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1 Participatory assessment of critical thresholds for resilient and 2 sustainable European farming systems

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23 Abstract

24 Farming systems in Europe are experiencing multiple stresses and shocks that may push systems beyond
25 critical thresholds after which system change is expected to occur. These critical thresholds may lie in the
26 economic, environmental, social and institutional domain. In this paper we take a participatory approach
27 with involvement of farming system stakeholders to assess the presence of critical thresholds in 11
28 European farming systems, and the potential consequence of surpassing those with regard to system
29 sustainability and resilience. First, critical thresholds of the main challenges, key system variables and
30 their interactions in the studied farming systems were assessed. Second, participants assessed the
31 potential developments of the key system variables in case critical thresholds for main system challenges
32 would be exceeded. All studied systems were perceived to be close, at or beyond at least one identified
33 critical threshold. Stakeholders were particularly worried about economic viability and food production
34 levels. Moreover, critical thresholds were perceived to interact across system levels (field, farm, farming
35 system) and domains (social, economic, environmental), with low economic viability leading to lower
36 attractiveness of the farming system, and in some farming systems making it hard to maintain natural
37 resources and biodiversity. Overall, a decline in performance of all key system variables was expected by
38 workshop participants in case critical thresholds would be exceeded. For instance, a decline in the
39 attractiveness of the area and a lower maintenance of natural resources and biodiversity. Our research
40 shows that concern for exceeding critical thresholds is justified and that thresholds need to be studied

41 while considering system variables at field, farm and farming system level across the social, economic
42 and environmental domains. For instance, economic variables at farm level (e.g. income) seem
43 important to detect whether a system is approaching critical thresholds of social variables at farming
44 system level (e.g. attractiveness of the area), while in multiple case studies there are also indications
45 that approaching thresholds of social variables (e.g. labor availability) are indicative for approaching
46 economic thresholds (e.g. farm income). Based on our results we also reflect on the importance of
47 system resources for stimulating sustainability and resilience of farming systems. We therefore stress the
48 need to include variables that reflect system resources such as knowledge levels, attractiveness of rural
49 areas and general well-being of rural residents when monitoring and evaluating the sustainability and
50 resilience of EU farming systems.

51

52

53 1. Introduction

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

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

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

75 Participatory approaches could help to complement existing monitoring frameworks. Participatory input is
76 a common way to define and assess environmental, economic as well as social indicators in an
77 integrative way based on stakeholder perceptions (König et al., 2013; Morris et al., 2011; Paas et al.,
78 2021; Van Calker et al., 2005). From a resilience perspective, closeness to critical thresholds of
79 economic, environmental or social sustainability indicators can be seen as a sign of lower resilience.
80 Perceived closeness to stakeholder-defined thresholds may hence be seen as a stress-signal of perceived
81 low resilience. However, it should be kept in mind that perceived resilience is not always the same as
82 resilience based on objectively defined and assessed resilience indicators (Jones, 2019; Jones and
83 d'Errico, 2019). Although subjective, perceived resilience may explain stakeholder decision-making and
84 resulting dynamics of the farming system. Closeness to critical thresholds may also inform the focus area
85 of certain policies. Participatory input of farming system actors is also useful as it provides opportunities
86 to take into account the local context and causal mechanisms at work. These are important to properly
87 assess resilience and to realize adequate resilience-enhancing policies (Biesbroek et al., 2017).

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

2. Critical thresholds and resilience

100 In social-ecological systems (SES) research, there is ample evidence for the existence of critical
101 thresholds whose exceedance leads to potentially undesired system transformations (Biggs et al., 2018;
102 Rocha et al., 2015). Evidence in SES research is usually based on empirical data, theoretical models and
103 statistics related to early warning signals (Rocha et al., 2015). Participatory approaches to identify
104 critical thresholds are also proposed (Resilience Alliance, 2010; Walker et al., 2002; Walker and Salt,
105 2012). Still, large transformations or so-called regime shifts are not commonly observed in SES (Biggs et
106 al., 2018; Carpenter et al., 2005). A hypothesis is that many SES are most of the time operating in a
107 growth or consolidation phase, while their phases of decline and re-organization are usually short
108 (Walker and Salt, 2012). Such a hypothesis may hold for the SES studied by Rocha et al. (2015) and
109 Biggs et al. (2018), e.g. with regard to natural vegetation cover change in terrestrial systems or fish
110 stock collapses in marine systems. In their studies, the focus is predominantly on passing critical
111 thresholds in the environmental domain, as the degree of control over environmental processes or
112 specific ecosystem services seems limited.

113 In SES such as contemporary European farming systems, anthropogenic inputs and human-induced
114 adaptation processes are primarily aimed at controlling the level of food production. Transformations in
115 farming systems may therefore be the result of gradually implemented adaptations in reaction to a
116 changing environment, such as the gradual change towards agri-industrial entrepreneurship farming
117 after the Second World War encountered in many European farming systems (Hardeman and Jochemsen,
118 2012). Therefore, in agricultural research, large transformations are often observed based on long-term
119 historical studies on farming systems (e.g. Allison and Hobbs 2004, Termeer et al. 2019, Meuwissen et
120 al. 2020), agricultural landscapes (e.g. Brown and Schulte 2011), or on a combination of both (e.g. Van
121 Apeldoorn et al. 2013). Farming systems operate at a regional level (Meuwissen et al., 2019), a level for
122 which Biggs et al. (2018) indicate that regime shifts develop slowly. This explains why large, gradual
123 transformations can only be observed at longer time scales. In land use dynamics studies, large
124 transformations can be simulated with quantitative models (e.g. Figueiredo and Pereira 2011, Brown et
125 al. 2019). In these models, critical economic thresholds beyond which decision makers change activities
126 are predefined inputs. However, apart from critical thresholds in the economic domain, critical thresholds
127 in the social and environmental domain also need to be taken into account (Kinzig et al., 2006; Walker
128 and Salt, 2012).

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

143 3. Methodology

144 Farming systems and study design

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

156 FoPIA-SURE-Farm 2 consists of a preparation phase, a stakeholder workshop and an evaluation phase.
157 The preparation and evaluation phase were exclusively conducted by the case study research teams. The
158 research teams have been studying the resilience in their own case studies between June 2017 and
159 August 2020. Stakeholder workshops were conducted in nine case studies between November 2019 and
160 March 2020. This was a second round of workshops in a series of two, where the first round was focused
161 on current and the second on future sustainability and resilience of farming systems. Participation in
162 workshops was limited to farming system stakeholders, i.e. farmers and other actors that are influenced
163 by and influence those farmers (Meuwissen et al., 2019), to make sure that participants had a good
164 understanding of the local context. Farmers and participants from the government, (processing)
165 industry, NGOs, agricultural advisors and researchers were present in the workshops (Supplementary
166 Materials 1). Farmers were the best represented stakeholder group. The stakeholder workshops lasted
167 about half a day. Individual workshop reports are presented as Supplementary Materials to Paas et al.
168 (2020) in Accatino et al. (2020). In BE-Dairy and FR-Beef, desk studies were performed, because
169 planned workshops had to be cancelled due to measures that were put in place in the context of the
170 COVID-19 outbreak.

171 Challenges, function indicators and resilience attributes

172 In this paper, we distinguish between system *challenges*, *function indicators* and *resilience attributes*. In
173 the context of resilience, *challenges* relate to the question “resilience to what?” (Carpenter et al., 2001;
174 Meuwissen et al., 2019), e.g. resilience to weather extremes. *Challenges* can affect the system regarding
175 the functions it provides. *Function indicators* are case-study specific characteristics of important system
176 functions, such as “Food production” or “Maintaining natural resources”, as direct metrics for those
177 functions are often not available (Meuwissen et al., 2019; for a complete overview of system functions
178 see the Appendix, Table A1). In the context of resilience, *function indicators* relate to the question
179 “resilience for what purpose?”, e.g. resilience to maintain “Food production”. Good values for *function*
180 *indicators* can be seen as signs of high sustainability (König et al., 2013; Paas et al., 2021). *Challenges*
181 can also affect the system regarding its *resilience attributes*, i.e. characteristics that convey general
182 resilience to a system (Cabell and Oelofse, 2012; Paas et al., 2021; Walker and Salt, 2012; Table A2 in
183 the Appendix). Resilience attributes address the question “what enhances resilience?” (Meuwissen et al.,
184 2019). High presence of *resilience attributes* is associated with high resilience. We argue that studying
185 *challenges*, *function indicators*, *resilience attributes* and their possible interactions provides an
186 opportunity to operationalize sustainability and resilience as complementary concepts (Paas et al., n.d.).
187 For more details on the concepts used in this study, see Table A1 in the Appendix.

188 For benchmarking purposes, case study research teams conducted an assessment of the current
189 performance levels and trends of a few main *function indicators* and *resilience attributes* of the farming
190 system. Main *function indicators* and *resilience attributes* were determined in the first round of
191 workshops with farming system stakeholders, which were conducted one year earlier within the same
192 research project (Paas et al., in press; Reidsma et al., 2020). In these previous workshops, eight system

193 *functions* were determined (Meuwissen et al. 2019) and *indicators* were selected in relation to these
194 functions. Perceived importance of both *functions* and *function indicators* was assessed by stakeholders,
195 resulting in main *function indicators* important to functioning of the system. For a set of 13 *resilience*
196 *attributes*, the presence and contribution to resilience was assessed by stakeholders, resulting in an
197 overview of perceived impact that attributes have on the resilience of the farming system. Contrary to
198 the first round of workshops, the assessments in the second round of workshops were limited by the
199 involved researchers to a few main *function indicators* and *resilience attributes* as critical system changes
200 are expected to be determined by a small set of key variables (Kinzig et al., 2006). The main *challenges*
201 of the respective farming system were also listed and described in each case study workshop.
202 Participants were presented with and asked to comment on proposed main *challenges*, and (performance
203 levels of) main *function indicators* and *resilience attributes*. In the following paragraphs, we present the
204 selection of *challenges*, *function indicators* and *resilience attributes* as obtained in the preparation phase,
205 and the expected developments. As they are results of our first round of workshops, we present these
206 here in order to keep a clear distinction from the results obtained in the second round of workshops and
207 the evaluation phase.

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

220 Main *function indicators* differed per case study to take into account the local context, but were
221 representative for system functions, allowing for comparisons across case studies (Paas et al., 2019).
222 *Function indicators* for "Economic viability" and "Food production" were most commonly discussed across
223 case studies. *Function indicators* for "Natural resources" were mainly discussed in the arable systems,
224 but also in SE-Poultry and IT-Hazelnut. *Function indicators* for "Attractiveness of the area" were mainly
225 discussed in case studies in which rural isolation or outmigration was experienced (BG-Arable, DE-
226 Arable&Mixed, IT-Hazelnut). In IT-Hazelnut for instance, the retention of young people was perceived to
227 be representative for this *function*. The number of farms in ES-Sheep was perceived to be representative
228 for "Quality of life". The happiness-index-of-farmers in UK-Arable was perceived to be representative for
229 "Quality of life" and also relates to social isolation and to acknowledgement to and acceptance of farmers
230 by society. (Supplementary Materials 1, Table SM1.3).

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

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

248 Assessing critical thresholds in farming systems

249 With reference to current performance and ongoing trends it is interesting to know between what levels
250 the main system *challenges*, *function indicators* and *resilience attributes* need to stay in order to
251 maintain the current system configuration. Critical thresholds were defined as levels beyond which
252 performance of all other key system functions is expected to drop below acceptable levels. Although
253 multiple types of critical thresholds can be distinguished, all types have in common that system change
254 after exceeding them is large and that reversing that change is challenging and costly (Kinzig et al.,
255 2006). To not overcomplicate the concept in a participatory setting, we therefore defined a critical
256 threshold as a point beyond which large and permanent, system change is expected. This change can
257 have a positive as well as a negative connotation. However, as *challenges* are the point of departure in
258 this study, overall change has predominantly a negative connotation.

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

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

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

291 The possibility of interactions between critical thresholds of *challenges*, *indicators* and *resilience*
292 *attributes* was discussed during the workshops. Based on this, and based on the information acquired in

293 the previous step and from literature, research teams aimed to reveal interacting thresholds across
294 domains (environmental, economic and social) and levels of integration (field, farm, farming system)
295 that cause farming system dynamics. Interacting thresholds are thresholds that, when exceeded, lead to
296 the exceedance of another threshold (Kinzig et al., 2006). Determining whether thresholds were
297 interacting was based on qualitative argumentation by researchers using input from workshops. Detailed
298 information on interacting thresholds per farming system is provided in Supplementary Materials 3. ¹

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

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.

305

4. Results

306 Closeness to critical thresholds

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

327
328

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 ¹ (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

329 ¹For BE-Dairy and FR-Beef desk studies were conducted instead of workshops. Results from these
330 case studies are hence not included in this table.

331 Participants could define critical thresholds for most system *function indicators* (Table 2); for instance,
332 critical thresholds for the yield per hectare, an indicator related to the function "Food production", e.g. in
333 BG-Arable, RO-Mixed and NL-Arable. Systems were perceived to be "close" to critical thresholds for
334 "Food production" and "Economic viability" and "somewhat close" to those for "Natural resources" and
335 "Attractiveness of the area". In IT-Hazelnut, for instance, the threshold for "Gross margin" relating to the
336 function "Economic viability" was assessed to be 5,000 Euros per hectare, but was expected to differ
337 from farm to farm. Based on current variability of markets and climate, it is likely that the value will
338 someday drop below the indicated threshold, which makes that the system may be close to this critical
339 threshold. For the seemingly low performing systems PL-Horticulture and ES-Sheep, some indicator
340 levels were perceived to be at or beyond the threshold. In these systems, immediate action seems
341 required, e.g. with regard to product prices and availability of labor in the area. Reaching critical
342 thresholds for soil quality, an indicator representing "Natural Resources", was a concern in UK-Arable and
343 NL-Arable. In those systems, participants mentioned that continuous adaptation is needed to prevent
344 further degradation. In NL-Arable, a participant from the regional water board indicated that in the long-
345 term water availability would decline, thus the system would approach a threshold. Most other

346 participants took a more medium- term stance and therefore proximity to this threshold was considered
 347 somewhat close. Overall, there was rarely a disagreement between participants about threshold levels.
 348 In BE-Dairy, where a desk-study was performed, water quality and greenhouse gas emissions were
 349 perceived to be beyond acceptable levels set by European and regional policy makers. Farmers in BE-
 350 Dairy are likely to disagree with these externally determined thresholds. In SE-Poultry, DE-Arable&Mixed,
 351 ES-Sheep and NL-Arable, participants indicated that critical thresholds for economic viability differ from
 352 farm to farm. Hence, exceeding critical thresholds in these case studies may foremost imply the
 353 disappearance of economically less competitive farms from the farming system, rather than an
 354 immediate decline of the entire farming system performance.

355 *Table 2. Number of times function indicators were assessed being in a certain position relative to the perceived critical threshold*
 356 *(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 ¹ (n)
		Not close	Somewhat close	Close	At threshold 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

357 ¹For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from
 358 these case studies are hence not included in this table.

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

379
380

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 ¹ (n)
	Not close	Somewhat close	Close	At threshold 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

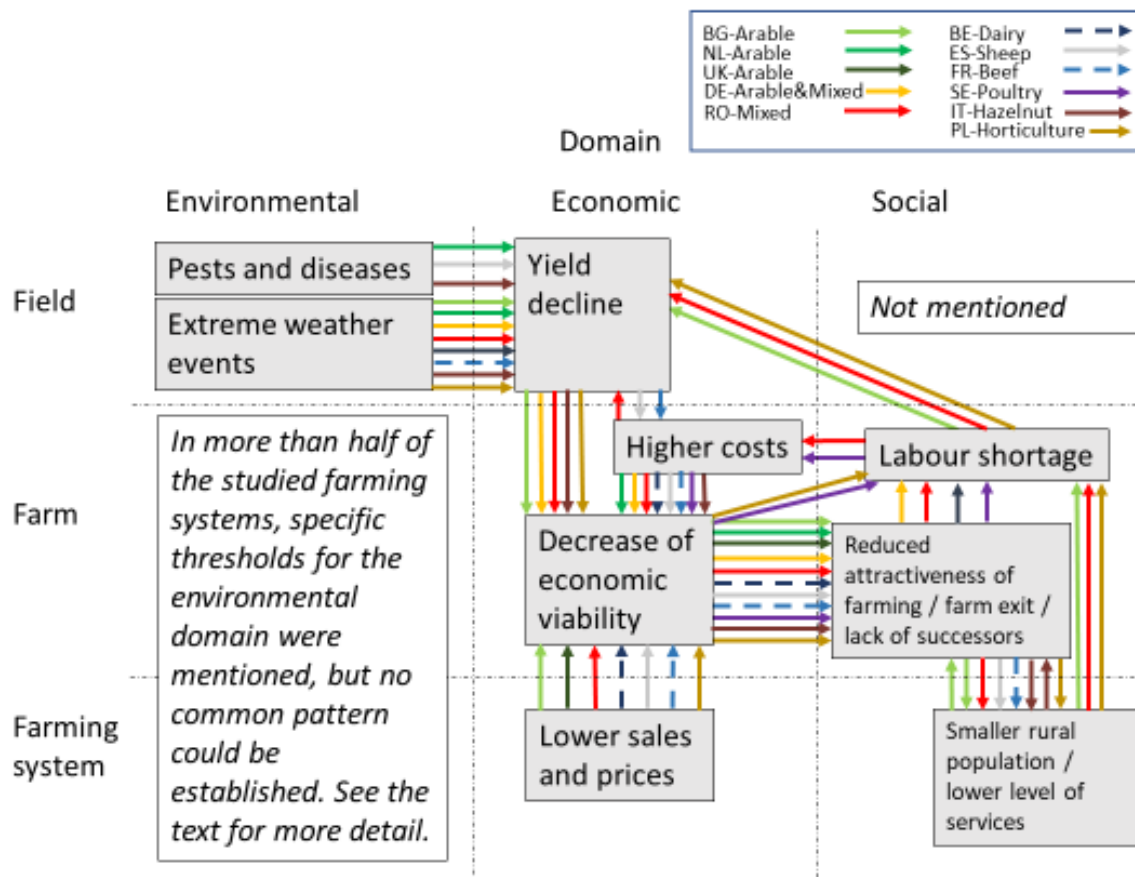
381 ¹For BE-Dairy and FR-Beef, desk studies were conducted instead of workshops and results from
382 these case studies are hence not included in this table.

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

403 Interacting thresholds and impact of exceeding these

404 In all case studies, interacting thresholds across level and/or domain were observed (Figure 1;
405 Supplementary Materials 3). More details on the interacting thresholds are presented in the
406 Supplementary Materials 3. Common interactions between critical thresholds occur between field-
407 environmental and field-economic, from field-economic to farm-economic, from farm-economic to farm-
408 social, from farm-social to farming system-social, and from farming system-social to farm-social (Figure
409 1). Generally, an environmental issue at field level, for instance, decreasing soil quality (NL-Arable, UK-
410 Arable), pest diseases (NL-Arable, IT-Hazelnut), wildlife attacks (ES-Sheep), or drought (DE-
411 Arable&Mixed, PL-Horticulture, RO-Mixed, BG-Arable) is so much of a shock or stress that it leads to
412 yields that are too low to sustain an adequate level of farm income (see Supplementary Materials 3). In a
413 majority of the farming systems, high input prices and decreasing output prices and sales further
414 diminish the farm income. Too low incomes at farm level were in all case studies resulting in reduced
415 attractiveness of farming, farmers quitting or the lack of finding a successor for the farm. In UK-Arable,
416 also reduced farmer happiness due to lack of recognition was mentioned as a reason for quitting a farm.
417 Farmers quitting their farm without having a successor was in multiple farming systems also considered
418 to contribute to a smaller rural population at farming system level (FR-Beef, ES-Sheep, RO-Mixed, BG-
419 Arable, IT-Hazelnut, PL-Horticulture; Figure 1). Interestingly, although socially oriented *function*
420 *indicators* and *resilience attributes* were less often formally included in the discussions, they eventually
421 appeared when explaining how challenges impact the farming system. Having less farms in the farming
422 system was also associated with a lower maintenance of natural resources and a less attractive
423 countryside (ES-Sheep, FR-Beef; Supplementary Materials 3). Interactions with critical thresholds in the
424 environmental domain at farm and farming system level were mentioned in a few other case studies. In
425 NL-Arable, at farm level in the environmental domain a narrow rotation in which starch potato is grown
426 every second year was expected to lead to increased pressure of plant parasitic nematodes (Figure
427 SM3.7). In UK-Arable, low income at farm level was expected to lead to declining soil health at field level
428 (Figure A5.11). In IT-Hazelnut and SE-Poultry, environmental regulations were expected to improve the
429 maintenance of natural resources at farming system level, but also to push farm income levels below a
430 threshold through increased costs (Figure SM3.6 and Figure SM3.10, respectively). Overall we observed
431 that environmental thresholds certainly feature, but differ in the level at which they play a role and in
432 what direction they evolve. In farming systems for which access to land is an issue (e.g. BE-Dairy, PL-
433 Horticulture), quitting of farmers may also be an opportunity, provided land becomes available on the
434 market for sale or to be leased. In ES-Sheep, quitting of farmers was experienced as a serious issue. In
435 IT-Hazelnut, the retention of young people on the farms was specifically mentioned as something that
436 could support the rural life and vice versa (Figure SM3.6). Both low economic viability at farm level and
437 low attractiveness of farming and a smaller rural population were considered to reduce the access to
438 labor at farm level in BG-Arable, SE-Poultry, PL-Horticulture, DE-Arable&Mixed, RO-Mixed, and ES-
439 Sheep. Access to labor in BG-Arable, PL-Horticulture and RO-Mixed was important for the continuation of
440 activities on farms, as lack of labor was expected to push yields below acceptable levels (Figure 1). In
441 BG-Arable lack of labor could be overcome by implementing new technologies, but this would require a
442 labor force with higher levels of education and qualification which is even harder to find. Lack of labor
443 was also expected to push production costs beyond critical thresholds in SE-Poultry and RO-Mixed.
444 Hence, in multiple systems, low economic viability, attractiveness of farming, rural depopulation and low
445 level of services at farming system level, and low access to labor seem to be part of a vicious cycle.

446



447

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

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

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

5. Discussion

470 Closeness to critical thresholds

471 All studied farming systems were perceived to be “close” or “at or beyond” at least one critical threshold
472 for *challenges*, *function indicators* or *resilience attributes* (Table 1-3). The actual state of the system may
473 be more or less close to a threshold than the participant’s perception. Obviously, for case studies that are
474 perceived to be “at or beyond” critical thresholds while still continuing business as usual, the actual state
475 must be at a different position than perceived. Still, perceived closeness can be seen as a clear stress
476 signal, indicating that change is needed, expected or even already experienced. An example refers to the
477 ban of crop protection products before alternatives are available. This stress signal could instigate a
478 study about a reasonable time to phase in/out regulations regarding the use of crop protection products
479 before actually implementing them. Perceptions of being close to or at critical thresholds also indicate
480 that, from the perspective of farming system actors, immediate action is needed to preserve the farming
481 system or guide it in its transition, thus avoiding a situation where sustainability is even lower. Looking
482 at multiple *challenges* puts individual *challenges* into perspective. To give an example, climate change
483 may be a problem causing regime shifts in many socio-ecological systems (Biggs et al., 2018), but for
484 the studied farming systems this is not the only *challenge* and often also not perceived to be the most
485 urgent, except for some arable systems (Table 1). This supports the notion that climate change should
486 be studied in the context of other drivers (Hermans et al., 2010; Mandryk et al., 2012; Reidsma et al.,
487 2015). At a global level, reducing anthropogenically induced climate change is, of course, urgent and
488 agricultural systems’ contribution to it must be reduced. Some challenges experienced by FS actors,
489 especially farmers, may also be implicitly caused by climate change; for instance changing legislation and
490 high input costs. For most of the farming systems in our study, climate awareness of some stakeholders,
491 such as conventional farmers, is however not likely triggered due to the impact of climate change on
492 their system per se. When deliberated in an appropriate manner with those stakeholders, new legislation
493 in the context of fighting climate change may however have considerably more effect regarding changing
494 stakeholder perceptions.

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

513 Defining critical thresholds seemed most difficult for *resilience attributes* (Table 3). According to Walker
514 and Salt (2012) it is actually impossible to determine critical thresholds for *resilience attributes* because
515 they all interact. However, *function indicators* also interact, but were easier to assess for participants. We
516 argue that difficulties in determining critical thresholds are probably more an indication of the perceived
517 redundancy of *resilience attributes* for system functioning: presence and contribution to resilience was
518 low to moderate according to stakeholders’ perceptions (Paas et al., 2021; Reidsma et al., 2020). This
519 could be related to a control rationale (Hoekstra et al., 2018), in which keeping a relatively stable

520 environment and improving efficiency is more important than increasing the presence of *resilience*
521 *attributes*. It should be noted, however, that participants often could indicate enabling conditions that
522 improve the *resilience attributes*. This could be an indication that participants are aware of the
523 importance of *resilience attributes*, but are in need for more concrete, locally adapted indicators that
524 represent the *resilience attributes*. In any case, suggesting improvements for *resilience attributes* could
525 be seen as an implicit acknowledgment by participants that building capacities for adaptation or
526 transformation is required.

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

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

556 Interaction of critical thresholds

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

563 In all farming systems, exceeding the critical threshold for economic viability at farm level affects the
564 attractiveness of the sector, the number of farm closures and the availability of farm successors, which
565 in turn in about half of the case studies contribute to lower availability of (qualified) labor and/or
566 depopulation, which finally can reinforce low economic viability. Hence, a vicious cycle is initiated. This
567 suggests that processes related to the economic and social domain can be driving dynamics of farming
568 systems as well as being reinforced by those dynamics. This potentially can turn a relatively slow social
569 process into a fast process. Social processes are therefore indeed important to monitor (Walker and Salt,

570 2012). This is already acknowledged in, for instance, in DE-Arable&Mixed, where participants emphasized
571 the attractiveness of the area, specifically regarding the development of infrastructure.

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

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

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

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

621 outside the farming system may help to create the enabling environment for innovations to improve
622 system functioning (Table A2).

623 Farm level responses to reaching critical thresholds of challenges

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

646

647 Implications for monitoring resilience

648 Social indicators

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

668 Monitoring resources

669 A common reflection in the discussion section so far is that having adequate system resources seems
670 essential for stimulating system *resilience attributes* and dealing with challenges. In cases of low farming
671 system resilience, building system resources may initially depend largely on external resources. This
672 implies a role for regional, national and EU government bodies, i.e. a pro-active role for actors in the
673 institutional domain outside the farming system. Given the tendency to focus on economic performance
674 at farm level, external resources in the form of economic subsidies should be increasingly conditional
675 regarding environmental and social functioning of the farming system. The emphasis on (accessible)
676 resources for building resilience is also acknowledged in several recent resilience frameworks (Duchek,
677 2020; Mathijs and Wauters, 2020), for instance with regard to knowledge and innovation systems (AKIS;
678 Mathijs and Wauters, 2020). To elaborate on the example of AKIS, we argue that, rather than only
679 monitoring and evaluating the amount of budget and the number of people that benefit from improved
680 AKIS (as is currently done in for instance the CMEF), also the amount of this resource and stakeholders`
681 access to it should be known and evaluated regularly. Similarly, other social and institutional resources
682 need to be monitored next to economic and environmental resources.

683

684 Reflection on methodology

685 Given the challenges regarding assessing and discussing critical thresholds in workshops (stakeholder
686 participation, differing stakeholder opinions, differing metrics, farm-specificity of thresholds, expert
687 judgments of case study researchers on proximity to those thresholds), all identified critical thresholds
688 could be seen as "Thresholds of potential concern" (TPCs; Walker and Salt 2012 citing Biggs and Rogers,
689 2003). In our case these TPCs would express the concerns of a selection of farming system stakeholders.
690 TPCs can be seen as a set of evolving management goals that are aimed at avoiding critical thresholds
691 that are expected, e.g. from experiences in other systems, but are not known. In case thresholds are
692 considered beforehand as TPC's, Q-methodology (McKeown and Thomas, 2013) may be an interesting
693 participatory method to define which TPC deserves most priority. Estimating main functions of a system
694 by assessing critical thresholds as TPCs, reduces the presence of clear sustainability goals. This makes
695 the threshold assessment less dependent on externally determined values and criteria than most
696 sustainability assessments (see e.g. Binder et al. 2010). Implicitly, the goal is to avoid a decline in
697 sustainability and resilience levels of the current system, which may give the participating system actors
698 the trust to provide details, expose interrelatedness between sustainability domains, and also come up
699 with solutions. Regarding the latter, it should be noted that avoiding exceedance of critical thresholds
700 does not automatically imply that a system is steering away from mediocre performance. This is why
701 after assessing critical thresholds, participants should also be stimulated to think about adaptations to
702 improve their system to desired sustainability and resilience levels (Paas et al. Submitted). Be it by
703 steering away or actual exceeding critical thresholds to arrive at higher sustainability levels. Paas et al.
704 (Submitted) suggest a back-casting approach, but other solution-oriented methods such as participatory
705 multi-criteria decision analysis may also be appropriate (Belton and Stewart, 2002). In any case, starting
706 with a threshold assessment before solution-oriented participatory methods may create path-
707 dependency, resulting in adaptations that lead to a reconfirmation of the current system where a
708 transformation might actually be more appropriate. This path-dependency is likely to be reinforced by
709 only inviting participants from within the farming system. Farming system actors are for instance
710 probably biased regarding depopulation and a loss of attractiveness of the rural area, as it is related to
711 farm closure. Considering the possibility that the closure of individual farms could be good for the
712 farming system as a whole might go beyond the mental models of some farming system actors.
713 Participatory methods involving so-called "critical friends" that have no direct stake in the system might
714 help to overcome this obstacle (Enfors-Kautsky et al., 2018). Involving external actors is especially
715 required in unsustainable systems that persist through the agency of only a subset of stakeholders.

716 It should be noted that critical thresholds are never static as they depend on the context (Kinzig et al.,
717 2006; Resilience Alliance, 2010). The need for labor for instance depends on the level of automatization
718 in agriculture. Critical thresholds may change because of slowly changing variables (Kinzig et al. 2006

719 citing Carpenter et al. 2003), which is also acknowledged in this study by presenting interacting
720 thresholds across levels and domains in multiple case studies. Different domains could be addressed by
721 including a variety of social, economic, institutional and environmental *challenges, function indicators*
722 and *resilience attributes*. Using the framework of Kinzig et al. (2006) forced in particular researchers in
723 some case studies to reflect on critical thresholds in the social domain, while focus of participants was
724 more on economic and environmental processes. The framework of Kinzig et al. (2006) can hence show
725 where knowledge of stakeholders is limited. This is an asset as exposing the limits of local knowledge is
726 often lacking in participatory settings (Mosse, 1994). Explicitly adding the institutional domain and a
727 level beyond the farming system to the framework of Kinzig et al. (2006) may further reveal the limits of
728 knowledge and improve the understanding of farming system dynamics. To further stimulate co-
729 production of knowledge, the figures with interacting thresholds (e.g. Figure 1) could be fed back to
730 farming system stakeholders in a follow-up workshop. In addition, farming system actors could be
731 stimulated to think about representative indicators for resilience attributes. These representative
732 indicators could add local meaning and thus improve stakeholders' understanding and assessment of the
733 resilience attributes and resilience mechanisms (see also Paas et al. submitted).

734 Becoming aware about a threshold can help reducing the likelihood of exceeding one (Resilience Alliance,
735 2010). Indeed, assessing critical thresholds may bring the awareness that is needed to move away from
736 the conditions that have caused them. Participatory methods that are more specifically aimed at social
737 processes could bring about awareness of system actors. However, interrelatedness with processes in
738 other domains are consequently likely to be lost out of sight. Still, specific attention for social processes
739 in the conducted workshops can improve the integrated nature of the assessments, for instance by pre-
740 selecting at least one indicator related to a social function and a resilience attribute related to social
741 conditions. For some case studies in this study, this would imply a suggestion that new functions and
742 system goals are needed. Although top-down, this could initiate the process of system actors picking up
743 this signal as being valuable (belief formation) and the process of redirecting the system as a whole to
744 an alternative state (conversion; Biesbroek et al. 2017).

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

758

6. Conclusion

760 In our participatory approach, all 11 studied systems in the European Union were perceived to be “close
761 to”, “at or beyond” at least one identified critical threshold (Table 1, 2 & 3). In particular, critical
762 thresholds in the economic domain were considered to be (almost) reached. This could explain the
763 economic orientation of farming system stakeholders and the current CMEF of the CAP. Overall, a strong
764 decline in system performance was expected if critical thresholds would be exceeded. We conclude that
765 concern for exceeding critical thresholds is justified, even though precise determination of a threshold
766 position based on a participatory approach is difficult. Stakeholder perceptions on critical thresholds
767 provide useful information as they serve as a stress signal and can be used as a starting point for a
768 dialogue with farming system actors. We suggest that critical thresholds could be seen as a “thresholds
769 of potential concern” for which management and policy goals may be developed. For instance, policies to
770 attract more agricultural workers to an area to avoid a shortage of labor. Those policy and management
771 goals should include the development of metrics that provide rigorous information on that specific
772 threshold. The analysis of critical thresholds provides a basis for early thinking about possible alternative
773 configurations of the systems. In this regard, the results can be used to reflect collectively about farming
774 system trajectories, as to system functions and the often-competing goals of the different stakeholders.
775 Therefore, the results of the analysis can be used to develop a contextualized, shared vision and to
776 identify, within each farming system of interest, where to focus regarding increasing the resilience and
777 sustainability of the farming system.

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

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

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