, the CAP entered a phase of *reorientation*, through the sequence of serious CAP reforms in 1992 (McSharry), 1998 (Agenda 2000), 2003 (Fischler) and 2013 (Ciolos), interspersed with periods of *equilibrium*. Political pressure on the large CAP budget and questions about its effectiveness in delivering sustainable and resilient farming systems suggest that another stage shift towards *reorientation* of the CAP is not unlikely.

The second adaptive cycle in governance at EU-level pertains to the regulatory framework. Here EU agricultural sectors experienced an *equilibrium* with state-led food safety regulation and light-touch environmental regulation until the 1980s. This was followed by several stages of regulatory *growth*: the adoption of diverse environmental directives (the Birds, Habitats and Nitrates Directives, respectively), food traceability regulation, genetically-modified organisms regulation and cross-compliance mechanisms. This growth path was punctuated by instances of *reorientation*, in particular the rise of private standards (e.g., GlobalGAP), public-private co-regulation and the move towards a comprehensive system of food risk management. Rising concerns about high transaction costs, competitiveness, and the effectiveness and efficiency of the regulatory framework make a shift towards another stage of *reorientation* likely.

With regard to risk management, strategies at EU level mainly pertain to the management of price and production risks. For normal risks, which can be dealt with at farm level, risk management historically focussed on farm diversification with farms having both crop and livestock activities (*equilibrium*). At the end of the 19th century in North-West Europe this was augmented with mutual insurance schemes covering specific risks such as cattle disease and hail damage (Interpolis, 1976), and, mostly after the 1930s, cooperatives which enabled to pool price risks among members (Fernández, 2013). With post-war increasing levels of farm specialisation, risk-sharing strategies became increasingly important, including contracts, financial leverage, commercial insurance and exchange of farmland (Meuwissen et al., 2001) (*growth*). From the 1980s onwards, vulnerability of specialised farms was among the reasons for certain farms to 'reinvest' in farm diversification (*reorientation*), initially focussing on multifunctional activities, such as agri-tourism and nature conservation (Van der Ploeg and Roep, 2003), and currently further stimulated towards the production of energy and processing of waste (DG Agri, 2017a). Also diversification through off-farm income plays a vital role for several farms (e.g. Mishra and Goodwin, 1997, McNamara and Weiss, 2005, Lien et al, 2010, Meraner and Finger, 2018). Alongside, specialised farms showed increasing interest in risk-sharing agreements, both with other farmers, e.g. through price pools (Van Asseldonk et al., 2016) and disease mutuals (Meuwissen et al., 2013), as well as with other chain actors (Assefa et al., 2017b) (*growth*). Factors driving this interest included decreasing intervention prices (DG Agri, 2017b), decreasing support from governments in case of epidemic disease outbreaks (Meuwissen et al., 2003), and increasing concentration rates in other stages of the chain (AMTF, 2016). In addition, since 2009, the CAP has introduced various risk management measures to support farmers' uptake of insurance and mutual funds (DG Agri, 2017b), e.g. with subsidies for multi-peril crop insurance being extended to 70% as of 2018 (EC, 2017). Yet, as uptake of risk management instruments is expected to stay relatively low, some *reorientation* is likely, incentivized by smart technology, e.g. to reduce transaction costs (Meuwissen et al., 2018), joint learning and co-creation to activate farmers to engage in joint initiatives such as producer organisations and mutual funds, and promoted capacity building, e.g. with regard to insurance and futures contracts (DG Agri, 2017a). With regard to the management of catastrophic risks, the adaptive cycle includes the already mentioned changes of intervention prices and CAP risk management measures over time, but also pertains to the provision of ad-hoc disaster aid. With regard to the latter, large differences exist between member states depending on political context and risk environment (OECD, 2009). However, given the growing support for risk management instruments in the CAP, member states increasingly develop public-private schemes to deal with catastrophic risks, e.g. in Finland (Liesivaara et al., 2017), indicating a phase of *reorientation*. Some member states even completely abandoned the provision of disaster relief for risks which can be insured through public-private partnerships, as illustrated during the 2017 extreme weather events in the Netherlands (Van Asseldonk et al., 2018).

2.3 Processes are interrelated

Phase shifts in one cycle can either suppress or accentuate the dynamics of the other cycles. For example, farm demographics are directly influenced, not only by agricultural policies, such as early retirement or new entrant schemes, but also indirectly by regulations on international labour migration and differing national taxation rules for the capital transfer involved in intergenerational hand-over. Correspondingly, the seasonality of agricultural production links with farm demographic processes, especially peak labour requirements driving the (seasonal) movements of the labour force. In turn, agricultural production processes also interrelate with policy. For instance, local contexts cause differences in local transpositions of agro-environmental and risk management tools of Rural Development Programmes.

3 The resilience framework and its components

The framework essentially aims at understanding the *dynamics* of a farming system's provision of its essential functions while facing a number of challenges, i.e. resilience does not reflect separate properties of a system, but describes the dynamics of its sustainable performance and the attributes contributing to these dynamics. Following Folke et al. (2010) we interpret the dynamics of the adaptive cycle stages described in Section 2.2 (growth, equilibrium, collapse, reorientation) along a scale of the following resilience types: *robustness*, adaptive capacity (*adaptability*) and capacity to transform (*transformability*). Robustness is the ability to maintain desired levels of outputs despite the occurrence of perturbations (Urruty et al., 2016). Adaptability is the capacity to adjust responses to changing external drivers and internal processes and thereby allow for development along the current trajectory while continuing important functionalities (stability domain) (Folke et al. 2010). Transformability is the capacity to create a fundamentally new system when environmental, economic, or social structures make the existing system untenable in order to provide important functionalities (Walker et al. 2004). Transformability is less about planning and controlling but more about preparing for opportunity or creating conditions of opportunity for navigating the transformations (Folke et al. 2010, citing Chapin et al. 2010). Socio-ecological systems can sometimes be trapped in very resilient but undesirable regimes in which adaptation is not an option. Escape from such regimes may require large external disruptions or internal transformations to bring about change.

Before analysing a system's dynamics and resilience attributes, one must first specify the system boundary and its configuration ('resilience *of* what'), the challenges of interest to the system ('resilience *to* what'), and the essential functions of the system ('resilience *for what purpose*'), see also Carpenter et al. (2001) and Herrera (2017). The various steps of the framework, including example indicators describing the dynamics (*resilience indicators*), and attributes contributing to these dynamics (*resilience attributes*) are outlined in Fig. 2. The lower part refers back to the main processes outlined in Section 2 and provides the basis for the attributes. Example attributes are derived from cycle phases described in Section 2.2 and from the general resilience attributes described by Cabell and Oelofse (2012). The various phases of the framework are explained below, i.e. (1) characterising the farming system, (2) appraising key challenges affecting the system, (3) framing the essential functions of the system, (4) assessing resilience along the scale of robustness, adaptability and transformability, and (5) identifying resilience attributes which contribute to the robustness, adaptability and transformability of the farming system.

System characteristics, challenges, and interpretation of attributes are dynamic concepts (complex systems continually change). Even the essential functions of farming systems change over time. Such dynamics complicate the analyses of resilience indicators and the identification of resilience enhancing attributes. To provide meaningful suggestions towards resilience enhancing attributes for EU farming systems it is therefore important to first describe and understand phases (1) to (3) for a specific trajectory before proceeding to the analysis of resilience indicators and attributes of the trajectory.

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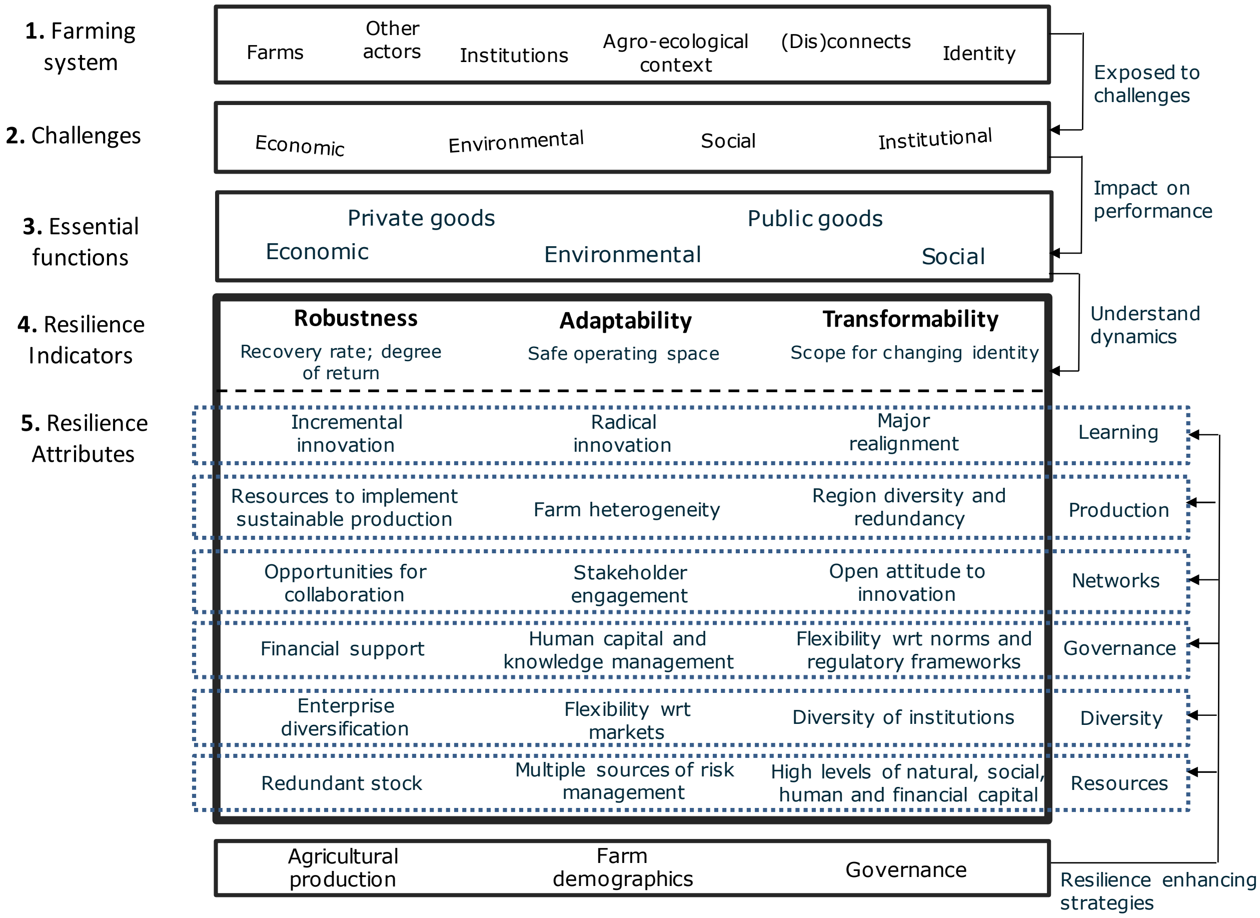

Figure 2. Framework to analyse the resilience of farming systems, including example resilience indicators and attributes.

3.1 Characterising the farming system (resilience of what)

The type of challenges a system is facing, as well as its response are largely affected by the characteristics of the system. Characterising the system is therefore the first step in our framework presented in Fig.2. This entails a description of key system characteristics such as farm types (Andersen et al., 2007; Andersen 2017), institutions in place, the agro-ecological context, (dis)connects related to the system's essential functions (Cumming et al., 2014), and the identity of the system (Cumming and Peterson, 2017).

Key actors within the system boundary are identified using the following selection criteria, i.e. *the boundary of a farming system is such that we include actors who influence farms, and, conversely, farms also influence these actors.* In contrast, we exclude actors who influence the farming system, but who are themselves scarcely influenced by the system. Fig.3 provides an example farming system for a specific trajectory. In this example financial institutions (banks, insurers etc.) will influence the farming system, but the farming system barely influences the bank – so, the bank is not included in the system. In contrast, the local credit union is strongly affected by the farms so is included in the farming system boundary. Also, in this example, farm households are part of the farming system as is mostly true for family farms, i.e. family members play an important role in the provision of capital, labour and land to the farm. Farm households' influence would be less if family members including the farmer provide most of their resources outside the farm. The pluri-active nature of farm households was described by e.g. Hansson et al. (2013). The example also illustrates that actors in farming systems can also refer to actors who influence and develop policies, such as ministries, EU institutions, lobbyist, farmers' organisations, and environmental organisations.

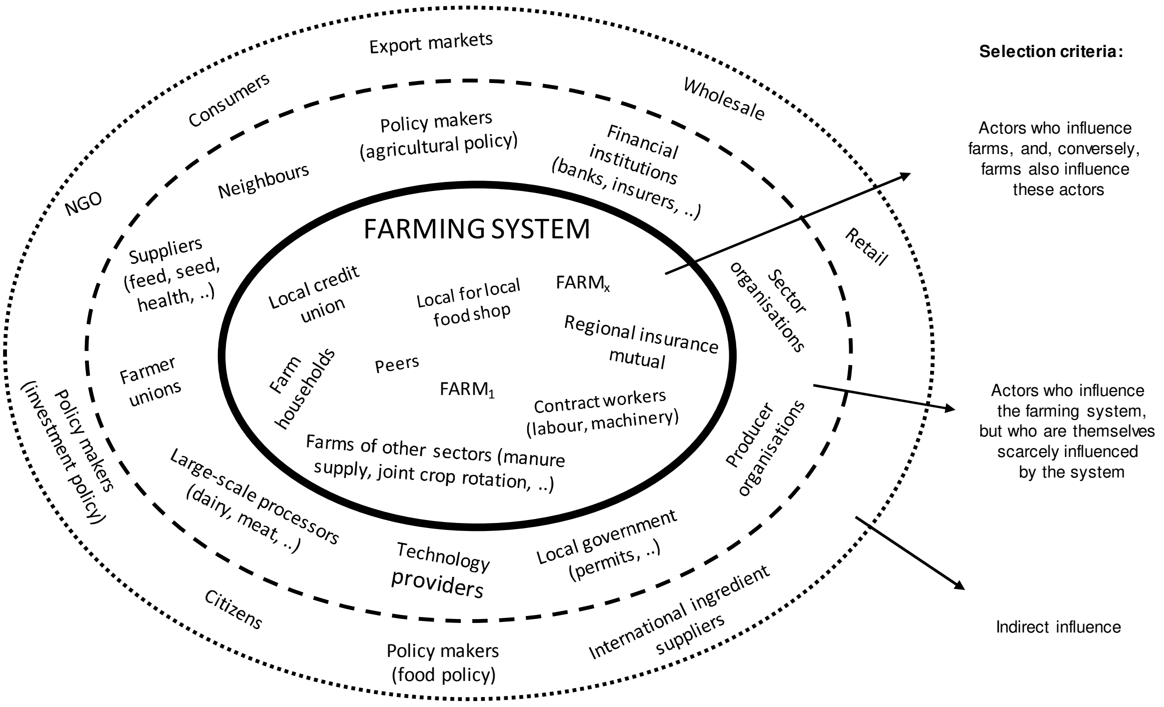

Figure 3: Selection criteria to identify actors within the system boundary of a farming system, incl. example actors.

With regard to the agro-ecological context, key characteristics at system level include climatic conditions (e.g. Metzger et al. 2005; Van Wart et al. 2013) and soil conditions (e.g.Hazeu et al. 2010; Hijbeek et al. 2014; ESDAC, 2017). Regarding the identity of the system, Cumming and Peterson (2017) refer to a system's identity as "key actors, system components, and interactions". They also mention the subjective nature of it ("[..] although subjective, it is not arbitrary; it requires establishment of key criteria [..]").

3.2 Key challenges (resilience to what)

To identify the variety of challenges farming systems are confronted with, we categorise the challenges along four dimensions, i.e. economic, environmental social and institutional risks. Also, we distinguish two ways of how these challenges affect farming systems: as shocks, or as a long-term pressure with inherent uncertainties. Adapted from Zseleczky and Yosef (2014), we define a shock as a sudden change in the risk environment of a farming system that influences (part of) the farming system on the short term through negative effects on people's current state of well-being, level of assets, livelihoods, or safety, or their ability to withstand future shocks. Examples of shocks are extreme price drops (*economic risk*), extreme weather events (*environmental risk*), sudden changes to on-farm social capital due to illness, divorce, or stress regarding ownership or succession (*social risk*), and geopolitical issues such as the Russian boycot (*institutional risk*). In contrast, long-term pressures refer to stressors slowly changing the context of a farming system, inherently leading to new uncertainties (adapted from Zseleczky and Yosef, 2014). There are ample examples of long-term pressures affecting farming systems, such as reduced availability of finance (*economic risk*), hydro-geological disturbances (*environmental risk*), demographic changes including rural outmigration (*social risk*), and changing policy objectives (*institutional risk*). Future impact studies often focus on long-term pressures (e.g. Porter et al. 2013 for climate change), while shocks may have more severe impacts (e.g. Schaap et al. 2013 for extreme climate events in the Netherlands). Distinction between various dimensions and sub-classifications (shock, long-term pressure) is somewhat arbitrary, but the classification can be useful as a 'checklist' (Annex 1).

3.3 Essential functions of the farming system (resilience for what purpose)

Depending on a system's location (e.g. close to a city centre, or remote), system functions may differ. Furthermore, institutional discourses on sustainable development espouse different sustainable development principles even though the general consensus as quoted in the Brundtland Report (1987), i.e. 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (quoted in Robinson, 2004: 227) may be the same. This is useful to recognise at a farming system level to understand the variety of 'essential functions'. In general, functions can be subdivided towards the provision of private goods and public goods. Private goods refer to (i) the availability of healthy and affordable food products, (ii) the availability of other bio-based resources for the processing sector, including fuels and fibres, (iii) the economic viability of farm as viable farms contribute to balanced territorial development, and (iv) improved quality of life by providing employment and offering decent working conditions. Public goods refer to (i) maintaining natural resources in good condition, (ii) protecting biodiversity of habitats, genes and species, (iii) ensuring that rural areas are attractive places for residence and tourism, and (iv) ensuring animal health and welfare. *We define these functions at the level of farming systems (not farms), implying that the framework is not primarily aimed at preserving individual (family) farms*. Although the interaction between the provision of various functions can provide significant synergies for farming systems, they are not always mutually supportive as there can be conflicts between e.g. social and economic dimensions and there are often trade-offs involved. Thus, the level of interdependency can vary according to the farming system and its system boundary. This means that each farming system has a level of sustainability which is relative to its own target functions and depending on system-specific interactions.

Multiple indicator frameworks exist to asses a system's performance regarding the essential functions (e.g. Alkan Olsson et al. 2009, Van Asselt et al. 2014). We use EC (2001) and SAFA guidelines (FAO, 2013) as a basis, augmented with own elaborations as indicated in Annex 2. In order to select the indicators measuring the performance of farming systems the first step is to *identify and prioritise functions* related to the provision of private and public goods and, as a second step, combine the functions with the *relevant indicators*, which are function and farming system specific. Then for the further selection of indicators, three principles can be applied. The first principle to consider is the type of *challenge* affecting the farming system. Different challenges can have different durations of impact (short- or long-term) therefore different indicators are needed to assess the potential sustainability impact. For example, for shocks such as extreme weather events an indicator such as productivity (t/Ha) can be appropriate, while for a long-term pressure such as climate change an indicator on soil erosion and/or water quality might be more appropriate. The second principle that can be considered is linked to the *use of resources* (human, natural and economic). Such resources are farming system specific. For example, for the large scale production of arable crops in the East of England key resources are labour, land and technology. Each can be assessed from different functions point of view, hence using different indicators. For instance, regarding land, indicators could refer to landscape maintenance (to reflect attractive rural areas), water and soil quality (as an indicator for maintained natural resources), and % land tenure (as an indicator for economic viability). Finally, a third principle is the *efficiency* with which the outcome of the farming system is obtained. In the case of arable crops, efficient outcomes for the resilience of the farming system can be the following: number of jobs created (quality of life), populations of key farmland animal and plant species, e.g. birds, butterflies, meadow plants (biodiversity), and liquidity and profitability (economic viability of farms). Essential functions may change over time. Also, there may be functions which could be provided by other systems.

3.4 Resilience indicators

Upfront classification of a system or nested subsystem into stages of robustness, adaptability or transformability is not straightforward. Instead, it seems better to start exploring (i) the dynamics of the essential functions (robustness) [Fig4.], (ii) the relation between risks (shocks, long-term pressures) and responses (adaptability) [Fig.5], and (iii) the occurrence of tipping points (drastic system changes, regime shifts within one generation, changed identity) (transformability) [Fig.6].

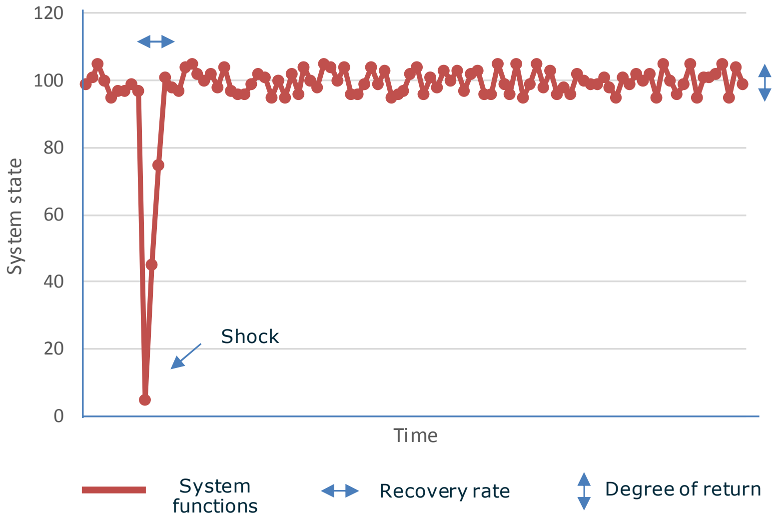

Figure 4: Exploring **robustness** of farming systems, i.e. ability to maintain desired levels of outputs despite the occurrence of perturbations (Urruty et al., 2016). The figure is adapted from Scheffer et al. (2012). The recovery rate shows that system functions (e.g. aggregate amount of food produced, or consumer trust) recover in 3 time steps after the shock, while degree of return indicates that system functions come back to their original level.

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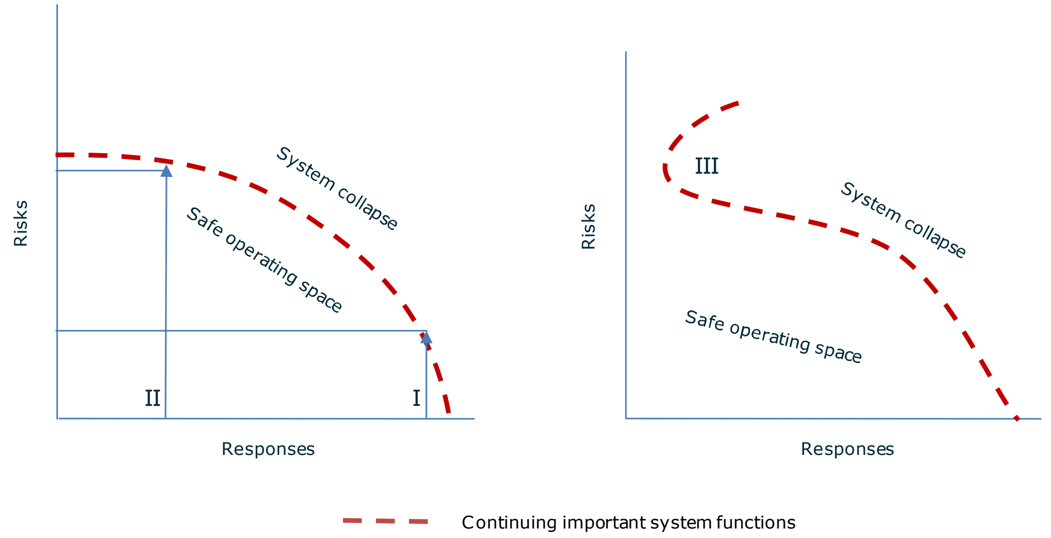

Figure 5: Exploring **adaptability** of farming systems, i.e. the capacity to adjust responses to changing external drivers and internal processes thereby allowing for development along the current trajectory while continuing important functionalities (stability domain) (Folke et al. 2010). Figures are adapted from Scheffer et al. (2015) and Carpenter et al. (2017). A local response that is currently at a safe level (I) needs to be adjusted to a lower value to keep the system within the safe operating space in a future more risky environment (II). The response may need to be adapted again once risks further increase (III). For instance, a high degree of individualistic behaviour of farmers (I) may suffice for a viable sector income if market power of upstream and downstream actors is relatively low. However, with increasing market power and reducing mechanisms of risk-sharing, the high degree of individualism becomes untenable and needs to be adapted to lower levels (II), implying more connectedness among the actors in the system. Too much connectedness may however suffocate innovations therefore requiring yet another response (III) once market power further increases.

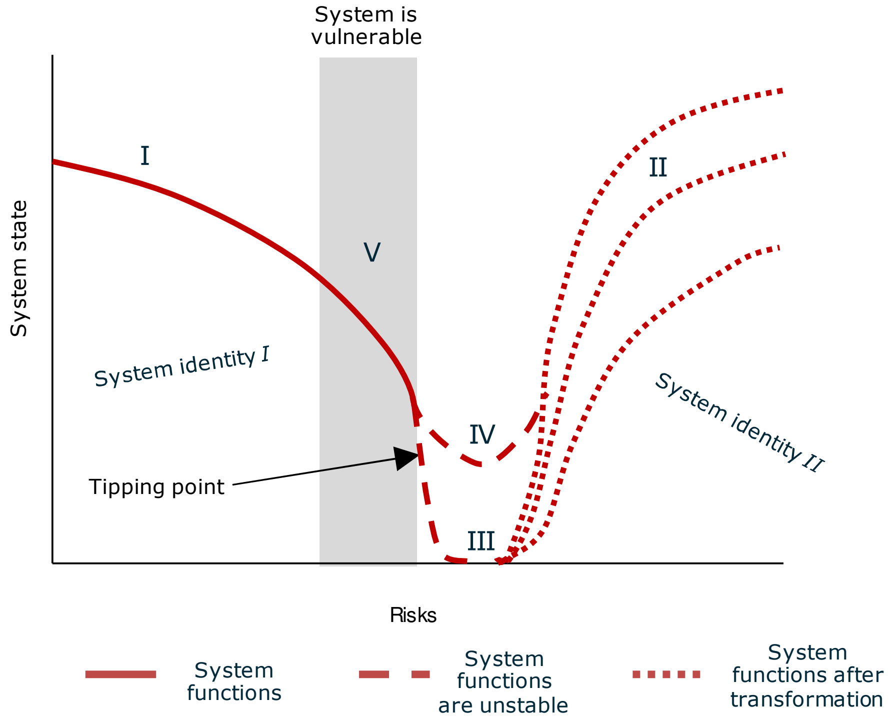

Figure 6: Exploring **transformability** of farming systems, i.e. the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable in order to provide important functionalities (Walker et al. 2004). The figure is adapted from Cumming and Peterson (2017). System functions after transformation (II) may diverge from functions in the previous system (I). A system is characterised as **transformed** if its **identity** (*II*) differs from the previous identity (*I*). Transformation may be the result of collapse (III) after a tipping point, or more gradual change (IV). Collapse is **subjectively** defined as loss of identity and persistent change in one or more key capitals, which could encompass social, financial, natural, built, or other forms of capital (Cumming and Peterson, 2017). Collapse is often preceded by vulnerability of the system *(*V*).*

Due to complexity of farming systems (e.g. Fig. 3), cycles can also occur at smaller scale (nested subsystems). It is therefore also meaningful to explore robustness, adaptability and transformability (Fig 4, 5 and 6 respectively) at e.g. farm or farm household level.

3.5 Resilience attributes

Resilience attributes contribute to the resilience of farming systems; they improve the resilience indicators. For instance, they determine the speed of recovery in Fig. 4, the variety of responses in the safe operating space (Fig. 5), or the pace at which a system can transform after a collapse (Fig. 6). Cabell and Oelofse (2012) identified 13 general attributes contributing to the resilience of agroecosystems, i.e. (i) *socially self-organised* networks of e.g. farmers, consumers and the community, (ii) *ecological self-regulation*, e.g. by farmers maintaining plant cover and incorporating more perennials, (iii) *appropriately connected*, e.g. crops planted in polycultures and collaboration between chain actors; (iv) *functional and response diversity*, e.g. by heterogeneity within landscapes and farms; (v) *optimal redundancy*, i.e. planting multiple varieties of crops, keeping equipment for various crops, and retrieving nutrients from multiple sources; (vi) *spatial and temporal diversity*, e.g. by a mosaic pattern of managed and unmanaged land and diverse cultivation practices; (vii) *exposed to disturbance*, dealt with by e.g. pest management and positive selection; (viii) *coupled with local natural capital*, e.g. by not depleting soil organic matter, and little need to import nutrients or export waste; (ix) *reflective and shared learning*, e.g. by record keeping and knowledge sharing between farmers; (x) *globally autonomous and locally interdependent*, e.g. by less reliance on commodity markets and reduced external inputs, more reliance on local markets, and shared resources such as equipment; (xi) *honors legacy*, e.g. by incorporating traditional cultivation techniques with modern knowledge; (xii) *building human capital*, e.g. by investing in infrastructure for education, and support for social events in farming communities, and (xiii) *reasonably profitable*, implying that farmers and farm workers earn a liveable wage, and the agricultural sector does not rely on distortionary subsidies. These 13 attributes are built on >50 references discussing resilience at various scales including farm (Darnhofer, 2010) and socio-ecological systems (Folke et al., 2010).

In our framework we aim to further specify how these attributes contribute to specific types of resilience, i.e. robustness, adaptability and transformability. In addition, although links between some resilience indicators and attributes have been proven (e.g. Gil et al., 2017; Cabell and Oelofse, 2012), this does not imply that such links are always and universally applicable. We therefore suggest that such links need to be empirically tested under different conditions. We focus on attributes closely fitting to the 3 main processes in this paper, i.e. agricultural production, farm demographics and governance processes. We expect that attributes are relatively more complex and intense in case of transformability compared to robustness. This is illustrated in Fig. 2 by a number of example attributes. For instance, for ***learning***, an important component for resilience building (Cundill et al. 2015; de Kraker 2017). In different stages of the adaptive cycle, learning plays different roles, including *incremental innovation* towards further growth ('single-loop learning'), more *radical innovation* in response to crises in the system ('double-loop learning') and transition to a different state or major *realignment*, such as transforming to organic farming practices ('triple-loop learning'). (Compare with aggregate attribute [ix] of Cabell and Oelofse (2012), i.e. reflective and shared learning). The second illustration in Fig. 2 refers to the way ***agricultural production*** is organised, i.e. as having *resources for implementing sustainable production*, with farms being diverse among themselves and having different production systems, technologies and products (*farm heterogeneity*), or with the whole region being biodiverse and having different sources of ecosystem services and redundancy of species (*region diversity and redundancy*). The third example relates to ***networks***, ranging from *opportunities for collaboration* reflecting a situation in which relationships among farmers support collaboration and exchange of resources, *stakeholder engagement* in which farmers are willing to collaborate among themselves and with government institutions, and *open attitude to innovation* with stakeholders willing to innovate, trying new processes and participating in new markets. The fourth example in Fig.2 is on ***governance***, with attributes ranging from *financial support* to ensure that farmers have access to cash when needed with government and financial institutions working together in offering credits and subsidies, *human capital and knowledge management* through formal and informal institutions fostering dialogue and helping to spread knowledge among farmers, and *flexibility* in which norms, legislation and regulatory frameworks are flexible enough for allowing experimentation and innovation. The fifth example is on ***diversity***, with attributes ranging from *enterprise diversification* to increase firms' ability to cope with shocks, *flexibility* e.g. regarding markets, and *diversity of institutions*, enabling the generation of new goods and services. The final example is on ***resources***, varying from keeping *redundant stock* to cope with supply disruptions, availability and use of *multiple sources of risk management* including joint risk prevention and risk pooling initiatives, and *high levels of natural, social and human capital* to foster reorientation towards new identity after collapse. The selection of attributes will always reflect aspirations for the specific type of farming system and resilience in a given case study.

While resilience attributes might be studied in isolation, we argue that the complexity of farming systems requires an integrated consideration. Fig. 7 presents an integrated analysis of selected attributes from Fig. 2.

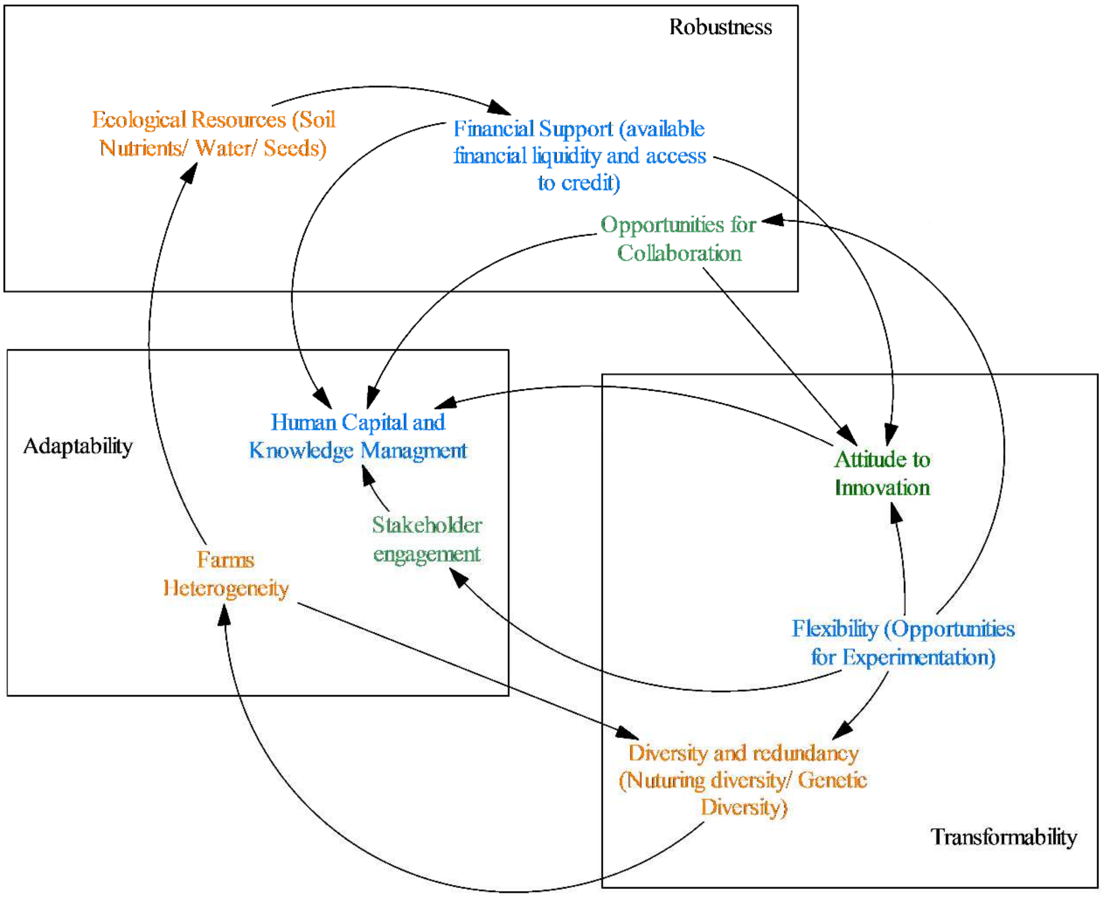

Figure 7: Interconnections and synergies between selected resilience attributes.
Note: Green (Farm demographics), Orange (Agricultural Production), Blue (Governance)

An integrated assessment allows to understand synergies among attributes. For instance, landscape heterogeneity in organic farming contributes to enhancing biodiversity (Rader et al., 2014). Simultaneously, genetic diversity offers farmers opportunities for incorporating different techniques, introducing different species and overall for configuring their farms in ways that suit better their particular landscape. These potential synergies are not restrictive to natural resources but also include social, organizational and economic attributes. For instance, participatory processes and stakeholder engagement result in the creation of knowledge and human capital that can be used to experiment and transform traditional farming systems. At the same time, flexibility also requires new knowledge and closer interaction between farmers (Sherman, 2014).

An integrated approach also demonstrates trade-offs between different attributes and resilience indicators. For example, an increase in farm heterogeneity might have adverse effects on farm productivity and consequently on farmers' financial liquidity. While heterogenic farms might be able to adapt better they will probably be less robust and more likely to show some visible changes in their own dynamics during a shock.

Retrieving attributes through co-creation

Although resilience attributes might be retrieved from retrospective (time series) analyses within specific trajectories and boundaries (Reidsma et al., 2010; Martin et al., 2017), the changing risk environment faced by EU farming systems may also require new responses to enhance robustness, adaptability and transformability fitting the new situation. Due to the importance of diversity and stakeholder engagement in many of the proposed resilience attributes, co-creation seems a suitable approach to identify such attributes. Co-creation refers to the participation of end-users in the product and services definition (Von Hippel, 1987), more recently also applied by companies to design value adding strategies (Prahalad and Ramaswamy, 2004) and by the public sector in the policy making process (Voorberg and Tummers, 2014). The Resilience Alliance (2010) proposed a participatory approach to assess resilience, including the identification of resilience attributes. In our framework, this approach will be merged with the Framework for Participatory Assessment (FoPIA; Morris et al., 2011; Konig et al., 2013) in order to not only assess resilience, but also the impact on public and private goods.

The principle of co-creation is the process of creating new products, strategies and policies *with* people affected by certain challenges and not *for* them. The co-creation call is addressed to a small group of people with specialized skills and shared interests on the challenge to deal with. Different strategies have been developed and proven successful to co-create: (i) organizing face to face workshops; (ii) planning big date events, and (iii) creating virtual platform/community. Regarding the latter, the development of new technologies facilitates developing virtual communities to bring together skilled people to discuss on topics related to their knowledge and expertise. The virtual platforms provide an excellent climate to enable the members of the community to submit contributions, comments on contributions from other participants, rate and vote.

In the context of farming systems a virtual co-creation platform is developed. The access to the virtual platform is private and limited to a selection of stakeholders. Between 40 and 60 key senior opinion stakeholders with proven experience in agricultural production, farm demographics, and governance issues are convened to participate in the virtual platform to co-create breakthrough solutions from a broad approach. A balanced selection of all the stakeholders - farmers' organizations, insurance companies, banks, value chain actors, policy makers, environmental and consumers' organizations and research institutes - is ensured as well as the geographical origin from EU Member States. The co-creation process follows the design thinking approach that comprises five phases: (i) gather information (which is the need); (ii) generate ideas (get breakthrough ideas); (iii) Make ideas tangible (learn how to make ideas better) and (iv) share the story (inspire other towards action) (Brown and Wyatt, 2010). The design thinking process is led by an expert who is in charge of encouraging the participation of the community members. With this purpose different activities can be performed in the co-creation platform in addition to the debates, like sharing videos, pictures, documents and participating in gamification features like questionnaires, points and levels and weights. The results obtained through the virtual co-creation platform are discussed at local level by organizing local co-creation workshops in the case study regions. The stakeholders identified within the farming system boundaries in case study regions (Figure 3) are invited to participate in the local co-creation workshops. With this double-level co-creation process, the feasibility of the virtual co-creation platform results is tested at case study level.

Non-resilience

Lack of the type of attributes described in Fig 2. may not necessarily lead to system collapse. Nevertheless, Cumming and Peterson (2017) describe among others the following mechanisms contributing to vulnerability (Fig. 6) and collapse: ecological degradation and excessive resource consumption, too much complexity, sunk cost effects, lack of diversity, and external disruptions. Sunk cost effects were also described by Williamson (1987): a high level of asset specificity could reduce the scope for adaptation and transformation. As it well known, economic agents commonly have a choice between special purpose and general purpose investments. While the former could permit larger cost savings than the latter form of investment, special purpose investments are also risky. This is because, if new conditions arise, specialised assets cannot be redeployed without sacrifice of productive value (Williamson, 1987). This causes imperfect resource mobility and reduces the room for transformation.

4 Discussion and conclusions

Farming systems are complex systems characterised by among others institutions and agro-ecological context. Previous resilience frameworks do not sufficiently capture this complexity. Also, previous frameworks do not distinguish between different types of resilience thereby diminishing the spectrum of solutions to enhance resilience. We distinguish 3 main adaptive cycle processes pertaining to farming systems, i.e. agricultural, farm demographics and governance processes, and build our framework around three types of resilience: robustness, adaptability and transformability. Exploring resilience is preceded by defining spatial, functional and temporal boundaries.

Preliminary applications of the framework in the SURE-Farm case study regions illustrates that the framework can be applied in a farming system context enabling to explore robustness, adaptability and transformability to specific risks. Preliminary case work however also illustrates the difficulties in applying the framework. For instance, key risks and essential functions depend on stakeholder perspectives and e.g. the occurrence of recent shocks, thereby reinforcing the need for clarity on spatial, functional and temporal boundaries of the system under consideration. A further challenge of the framework is the identification of meaningful indicators to reflect the performance of a selected system function over time. Single parameter indicators likely forego the complexity of farming systems including historical context. We may therefore need to move to composite indicators or simultaneous analysis of multiple indicators. A further issue is that example attributes shown in Fig. 2 'start to live their own live', i.e. they are taken for granted without being verified yet. For example, it has been often shown that the attribute diversity contributes to improved resilience to climate variability and change (Gil et al., 2017). However, this is not the case in all situations, and resilience to climate variability and change does not necessarily imply that systems are also resilience to technological change. Although these example attributes are useful for prototyping, exact interpretations in different context need further elaboration and evidence. In addition, this elaboration will be challenging in itself as most attributes (especially under adaptability and transformability) are slowly changing variables (Carpenter et al. 2011). "[..] Learning about slow variables takes a long time, so it is easy to miss important processes or focus attention on the wrong hypotheses". Also, preliminary case work illustrates that different types of resilience can occur simultaneously. Before concluding on 'the resilience of a system', it needs to be understood which types of resilience best suit certain risks and system functions.

In current literature the word of 'resilience' is used abundantly. Our framework provides structure and definition to this multi-facetted concept. It also stipulates a structure to discuss sensitive topics among stakeholders, such as professional reorientation, negative feedbacks between attributes, stakeholder awareness and action plans regarding resilience of farming systems, and disputes about short-term versus long-term solutions. Due to its multiple entry points (e.g. top-down and bottom-up) we expect that the framework can be used by researchers to retrospectively understand the dynamics of sustainability in farming systems, and by decision makers to pro-actively identify differentiated attributes, i.e. resilience-enhancing strategies, across EU farming systems depending on context-specific risks and available resources.

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ANNEX 1: Examples of environmental, economic, social and institutional challenges, subdivided into shocks and long-term pressures.

	Environmental	Economic	Social	Institutional
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 (volatility) - Food or feed safety crisis - Changes in interest rates	- Media attention to a food safety or pest/disease issue (food scares) - Sudden changes to on-farm social capital (illness, death, divorce, children deciding not to go into farming, stress regarding ownership and the succession of the farm) - Insufficient availability of seasonal labour	- Changes in access to markets (e.g. Brexit in the UK, Russian embargo)
Long-term pressures	- Reduced soil fertility (soil mining, depletion of soils nutrients) - Climate change - Deforestation - Pollution by heavy metals - Hydro-geological disturbance - Impacts on drinking water - Species extinction - Decline of pollinators - Antimicrobial resistance - Loss of habitats - Altered phosphorous cycle - Altered nitrate cycle	- Reduced access to bank loans - Higher speed of information-sharing and inherent lack of time for verification - Changes in buying strategies of downstream actors - Increased cost of hired labour - New competitors in internationalised and liberalised markets, competition on and reallocation of resources - Upstream and downstream market power along the value chain - 'Financialisation' of agricultural and land markets - High (start-up) costs - Resource fixity leading to 'locked-in situation' - Changing quality and frequency of interactions between farmers and suppliers, financial institutions and other direct stakeholders	- Reduced trust and commitment towards cooperatives - Remoteness, reduced access to social services (housing, education, health), less developed infrastructure (transportation, ICT) - Gender gap - Reduced access to extension or advisory services & skills training - Changing societal concerns about agriculture (safety, odour, animal welfare, anti 'factory farming', resource utilisation, landscape issues) - Changing consumer preferences (local produce, organic) - Public distrust - Demographic change (increasing urbanisation, rural outmigration, migration) - Ageing of rural areas (lack of generational renewal) - Changing attitude towards farm employability (succession, hired labour, part-time farming)	- Changing national and EU environmental policy - Changes in government support for agriculture - Changes in regulations in destination markets (non-tariff barriers). - Restrictive standards (e.g. GM-free standards and regulations) - Intellectual property ('biopatents') - Changing policy objectives and administrative demands - Changes in land tenure regulations - Changes in food safety regulations - Changes in production control policies (quota) - Land-grabbing - Other countries agricultural policies (e.g. American Farm Bill, ASEAN policies, BRICS policies) - Trade and WTO reforms - Wars and conflicts (African wars, Ukraine) - Changes in quota

ANNEX 2: Functions of farming systems subdivided into private goods and public goods, including indicators.

	Indicators[1]
Private goods	
- Deliver healthy and affordable food products	- Productivity (e.g. ton/ha)[a,b] - Price differentials (domestic price/international market price)[b] - Nutritional quality[d] - Loss of crops/livestock due to pests/disease[d] - Food quality (e.g. share of food produced that successfully passes a quality control)[b]
- Deliver other bio-based resources for the processing sector	- Productivity (e.g. ton/ha) [d] - Use of agricultural waste (e.g. straw for energy production)[d]
- Ensure economic viability (viable farms help to strengthen the economy and contribute to balanced territorial development).	- Net farm income (level, downside risk)[a,b] - Cost of production[b] - Distribution of profit (i.e. share of producers' price on the sale price)[d] - % farms that are owned/tenanted[a] - Age structure[a] - Debt/asset ratio[a,b] - Added value of the whole supply chain[a] - Farmer associations and platforms for learning[d] - Number of forced farm exits[a] - Share of farms that are locked-in (due to high sunk costs)[d]
- Improve quality of life in farming areas by providing employment and offering decent working conditions.	- Income for agricultural workers (wage level)[a,b] - Number of on-farm and agribusiness jobs (annual working units/ha)[b] - Unemployment rate in the area[b] - Work quality (absence of labour force due to sickness)[b] - Right to quality of life (% of workers and producers with a good quality of life)[a,b] - Capacity development (trainings and opportunities for workers to grow professionally)[b] - Fair access to means of production[b] - Employment relations[b] - Non-discrimination[b] - Gender equality[b] - Health coverage[b]
Public goods	
- Maintain natural resources in good condition (water, soil, air)	- Soil erosion (physical, chemical and biological quality of the soil, e.g. % of area with stable soil)[b] - Water quality (e.g. pesticides and nitrates in rivers)[b] - Nutrient balance (Nitrogen Use efficiency (kg N output/ k N input); N surplus (kg N/ha); P surplus (kg P/ha))[b] - GHG balance (Mg CO_2e M $kcal^{-1}$)[b] - Use of pesticides (tons per 1,000 ha)[d] - Waste management[d] - Energy efficiency[b] - Share of total energy coming from renewable resources[b]
- Protect biodiversity of habitats, genes, and species	- Diversity and abundance of key farmland animal, plant and insect species (e.g. birds, butterflies, meadow plants)[b] - Woodland cover[d] - Agri-environmental payments[d] - % agricultural land with commitment to environmental conservation[d]; % committed to organic agriculture[a]; % high nature value farm land[c] - % agricultural land providing wildlife corridors/habitat connectivity[d] - Use of pesticides (tons per 1,000 ha)[d] - Use of GMO (for animal feed)[d] - Habitat connectivity[b] - Diversity of production (to promote diversity of crops and breeds and protection of genetic diversity in domestic species)[b]
- Ensure that rural areas are attractive places for residence and tourism (countryside, social structures)	- House prices[d] - Broadband coverage[d] - Happiness index (OECD) of rural populations[d] - In- versus out-migration[d] - Landscape maintenance and preservation budgets[d] - Rate of pluri-active farms[d] - Regional agri-tourism offered[c]

	- Rate of alternative farming systems (e.g. CSA farming, organic farming)[d] - Extent of public access (e.g. footpaths, bridleways etc.)[d] - Planning policies that protect the rural nature of the countryside[d]
- Ensure animal health & welfare[2]	- Evidenced compliance with animal welfare regulation[b] - Enrolment in certification schemes[d] - Market share of products with certified higher levels of animal welfare[d] - % animals not requiring medical treatments[b] - % animals free from stress/pain/discomfort[b] (e.g. based on physiological measures (cortisol level) or behavioural indicators (biting/stinging behaviour)[d] - Use of antibiotics (e.g. average number of dairy cows treated per year)[d]

[1] Sources are a: EC (2001); b: FAO (2013); c: Paracchini et al. (2008); and d: own elaboration. Indicators reflect practices (e.g. use of pesticides per ha) or outcomes (e.g. pesticides and nitrates in rivers).

[2] In FAO (2013) included under ‘environmental integrity’.