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

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ABSTRACT

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

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attractiveness of rural areas and general well-being of rural residents when monitoring and evaluating the sustainability and resilience of EU farming systems.

1. Introduction

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

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

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

Participatory approaches could help to complement existing monitoring frameworks. Participatory input is a common way to define and assess environmental, economic as well as social indicators in an integrative way based on stakeholder perceptions (König et al., 2013; Morris et al., 2011; Paas et al., 2021a; Van Calker et al., 2005). From a resilience perspective, closeness to critical thresholds of economic, environmental or social sustainability indicators can be seen as a sign of lower resilience. Perceived closeness to stakeholder-defined thresholds may hence be seen as a stress-signal of perceived low resilience. However, it should be kept in mind that perceived resilience is not always the same as resilience based on objectively defined and assessed resilience indicators (Jones, 2019; Jones and d'Errico, 2019). Although subjective, perceived resilience may explain stakeholder decision-making and resulting dynamics of the farming system. Closeness to critical thresholds may also inform the focus area of certain policies. Participatory input of farming system actors is also useful as it provides opportunities to take into account the local context and causal mechanisms at work. These are important to properly assess resilience and to realize adequate resilience-enhancing policies (Biesbroek et al., 2017).

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

2. Critical thresholds and resilience

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

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

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

3. Methodology

3.1. Farming systems and study design

This study is based on the "Framework of Participatory Impact Assessment for Sustainable and Resilient Farming Systems: future sustainability and resilience" (FoPIA-SURE-Farm 2; Paas et al., 2021b; Paas and Reidsma, 2020) applied to eleven European farming systems: large-scale arable farming in Northeast Bulgaria (BG-Arable), intensive arable farming in the Veenkoloniën, the Netherlands (NL-Arable), arable farming in East of England, United Kingdom (UK-Arable), large-scale corporate arable farming with additional livestock activities in Altmark, Germany (DE-Arable&Mixed), small-scale mixed farming in Nord-Est Romania (RO-Mixed), intensive dairy farming in Flanders, Belgium (BE-Dairy), extensive beef cattle systems in the Massif Central, France (FR-Beef), extensive sheep farming in Huesca, Spain (ES-Sheep), high-value egg and broiler systems in southern Sweden (SE-Poultry), small-scale hazelnut production in Lazio, Italy (IT-Hazelnut), and fruit and vegetable farming in the Mazovian region, Poland (PL-Horticulture).

FoPIA-SURE-Farm 2 consists of a preparation phase, a stakeholder workshop and an evaluation phase. The preparation and evaluation phase were exclusively conducted by the case study research teams. The research teams have been studying the resilience in their own case studies between June 2017 and August 2020. Stakeholder workshops were conducted in nine case studies between November 2019 and March 2020. This was a second round of workshops in a series of two, where the first round was focused on current and the second on future sustainability and resilience of farming systems. Participation in workshops was limited to farming system stakeholders, i.e. farmers and other actors that are influenced by and influence those farmers (Meuwissen et al., 2019), to make sure that participants had a good understanding of the local context. Farmers and participants from the government, (processing) industry, NGOs, agricultural advisors and researchers were present in the workshops (Supplementary Materials 1). Farmers were the best represented stakeholder group. The stakeholder workshops lasted about half a day. Individual workshop reports are presented as Supplementary Materials to Paas et al. (2020) in Accatino et al. (2020). In BE-Dairy and FR-Beef, desk studies were performed, because planned workshops had to be cancelled due to measures that were put in place in the context of the COVID-19 outbreak.

3.2. Challenges, function indicators and resilience attributes

In this paper, we distinguish between system *challenges*, *function indicators* and *resilience attributes*. In the context of resilience, *challenges* relate to the question "resilience to what?" (Carpenter et al., 2001; Meuwissen et al., 2019), e.g. resilience to weather extremes. *Challenges* can affect the system regarding the functions it provides. *Function indicators* are case-study specific characteristics of important system functions, such as "Food production" or "Maintaining natural resources", as direct metrics for those functions are often not available (Meuwissen et al., 2019; for a complete overview of system functions see the Appendix, Table A1). In the context of resilience, *function indicators* relate to the question "resilience for what purpose?", e.g. resilience to maintain "Food production". Good values for *function indicators* can be seen as signs of high sustainability (König et al., 2013; Paas et al., 2021a). *Challenges* can also affect the system regarding its *resilience attributes*, i.e. characteristics that convey general resilience to a system (Cabell and Oelofse, 2012; Paas et al., 2021a; Walker and Salt, 2012; Table A2 in the Appendix). Resilience attributes address the question "what enhances resilience?" (Meuwissen et al., 2019). High presence of *resilience attributes* is associated with high resilience. We argue that studying *challenges, function indicators*, *resilience attributes* and their possible interactions provides an opportunity to operationalize sustainability and resilience as complementary concepts (Paas et al., 2021b). For more details on the concepts used in this study, see Table A1 in the Appendix.

For benchmarking purposes, case study research teams conducted an assessment of the current performance levels and trends of a few main *function indicators* and *resilience attributes* of the farming system. Main *function indicators* and *resilience attributes* were determined in the first round of workshops with farming system stakeholders, which were conducted one year earlier within the same research project (Paas et al., 2019, 2021a; Reidsma et al., 2020). In these previous workshops, eight system *functions* were determined (Meuwissen et al., 2019) and *indicators* were selected in relation to these functions. Perceived importance of both *functions* and *function indicators* was assessed by stakeholders, resulting in main *function indicators* important to functioning of the system. For a set of 13 *resilience attributes*, the presence and contribution to resilience was assessed by stakeholders, resulting in an overview of perceived impact that attributes have on the resilience of the farming system. Contrary to the first round of workshops, the assessments in the second round of workshops were limited by the involved researchers to a few main *function indicators* and *resilience attributes* as critical system changes are expected to be determined by a small set of key variables (Kinzig et al., 2006). The main *challenges* of the respective farming system were also listed and described in each case study workshop. Participants were presented with and asked to comment on proposed main *challenges,* and (performance levels of) main *function indicators* and *resilience attributes*. In the following paragraphs, we present the selection of *challenges*, *function indicators* and *resilience attributes* as obtained in the preparation phase, and the expected developments. As they are results of our first round of workshops, we present these here in order to keep a clear distinction from the results obtained in the second round of workshops and the evaluation phase.

Challenges were encountered in the agronomic, economic, environmental, social and institutional domain. We regard the challenges from the institutional domain as exogenous, where challenges from other domains may be endogenous as well as exogenous to the system. Common *challenges* in the economic domain across most case studies were low commodity prices and price fluctuations or high production costs. In the environmental domain, extreme weather events were experienced as a challenge in the studied arable, perennial and mixed crop-livestock systems. When extreme weather was mentioned in case studies, the occurrence of drought was defined as the most important extreme event. Environmental *challenges* damaging main products in case studies were encountered in NL-Arable (plant parasitic nematodes), ES-Sheep (wildlife attacks) and IT-Hazelnut (pests that reduce yield quantity and quality). A challenge in the social domain in multiple case studies was the low attractiveness of the area and labor availability. In the institutional domain, laws and legislations, and their continuous change, were experienced as *challenges* in most studied systems (Supplementary Materials 1, Table SM1.2).

Main *function indicators* differed per case study to take into account the local context, but were representative for system functions, allowing for comparisons across case studies (Paas et al., 2021a; Reidsma et al., 2020). *Function indicators* for “Economic viability” and “Food production” were most commonly discussed across case studies. *Function indicators* for “Natural resources” were mainly discussed in the arable systems, but also in SE-Poultry and IT-Hazelnut. *Function indicators* for “Attractiveness of the area” were mainly discussed in case studies in which rural isolation or outmigration was experienced (BG-Arable, DE-Arable&Mixed, IT-Hazelnut). In IT-Hazelnut for instance, the retention of young people was perceived to be representative for this *function*. The number of farms in ES-Sheep was perceived to be representative for “Quality of life”. The happiness-index-of-farmers in UK-Arable was perceived to be representative for “Quality of life” and also relates to social isolation and to acknowledgment to and acceptance of farmers by society. (Supplementary Materials 1, Table SM1.3).

Resilience attributes were selected by researchers based on stakeholder perceptions in the first round of workshops. In those workshops, a pre-defined list of 13 attributes (Appendix, Table A2) was used and could, therefore, be directly compared across farming systems. *Resilience attributes* that were discussed in most case studies were “Infrastructure for innovation”, and “Production coupled with local and natural capital”. *Resilience attributes* related to diversity, policies or connection with actors outside the farming system were least discussed. In SE-Poultry and PL-Horticulture the “Functional diversity” and “Response diversity” was emphasized. In DE-Arable&Mixed, RO-Mixed and to a lesser extent in IT-Hazelnut, “Support rural life” relating to the embeddedness of the farming system in the rural society was discussed because of rural isolation and/or outmigration that is experienced (see also previous paragraph). In ES-Sheep and IT-Hazelnut, the resilience attribute “Diverse policies” was discussed due to the pressure experienced from environmental regulations that reduce the competitive advantage because of higher production costs (Supplementary Materials 1, Table SM1.4).

Levels of most of the main *function indicators* and *resilience attributes* are currently perceived to be slightly decreasing. In the perceived moderately performing systems IT-Hazelnut, SE-Poultry and NL-Arable (Reidsma et al., 2020), overall moderately positive indicator developments were expected. In the perceived low performing systems ES-Sheep and PL-Horticulture (Reidsma et al., 2020), and also in UK-Arable, negative developments were expected.

3.3. Assessing critical thresholds in farming systems

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

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

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

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

The possibility of interactions between critical thresholds of *challenges*, *indicators* and *resilience attributes* was discussed during the workshops. Based on this, and based on the information acquired in the previous step and from literature, research teams aimed to reveal interacting thresholds across domains (environmental, economic and social) and levels of integration (field, farm, farming system) that cause farming system dynamics. Interacting thresholds are thresholds that, when exceeded, lead to the exceedance of another threshold (Kinzig et al., 2006). Determining whether thresholds were interacting was based on qualitative argumentation by researchers using input from workshops. Detailed information on interacting thresholds per farming system is provided in Supplementary Materials 3.[1]

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

4. Results

4.1. Closeness to critical thresholds

More than half of the identified *challenges* were perceived to be “close” or “at or beyond” critical thresholds (Table 1). For extreme weather, closeness differed between farming systems: NL-Arable, IT-Hazelnut, PL-Horticulture, were perceived “somewhat close” to, DE-Arable&Mixed and BG-Arable seemed “close” to and RO-Mixed seems “at or beyond” the perceived critical thresholds. For the environmental *challenge* “pest & diseases”, NL-Arable, challenged by plant parasitic nematodes, and IT-Hazelnut, challenged by phytophatologies, were perceived to be “somewhat close” to critical thresholds. For *challenges* in the social, economic and institutional domain, participants perceived more often that critical thresholds were reached than for the environmental domain. In ES-Sheep, participants indicated that for all *challenges* critical thresholds were reached, except for wildlife attacks (no threshold defined). In DE-Arable&Mixed, the lack of infrastructure and low attractiveness of the area were perceived to be at or beyond a critical threshold. In SE-Poultry, the perceived mismatch between economic viability on the one hand and the high production standards and strict environmental regulations on the other hand made participants indicate that for both *challenges* critical thresholds were reached. Continuous change of laws and regulations was seen as a main *challenge* in NL-Arable, UK-Arable, PL-Horticulture as well as BG-Arable. Participants in these case studies, for instance, perceived a critical threshold in the case that certain crop protection products would be banned before replacements had become available. A policy implication here would be to study a reasonable time for phasing out/in of policies. In DE-Arable&Mixed, SE-Poultry and RO-Mixed, inadequate alignment of policies and regulations at national and EU level was mentioned: national production quality standards increase production costs, while abiding with EU trade regulations allows for cheaper imports from countries with lower production standards and constraints.

Participants could define critical thresholds for most system *function indicators* (Table 2); for instance, critical thresholds for the yield per hectare, an indicator related to the function “Food production”, e.g. in BG-Arable, RO-Mixed and NL-Arable. Systems were perceived to be “close” to critical thresholds for “Food production” and “Economic viability” and “somewhat close” to those for “Natural resources” and “Attractiveness of the area”. In IT-Hazelnut, for instance, the threshold for “Gross margin” relating to the function “Economic viability” was assessed to be 5000 Euros per hectare, but was expected to differ from farm to farm. Based on current variability of markets and climate, it is likely that the value will someday drop below the indicated threshold, which makes that the system may be close to this critical threshold. For the seemingly low performing systems PL-Horticulture and ES-Sheep, some indicator levels were perceived to be at or beyond the threshold. In these systems, immediate action seems required, e.g. with regard to product prices and availability of labor in the area. Reaching critical thresholds for soil quality, an indicator representing “Natural Resources”, was a concern in UK-Arable and NL-Arable. In those systems, participants mentioned that continuous adaptation is needed to prevent further degradation. In NL-Arable, a participant from the regional water board indicated that in the long-term water availability would decline, thus the system would approach a threshold. Most other participants took a more medium-term stance and therefore proximity to this threshold was considered somewhat close. Overall, there was rarely a disagreement between participants about threshold levels. In BE-Dairy, where a desk-study was performed, water quality and greenhouse gas emissions were perceived to be beyond acceptable levels set by European and regional policy makers. Farmers in BE-Dairy are likely to disagree with these externally determined thresholds. In SE-Poultry, DE-Arable&Mixed, ES-Sheep and NL-Arable, participants indicated that critical thresholds for economic viability differ from farm to farm. Hence, exceeding critical thresholds in these case studies may foremost imply the disappearance of economically less competitive farms from the farming system, rather than an immediate decline of the entire farming system performance.

For *resilience attributes*, relatively fewer critical thresholds were defined than for *function indicators* (Table 3; 22 out of 37 vs. 35 out of 42). Thresholds of *resilience attributes* were mostly (semi-) qualitatively determined. For instance, in DE-Arable& Mixed “Supports rural life” was assessed to be on the lower end of a 1 to 5 scale where 1 implied very low and 5 implied a very high support. Participants indicated that a further decline in support would imply crossing a critical threshold. Overall, when defined, *resilience attributes* seem less close to critical thresholds than *function indicators*. From a methodological point of view, *resilience attributes* might be harder to grasp, and therefore more difficult to define and also perceived to be less close to critical thresholds than *function indicators.* From a theoretical point of view, the distance to critical thresholds could suggest that under the current *challenges*, resilience capacities are still sufficient to, for instance, start an adaptation or transformation process that steers away from critical thresholds of system *challenges* and *indicators*. However, the presence of some attributes e.g. “Reasonably profitable”, when discussed and when a critical threshold was defined, was perceived to be close to a critical threshold, similar to the function “Economic viability” in most case studies (previous section). For the resilience attribute “Diverse policies”, i.e. policies that equally support robustness, adaptability and transformability (Paas et al., 2021a), the systems in ES-Sheep and IT-Hazelnut were perceived to be at or beyond a critical threshold. In IT-Hazelnut the system was perceived to be close to a critical threshold regarding “Infrastructure for innovation”. In IT-Hazelnut, current innovation levels were perceived already high, but would benefit from more to ensure further adaptation and improvement. For most other *resilience attributes* the system was perceived to be (somewhat) close to critical thresholds.

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

Table 1
Number of times challenges were assessed being in a certain position relative to the perceived critical threshold (aggregated results across 9 case studies; only main challenges were discussed in each farming system).

Challenge	Domain	Position relative to perceived critical threshold				No threshold defined	Not discussed	Total[a] (n)
		Not close	Somewhat close	Close	At or beyond			
Change in technology	Agronomic			1				1
Low prices and price fluctuations	Economic	1	2	2	1			6
High production costs	Economic			2	1			3
Extreme weather	Environmental	1	2	2	1			6
Pests & diseases	Environmental		1	1				2
Wildlife attacks	Environmental	1						1
Continuous change of laws and regulations	Institutional		3	2				5
Economic laws & regulations	Institutional	1	1		2			4
Environmental laws & regulations	Institutional		1	1	1			3
Lack of infrastructure	Social				1			1
Low attractiveness of rural areas	Social				1			1
Low labor availability	Social		1	1	1			3
Changes in consumer preferences	Social				1		1	2
Total (n)		**4**	**11**	**12**	**10**	-	**1**	**38**

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

Table 2
Number of times function indicators were assessed being in a certain position relative to the perceived critical threshold (aggregated results across nine farming systems; only main function indicators were discussed in each farming system).

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

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

Table 3
Number of times resilience attributes were assessed being in a certain position relative to the perceived critical threshold (aggregated results across 9 farming systems; only main resilience attributes were discussed in each farming system).

Resilience attribute	Position relative to perceived critical threshold				No threshold defined	Not discussed	Total[a] (n)
	Not close	Somewhat close	Close	At or beyond			
Reasonably profitable			3			1	4
Production coupled with local and natural capital		2	1		2	1	6
Functional diversity					1	1	2
Response diversity		1			1	1	3
Exposed to disturbances			1			1	2
Heterogeneity of farm types			1		1		2
Supports rural life		2	1				3
Socially self-organized	1	2	1				4
Appropriately connected with actors outside the farming system	1				1		2
Legislation coupled with local and natural capital		1					1
Infrastructure for innovation			2	1	3		6
Diverse policies				2			2
Total (n)	**2**	**7**	**10**	**3**	**10**	**5**	**37**

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

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

Mixed, SE-Poultry) and access to knowledge, finance and/or land (BG-Arable, DE-Arable&Mixed, PL-Horticulture, RO-Mixed). Enabling conditions in the social domain were e.g. related to rural demographics and/or availability of labor (BG-Arable, IT-Hazelnut, PL-Horticulture, RO-Mixed, SE-Poultry, ES-Sheep, DE-Arable&Mixed) and more horizontal and vertical cooperation and social self-organization (BG-Arable, ES-Sheep, PL-Horticulture, RO-Mixed, UK-Arable). Specifically, in BG-Arable and RO-Mixed emphasis was put on enabling conditions in the institutional and social domain.

4.2. Interacting thresholds and impact of exceeding these

In all case studies, interacting thresholds across level and/or domain were observed (Fig. 1; Supplementary Materials 3). More details on the interacting thresholds are presented in the Supplementary Materials 3. Common interactions between critical thresholds occur between field-environmental and field-economic, from field-economic to farm-economic, from farm-economic to farm-social, from farm-social to farming system-social, and from farming system-social to farm-social (Fig. 1). Generally, an environmental issue at field level, for instance, decreasing soil quality (NL-Arable, UK-Arable), pest diseases (NL-Arable, IT-Hazelnut), wildlife attacks (ES-Sheep), or drought (DE-Arable&Mixed, PL-Horticulture, RO-Mixed, BG-Arable) is so much of a shock or stress that it leads to yields that are too low to sustain an adequate level of farm income (see Supplementary Materials 3). In a majority of the farming systems, high input prices and decreasing output prices and sales further diminish the farm income. Too low incomes at farm level were in all case studies resulting in reduced attractiveness of farming, farmers quitting or the lack of finding a successor for the farm. In UK-Arable, also reduced farmer happiness due to lack of recognition was mentioned as a reason for quitting a farm. Farmers quitting their farm without having a successor was in multiple farming systems also considered to contribute to a smaller rural population at farming system level (FR-Beef, ES-Sheep, RO-Mixed, BG-Arable, IT-Hazelnut, PL-Horticulture; Fig. 1). Interestingly, although socially oriented *function indicators* and *resilience attributes* were less often formally included in the discussions, they eventually appeared when explaining how challenges impact the farming system. Having less farms in the farming system was also associated with a lower maintenance of natural resources and a less attractive countryside (ES-Sheep, FR-Beef; Supplementary Materials 3). Interactions with critical thresholds in the environmental domain at farm and farming system level were mentioned in a few other case studies. In NL-Arable, at farm level in the environmental domain a narrow rotation in which starch potato is grown every second year was expected to lead to increased pressure of plant parasitic nematodes (Figure SM3.7). In UK-Arable, low income at farm level was expected to lead to declining soil health at field level (Figure A5.11). In IT-Hazelnut and SE-Poultry, environmental regulations were expected to improve the maintenance of natural resources at farming system level, but also to push farm income levels below a threshold through increased costs (Figure SM3.6 and Figure SM3.10, respectively). Overall we observed that environmental thresholds certainly feature, but differ in the level at which they play a role and in what direction they evolve. In farming systems for which access to land is an issue (e.g. BE-Dairy, PL-Horticulture), quitting of farmers may also be an opportunity, provided land becomes available on the market for sale or to be leased. In ES-Sheep, quitting of farmers was experienced as a serious issue. In IT-Hazelnut, the retention of young people on the farms was specifically mentioned as something that could support the rural life and vice versa (Figure SM3.6). Both low economic viability at farm level and low attractiveness of farming and a smaller rural population were considered to reduce the access to labor at farm level in BG-Arable, SE-Poultry, PL-Horticulture, DE-Arable&Mixed, RO-Mixed, and ES-Sheep. Access to labor in BG-Arable, PL-Horticulture and RO-Mixed was important for the continuation of activities on farms, as lack of labor was expected to push yields below acceptable levels (Fig. 1). In BG-Arable lack of labor could

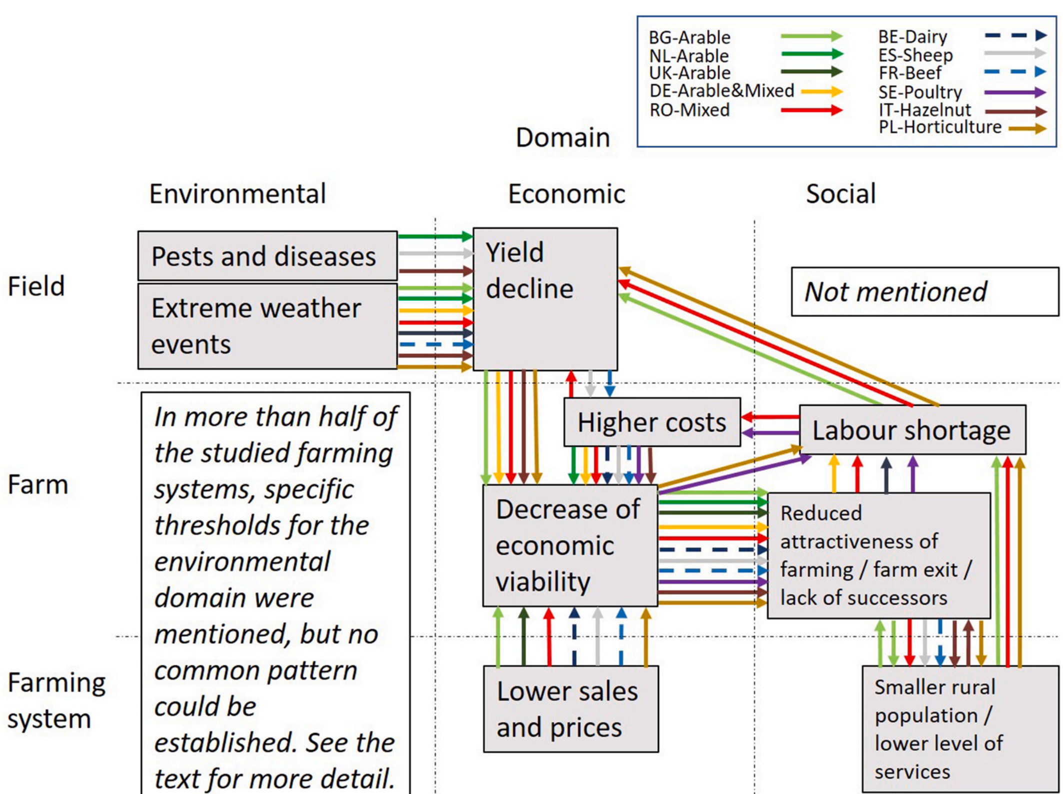

Fig. 1. A synthesis of main interactions across scales and domains for 11 EU farming systems (based on the framework of Kinzig et al., 2006).

be overcome by implementing new technologies, but this would require a labor force with higher levels of education and qualification which is even harder to find. Lack of labor was also expected to push production costs beyond critical thresholds in SE-Poultry and RO-Mixed. Hence, in multiple systems, low economic viability, attractiveness of farming, rural depopulation and low level of services at farming system level, and low access to labor seem to be part of a vicious cycle.

Following from Fig. 1, it can be made plausible that after exceeding critical thresholds of *challenges*, a decline in performance of system's main *function indicators* and *resilience attributes* was expected by workshop participants in most case studies (see Supplementary Materials 1 for details). Across farming systems, the functions "Food production", "Economic viability", and the "Natural resources" were in most cases expected to decline moderately or strongly (Supplementary Materials 1 Table SM1.5). Especially system functions in arable systems were perceived to be moderately to strongly affected. In ES-Sheep, ongoing decline of function performance was expected to be aggravated. When discussed in case studies, "Biodiversity & habitat" and "Animal health & welfare" were on average expected to be less impacted compared to other functions.

When exceeding critical thresholds of challenges, also a decline in *resilience attributes* was expected in most case studies, mainly because of a decline in profitability, production being less coupled with local and natural capital, a declining support of rural life and lower levels of self-organization (Supplementary Materials 1, Table SM1.5). By contrast, participants in BG-Arable and SE-Poultry generally expected improvements in *resilience attributes* after critical thresholds are exceeded (Table SM1.5). For instance, infrastructure for innovation was expected to develop positively in BG-Arable and SE-Poultry, while it was expected to develop negatively in other case studies (DE-Arable&Mixed, ES-Sheep, NL-Arable, UK-Arable). In the case of BG-Arable, participants expected increased collaboration, leading to innovation, in case the system would collapse. In the case of ES-Sheep, participants expected that the current low profitability of farmers will not allow investment in new infrastructures for innovation.

5. Discussion

5.1. Closeness to critical thresholds

All studied farming systems were perceived to be "close" or "at or beyond" at least one critical threshold for *challenges*, *function indicators* or *resilience attributes* (Tables 1–3). The actual state of the system may be more or less close to a threshold than the participant's perception. Obviously, for case studies that are perceived to be "at or beyond" critical thresholds while still continuing business as usual, the actual state must be at a different position than perceived. Still, perceived closeness can be seen as a clear stress signal, indicating that change is needed, expected or even already experienced. An example refers to the ban of crop protection products before alternatives are available. This stress signal could instigate a study about a reasonable time to phase in/out regulations regarding the use of crop protection products before actually implementing them. Perceptions of being close to or at critical thresholds also indicate that, from the perspective of farming system actors, immediate action is needed to preserve the farming system or guide it in its transition, thus avoiding a situation where sustainability is even lower. Looking at multiple *challenges* puts individual *challenges* into perspective. To give an example, climate change may be a problem causing regime shifts in many socio-ecological systems (Biggs et al., 2018), but for the studied farming systems this is not the only *challenge* and often also not perceived to be the most urgent, except for some arable systems (Table 1). This supports the notion that climate change should be studied in the context of other drivers (Hermans et al., 2010; Mandryk et al., 2012; Reidsma et al., 2015). At a global level, reducing anthropogenically induced climate change is, of course, urgent and agricultural systems' contribution to it must be reduced. Some challenges experienced by FS actors, especially farmers, may also be implicitly caused by climate change; for instance changing legislation and high input costs. For most of the farming systems in our study, climate awareness of some stakeholders, such as conventional farmers, is however not likely triggered due to the impact of climate change on their system per se. When deliberated in an appropriate manner with those stakeholders, new legislation in the context of fighting climate change may however have considerably more effect regarding changing stakeholder perceptions.

Function indicators for food production and economic viability were often perceived to be close to critical thresholds. This confirms the need to closely monitor economic indicators as is done in the CMEF of the CAP (European Commission, 2015). When discussed, social *function indicators* were generally perceived to be "not close" or "somewhat close" to a critical threshold, except for ES-sheep where participants experienced that a critical threshold was exceeded (e.g., quality of life through number of farms, which lead to work generation) (Table 2). Environmental *function indicators* were in most cases perceived to be "not close" or "somewhat close" to critical thresholds (Table 2). Only in arable systems, environmental functions were experienced "close" or "at or beyond" critical thresholds. This was mainly related to the capacity of soils (at farm or field level) to deal with an excess or lack of water, often due to climate change. Participants in workshops of arable systems indicated that a lot of effort was already required to maintain rather than to improve the current soil quality. Arable systems, in need for soil improvement to avoid critical thresholds, would benefit from enabling conditions at national and EU level that foster the maintenance of natural resources. Mitter et al. (2020), based on a mechanistic scenario development approach for EU agriculture, expect improved attention for natural resources only in a scenario following a "sustainability pathway" out of five possible future scenarios. Current conditions and their future development hence do not seem to support a resilient future of arable systems. Overall, perceived closeness to critical economic thresholds could explain the perceived lower importance of social and environmental functions compared to economic and production functions (Reidsma et al., 2020).

Defining critical thresholds seemed most difficult for *resilience attributes* (Table 3). According to Walker and Salt (2012) it is actually impossible to determine critical thresholds for *resilience attributes* because they all interact. However, *function indicators* also interact, but were easier to assess for participants. We argue that difficulties in determining critical thresholds are probably more an indication of the perceived redundancy of *resilience attributes* for system functioning: presence and contribution to resilience was low to moderate according to stakeholders' perceptions (Paas et al., 2021a; Reidsma et al., 2020). This could be related to a control rationale (Hoekstra et al., 2018), in which keeping a relatively stable environment and improving efficiency is more important than increasing the presence of *resilience attributes*. It should be noted, however, that participants often could indicate enabling conditions that improve the *resilience attributes*. This could be an indication that participants are aware of the importance of *resilience attributes*, but are in need for more concrete, locally adapted indicators that represent the *resilience attributes*. In any case, suggesting improvements for *resilience attributes* could be seen as an implicit acknowledgment by participants that building capacities for adaptation or transformation is required.

Perceived thresholds may be different than the real threshold. For the systems that are perceived to be "at or beyond" critical thresholds, it is not necessarily too late to adapt in case the real threshold is actually at a different level than the perceived one. The extensive sheep system in Spain was judged to be close to a collapse, but alternative systems and strategies to reach those have been proposed (Paas et al., 2021b). In IT-Hazelnut, introduction of new machinery in the past has made farming more attractive for the younger generation, thus avoiding depopulation (Nera et al., 2020). Further developments in IT-Hazelnut regarding local value chain activities at farming system level rather than farm scale enlargement, are aimed to further stimulate economic viability and the retention of young people in the area (Nera et al., 2020; Paas et al., 2020). In PL-Horticulture, the case study is relatively close to Poland's capital where access to land is limited, system actors aim at increasing the economic viability via vertical and horizontal cooperation at farming system level, which keeps re-attracting seasonal laborers from nearby Ukraine, where wages are lower, to the region. The common factor in these examples of adaptation is that resources are needed to implement them. Be it financial, human, social or other forms of resources. The examples above also suggest that coming back to a desired state, even after exceeding a critical threshold, is possible, provided the disturbance causing the exceedance does not last too long (e.g. Van Der Bolt et al., 2018), and adaptation strategies are available (e.g. Schuetz, 2020). The notion of a critical threshold being a combination of magnitude (level) and duration was not discussed much in the workshops but could help to further define critical thresholds. For instance with regard to the number of years the farming system can deal with extreme weather events as was done in NL-Arable.

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

5.2. Interaction of critical thresholds

Based on workshop results and further reflections, interactions between critical thresholds are expected to (in)directly affect the economic viability at farm level, a central critical threshold observed in all farming systems (Fig. 1). Economic viability at farm level is a relatively fast and measurable indicator. This gives another argument for monitoring income and other economic indicators in the monitoring frameworks such as the CMEF. The lack of a consistent pattern with regard to environmental thresholds indicates the importance of the local context.

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

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

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

Avoiding exceedance of critical thresholds without further adaptation or transformation, implies a performance at or below the current low to moderate levels for most system *function indicators* and *resilience attributes* (Reidsma et al., 2020). A potential exceedance of a critical (and interacting) threshold in the coming ten years is expected to lead to negative developments for most system *function indicators* and *resilience attributes*. Negative developments of *function indicators* are expected in the economic, social as well as the environmental domain. On average, across all farming systems, we did not observe any differences in the magnitude of the effect between domains for *function indicators*. This consistent development confirms the idea that the different domains are interacting.

The consistent expected developments for *function indicators* and *resilience attributes* after exceeding critical thresholds suggest a perceived interaction between them. One could argue that a system needs resources to react to shocks and stresses (Meadows, 2008; Walker and Salt, 2012), especially for adaptation and transformation. These resources can only be adequately realized when there is an enabling environment and when system functions are performing well. The other way around, *resilience attributes* can be seen as "resources" to support system functions on the way to more sustainability. For instance, existing diversity of activities and farm types makes visible what works in a specific situation, openness of a system helps to timely introduce improved technologies, and connection with actors outside the farming system may help to create the enabling environment for innovations to improve system functioning (Table A2).

5.3. Farm level responses to reaching critical thresholds of challenges

Impact of *challenges* is primarily experienced at the farm level, resulting in the disappearance of (certain) farms from the farming system. In multiple case studies (SE-Poultry, DE-Arable&Mixed, NL-Arable), participants indicated that identified critical thresholds would be perceived differently among farmers. As mentioned before, farm closure generally leads to a less attractive countryside, a long-term process that is currently not perceived the most important issue in most studied farming systems, according to stakeholder input. Increasing farm size could be seen as a solution to compensate for the loss of farms and farmers in the farming system. Increasing the farm size is often associated with the advantage of economies of scale. For multiple farming systems in our study (NL-Arable, UK-Arable, SE-Poultry, BE-Dairy, ES-Sheep), production margins are low, which could further stimulate this thinking. However, from the farm level perspective, beyond a certain size, further economies of scale are not realized in some of the studied farming systems, i.e. there are limits to growth dependent on the rural context. In BE-Dairy, for instance, increasing farm size seems to be limited due to environmental standards. In ES-Sheep, further reduction of the farmer population is perceived to be harming the farming system, e.g. through reduction of facilities such as farmer networks, agricultural research initiatives, etc., but also hospitals, schools, etc. Besides, to further increase farm size, farmers in ES-Sheep depend on extra labor that is not available because of low attractiveness of the countryside, while investment in labor saving technology does not pay off with the current market prices. This is an example of the reflection of Kinzig et al. (2006) that a seemingly reversible threshold (no hysteresis effect) becomes irreversible because a certain management option to reverse processes is not available anymore. Based on Fig. 1, we argue that this specific example may be true for more farming systems where a lack of labor force is experienced and investment in labor saving technology are not likely to pay off (e.g. RO-Mixed).

5.4. Implications for monitoring resilience

5.4.1. Social indicators

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

5.4.2. Monitoring resources

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

5.4.3. Reflection on methodology

Given the challenges regarding assessing and discussing critical thresholds in workshops (stakeholder participation, differing stakeholder opinions, differing metrics, farm-specificity of thresholds, expert judgments of case study researchers on proximity to those thresholds), all identified critical thresholds could be seen as "Thresholds of potential concern" (TPCs; Walker and Salt, 2012 citing Biggs and Rogers, 2003). In our case these TPCs would express the concerns of a selection of farming system stakeholders. TPCs can be seen as a set of evolving management goals that are aimed at avoiding critical thresholds that are expected, e.g. from experiences in other systems, but are not known. In case thresholds are considered beforehand as TPC's, Q-methodology (McKeown and Thomas, 2013) may be an interesting participatory method to define which TPC deserves most priority. Estimating main functions of a system by assessing critical thresholds as TPCs, reduces the presence of clear sustainability goals. This makes the threshold assessment less dependent on externally determined values and criteria than most sustainability assessments (see e.g. Binder et al., 2010). Implicitly, the goal is to avoid a decline in sustainability and resilience levels of the current system, which may give the participating system actors the trust to provide details, expose interrelatedness between sustainability domains, and also come up with solutions. Regarding the latter, it should be noted that avoiding exceedance of critical thresholds does not automatically imply that a system is steering away from mediocre performance. This is why after assessing critical thresholds, participants should also be stimulated to think about adaptations to improve their system to desired sustainability and resilience levels (Paas et al., 2021b). Be it by steering away or actual exceeding critical thresholds to arrive at higher sustainability levels. Paas et al. (2021b) suggest a back-casting approach, but other solution-oriented methods such as participatory multi-criteria decision analysis may also be appropriate (Belton and Stewart, 2002). In any case, starting with a threshold assessment before solution-oriented participatory methods may create path-dependency, resulting in adaptations that lead to a reconfirmation of the current system where a transformation might actually be more appropriate. This path-dependency is likely to be reinforced by only inviting participants from within the farming system. Farming system actors are for instance probably biased regarding depopulation and a loss of attractiveness of the rural area, as it is related to farm closure. Considering the possibility that the closure of individual farms could be good for the farming system as a whole might go beyond the mental models of some farming system actors. Participatory methods involving so-called "critical friends" that have no direct stake in the system might help to overcome this obstacle (Enfors-Kautsky et al., 2018). Involving external actors is especially required in unsustainable systems that persist through the agency of only a subset of stakeholders.

It should be noted that critical thresholds are never static as they depend on the context (Kinzig et al., 2006; Resilience Alliance, 2010). The need for labor for instance depends on the level of automatization in agriculture. Critical thresholds may change because of slowly changing variables (Kinzig et al., 2006 citing Carpenter et al., 2003), which is also acknowledged in this study by presenting interacting thresholds across levels and domains in multiple case studies. Different domains could be addressed by including a variety of social, economic, institutional and environmental *challenges*, *function indicators* and *resilience attributes*. Using the framework of Kinzig et al. (2006) forced in particular researchers in some case studies to reflect on critical thresholds in the social domain, while focus of participants was more on economic and environmental processes. The framework of Kinzig et al. (2006) can hence show where knowledge of stakeholders is limited. This is an asset as exposing the limits of local knowledge is often lacking in participatory settings (Mosse, 1994). Explicitly adding the institutional domain and a level beyond the farming system to the framework of Kinzig et al. (2006) may further reveal the limits of knowledge and improve the understanding of farming system dynamics. To further stimulate co-production of knowledge, the figures with interacting thresholds (e.g. Fig. 1) could be fed back to farming system stakeholders in a follow-up workshop. In addition, farming system actors could be stimulated to think about representative indicators for resilience attributes. These representative indicators could add local meaning and thus improve stakeholders' understanding and assessment of the resilience attributes and resilience mechanisms (see also Paas et al., 2021b).

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

The study presented in this paper is a resilience assessment that is partly objectively and partly subjectively defined: we worked with a set of *function indicators* and *resilience attributes* selected in a previous workshop by stakeholders based on lists prepared by researchers (Paas et al., 2021a; Reidsma et al., 2020). Such an approach may not be feasible at EU scale, but has proven effective for postulating candidate indicators for monitoring frameworks such as the CMEF. More participatory workshops in a diverse range of EU farming systems are advised to find more of these indicators that can enrich those monitoring frameworks. It should be noted however, that assessments inclining towards a subjective definition and evaluation of resilience are poorly researched and that translation issues and cultural biases can limit these kind of assessments (Jones, 2019). Further elaboration and study of participatory methodologies is therefore necessary to improve its use for evaluating sustainability and resilience at farming system, national and EU level. Specifically the desired or acceptable degree of objectivity vs. subjectivity in assessments across different levels (field, farm, farming system) and domains (economic, environmental, social) should be discussed.

6. Conclusion

In our participatory approach, all 11 studied systems in the European Union were perceived to be "close to", "at or beyond" at least one identified critical threshold (Tables 1–3). In particular, critical thresholds in the economic domain were considered to be (almost) reached. This could explain the economic orientation of farming system stakeholders and the current CMEF of the CAP. Overall, a strong decline in system performance was expected if critical thresholds would be exceeded. We conclude that concern for exceeding critical thresholds is justified, even though precise determination of a threshold position based on a participatory approach is difficult. Stakeholder perceptions on critical thresholds provide useful information as they serve as a stress signal and can be used as a starting point for a dialogue with farming system actors. We suggest that critical thresholds could be seen as a "thresholds of potential concern" for which management and policy goals may be developed. For instance, policies to attract more agricultural workers to an area to avoid a shortage of labor. Those policy and management goals should include the development of metrics that provide rigorous information on that specific threshold. The analysis of critical thresholds provides a basis for early thinking about possible alternative configurations of the systems. In this regard, the results can be used to reflect collectively about farming system trajectories, as to system functions and the often-competing goals of the different stakeholders. Therefore, the results of the analysis can be used to develop a contextualized, shared vision and to identify, within each farming system of interest, where to focus regarding increasing the resilience and sustainability of the farming system.

Critical thresholds were perceived to interact across levels of integration (field, farm, farming system) and domains (social, economic, environmental) in all case studies (Fig. 1). Common across case studies was the central role of economic performance at farm level, which was mainly affected by price levels and yield levels. This is another confirmation of the importance of economic indicators in the CMEF. However, in all case studies, exceeding the critical threshold of economic performance at farm level was associated with social issues such as lower attractiveness of farming, lower availability of successors or farm exit. In some farming systems, these social consequences were also experienced as critical thresholds contributing to lower labor availability reinforcing the low economic performance or contributing to depopulation, which encourages the loss of attractiveness of farming. This reinforcing effect may speed up the erosion of resources in the social domain. Social indicators are therefore important to consider when assessing the sustainability and resilience of farming systems.

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

Ethical statement

This human subject research in the context of the SURE-Farm project has been approved by the Social Sciences Ethics Committee of Wageningen University & Research. Informed consent was obtained from all individual participants in the study.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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