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## Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive capacity of temperate agricultural systems

Manon Dardonville, Christian Bockstaller, Olivier Therond

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1     **Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive**  
2   **capacity of temperate agricultural systems**

3

4     **Authors**

5     Manon DARDONVILLE<sup>1,2\*</sup>, Christian BOCKSTALLER<sup>1</sup>, Olivier THEROND<sup>1</sup>

6     <sup>1</sup> Université de Lorraine, INRAE, LAE, F-68000 Colmar, France

7     <sup>2</sup>Agrosolutions, 75782, Paris, France

8     \*Corresponding author, manon.dardonville@inrae.fr

9     **Abstract**

10    Vulnerability, resilience, robustness and adaptive capacity are four key concepts that  
11    characterize dynamics of systems when disturbance occurs. However, rendering them  
12    operational for agricultural systems using an approach to quantify dynamics remains a  
13    challenge. To provide a synthesis of studies that attempt to do so, we systematically reviewed  
14    scientific articles that quantified the vulnerability, resilience, robustness or adaptive capacity of  
15    agricultural systems in temperate zones. Our semi-automatic selection based on the Web of  
16    Science and textual visualization with VOSviewer enabled us to identify only 53 articles. They  
17    focus mainly on the effect of climate change on yield dynamics but are diverse in terms of  
18    agricultural systems (organizational levels, type of production), methods, criteria of dynamics  
19    (e.g. trend, variability, recovery, resistance) and explanatory factors tested (e.g. diversity,  
20    intensification, management). Studies that refer to one of these four investigated concepts use

21 criteria of dynamics interchangeably to analyze dynamics, confirming the fuzzy definition of  
22 these concepts. While a wide range of methods are used, most studies focus on only one  
23 performance attribute, mainly yield, which hides the multifunctionality of agriculture. However,  
24 half of the studies use multiple criteria of dynamics to describe them in a multifaceted manner.  
25 We highlight that combining short-term and long-term studies is rare, and social and ecological  
26 explanatory factors are rarely tested. Identifying key generic explanatory factors (properties)  
27 that determine vulnerability, resilience, robustness or adaptive capacity requires identifying a  
28 shared core set of factors to investigate systematically. We show that this set of properties  
29 could be identified through cross-sectional analysis of results of expert-based and quantitative  
30 assessments.

## 31 **1. Introduction**

32 Agricultural systems are facing increasing climatic and economic disturbances (IPCC, 2013;  
33 Wright, 2011). Characterizing agricultural systems able to manage shocks (e.g. economic crisis)  
34 or disturbance trends (e.g. increasing temperature) while ensuring their essential functions  
35 remains an issue (Tendall et al., 2015). Vulnerability, resilience, robustness and adaptive  
36 capacity (VRRAC, Table 1) are key concepts used to characterize dynamics when disturbance  
37 occurs (Gallopín, 2006; Mumby et al., 2014). These concepts are related, and their definitions  
38 and overlaps remain an open debate (Miller et al., 2010; Mumby et al., 2014; Turner, 2010;  
39 Urruty et al., 2016; Wu, 2013). Although developed and discussed in multiple disciplinary  
40 communities, they remain challenging to operationalize (i.e. to translate into an operational  
41 evaluation approach) (Callo-Concha and Ewert, 2014; Ge et al., 2016, 2016; M. Li et al., 2019;

42 Martin et al., 2017; Quinlan et al., 2016; Urruty et al., 2016). For example, how to evaluate  
 43 resilience is currently being debated (Allen et al., 2019; Grafton et al., 2019; Pimm et al., 2019).

44 Table 1. Definitions of the four concepts investigated.

<b>Concepts</b>	<b>Definitions</b>	<b>Reference</b>
<b>Resilience</b>	<i>“the ability to ensure the provision of the system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses”</i>	Meuwissen et al. (2019)
<b>Vulnerability</b>	<i>“the degree to which a system is harmed due to disturbances or stress”</i>	Turner et al. (2003)
<b>Robustness</b>	<i>“the ability to maintain desired levels of system outputs, [...] despite the occurrence of disturbances”</i>	Urruty et al. (2016)
<b>Adaptive capacity</b>	<i>“the ability of a system to prepare for stresses and changes in advance or adjust and respond to the effects caused by the stresses”</i>	Smit and Pillifosova (2003)

45 In the literature, two approaches for addressing quantitatively the operationalization of VRRAC  
 46 frameworks can be identified (AminShokravi and Heravi, 2020; Prosperi et al., 2016; Tendall et  
 47 al., 2015; Zhang et al., 2019). First, based on expert opinion or a literature review, a set of  
 48 system properties (characteristics) is considered a set of key factors that determine VRRAC  
 49 (Biggs et al., 2012; Bonisoli et al., 2018; Cabell and Oelofse, 2012; Gillespie-Marthaler et al.,  
 50 2019; Prosperi et al., 2016; Quinlan et al., 2016; Wiréhn et al., 2015). Here, VRRAC is considered  
 51 the “sum of a range of characteristics” (Douxchamps et al. 2017). For example, Cabell and  
 52 Oelofse (2012), in a qualitative review, identified 13 properties (called “behavior-based  
 53 indicators”) of agroecosystem resilience (*Table 4*). In another example, based on thorough  
 54 expert knowledge and a qualitative literature review, Biggs et al. (2012) defined three system  
 55 properties (diversity and redundancy, connectivity, and slow variables and feedbacks) and four

56 management principles (consider the complex adaptivity of socio-ecological systems; and  
57 enhance learning, participation, and polycentric governance) that promote the resilience of  
58 ecosystem services in social-ecological systems. These two key studies are the foundation for  
59 recent studies that define conceptual frameworks (Meuwissen et al., 2019; Stockholm  
60 Resilience Center, 2015) or identify pre-defined properties of VRRAC (Diserens et al., 2018;  
61 Gillespie-Marthaler et al., 2019; Martin et al., 2019; Nyström et al., 2019). Douxchamps et al.  
62 (2017) mentioned that the study of Cabell and Oelofse (2012) remains innovative due to the  
63 indicators they developed to integrate aspects of social, ecological and system connectivity and  
64 diversity. In this approach, VRRAC is operationalized by estimating levels of predefined  
65 properties (e.g. diversity, connectivity) (e.g. in Allen et al., (2018); Altieri et al., (2015); Brooks et  
66 al., (2005); Corobov et al., (2013); Dalsgaard et al., (1995); Schmitt et al., (2017); Žurovec et al.,  
67 (2017)). In agronomy, however, this *predefined-properties approach* can suffer from little  
68 experimental evidence for the properties used (Dardonville et al., 2020; Gil et al., 2017). The  
69 properties rely mostly on experts' viewpoints (Urruty et al. 2016) or transposition of proven  
70 properties of VRRAC from one scientific field to another (e.g. from ecology to agronomy  
71 (Peterson et al., 2018)). This is usually the case when considering that diversity is a property of  
72 resilience of agricultural systems, while the experimental evidence remains unclear (Gil et al.,  
73 2017). The second approach is based on analysis of (i) observed or simulated dynamics of one or  
74 more functions of a studied system that is experiencing disturbances and (ii) relationships  
75 between system dynamics and multiple system characteristics to identify key explanatory  
76 factors of its dynamics (Brzezina et al., 2016; Nelson et al., 2019). In this *dynamics-analysis*  
77 *approach*, performance attributes characterize the functions of systems to maintain

78 (Meuwissen et al., 2019). For example, yield performance characterizes the food production  
79 function of agricultural systems. Evaluation criteria, such as recovery or variability, are used to  
80 summarize the dynamics of the performance attribute quantitatively (Barkaoui et al., 2016;  
81 Grafton et al., 2019; Martin et al., 2017 (i.e. “characterize systems’ behavior” in Müller (2005)).  
82 Analysis of relationships between these VRRAC criteria of dynamics and system characteristics  
83 allows endogenous (eg. crop diversity, Piedra-Bonilla et al. (2020)) or exogenous (eg. policies,  
84 Singh and Dhadse (2021)) explanatory factors of VRRAC to be identified. These factors provide  
85 insights into pathways for improving resilience (Coomes et al., 2019; Meuwissen et al., 2019).  
86 Based on observed or simulated data, this approach can provide “objective” information about  
87 properties of VRRAC. Once properties of VRAAC are identified (i.e. explanatory factors  
88 supported by evidence), they can be used as proxies of resilience in the *predefined-properties*  
89 *approach* (Tendall et al., 2015). For example, if *dynamics analysis* shows that crop diversity  
90 enhances resilience in agricultural systems, then resilience can be evaluated as a function of  
91 crop diversity. In short, the properties that determine VRRAC are pre-determined in the  
92 *predefined-properties* approach, while they are outcomes of assessments in the *dynamics-*  
93 *analysis* approach.

94 While the first approach is widely known and disseminated, the second approach is applied  
95 much less due to the complexity of the mathematical methods involved and the data or models  
96 required (Brzezina et al., 2016; Callo-Concha and Ewert, 2014a; Coomes et al., 2019; Gillespie-  
97 Marthaler et al., 2019; Prospero et al., 2016). However, the *dynamics-analysis* approach is  
98 necessary to identify objectively the level and properties of VRRAC systems, based on  
99 quantitative analysis of observed or predicted dynamics of stressed systems. Once identified

100 well, these properties can be used in the *predefined-properties* approach. In other words, the  
101 second approach can provide the first one with well-identified properties.

102 To our knowledge, no exhaustive review of studies with this second approach exists in  
103 agricultural research (but see the review of Donohue et al. (2016) in ecology). The few reviews  
104 available focus on only one concept and one explanatory factor (resilience and diversity in Gil et  
105 al., 2017), a qualitative and non-exhaustive analysis of the literature (Urruty et al., 2016) or only  
106 a small set of both qualitative and quantitative studies (n=10 in Callo-Concha and Ewert, 2014).  
107 An exhaustive synthesis of the quantitative *dynamics-analysis* approach that considers the four  
108 parent concepts (V, R, R and AC) is needed. It would help disseminate and thus facilitate the use  
109 of available methods and to identify key explanatory factors of VRRAC (and feed the *predefined-*  
110 *properties* approach). Ultimately, it would provide future researchers with the main  
111 characteristics of past studies and warnings and tips for future studies.

112 To this end, we conducted a systematic review of studies that had used a *dynamics-analysis*  
113 approach of VRRAC of agricultural systems (crop and livestock systems). It was based on a  
114 generic query and semi-automated sorting and focused on agricultural systems of temperate  
115 climatic zones. We focused on studies of temperate zones to address ecological and socio-  
116 economic systems that function in a similar manner (Gil et al., 2017; Dardonville et al., 2020).

117 Through this review we sought to address the following research questions. What are the  
118 natures of the agricultural systems and disturbances studied most by this research community?  
119 Which VRRAC concepts are used most in these studies? Which methods are used to evaluate  
120 VRRAC quantitatively? Which performances have had their dynamics studied in the face of  
121 disturbance? What criteria of dynamics are used to describe the dynamics of the performances?

122 Are the criteria associated with specific concepts? What explanatory factors are tested to  
123 determine whether they are properties of VRRAC? We conclude our review by discussing  
124 shortfalls in the reviewed studies and research needs, providing recommendations for future  
125 studies and illustrating how key properties of VRRAC could be identified by comparing and  
126 coupling the two VRRAC analysis approaches (i.e. *predefined-properties- and dynamics-analysis*).

127 Hereafter, we present the methodology used to select the studies reviewed, the results that  
128 answer the research questions and the discussion, which provides recommendations to other  
129 researchers.

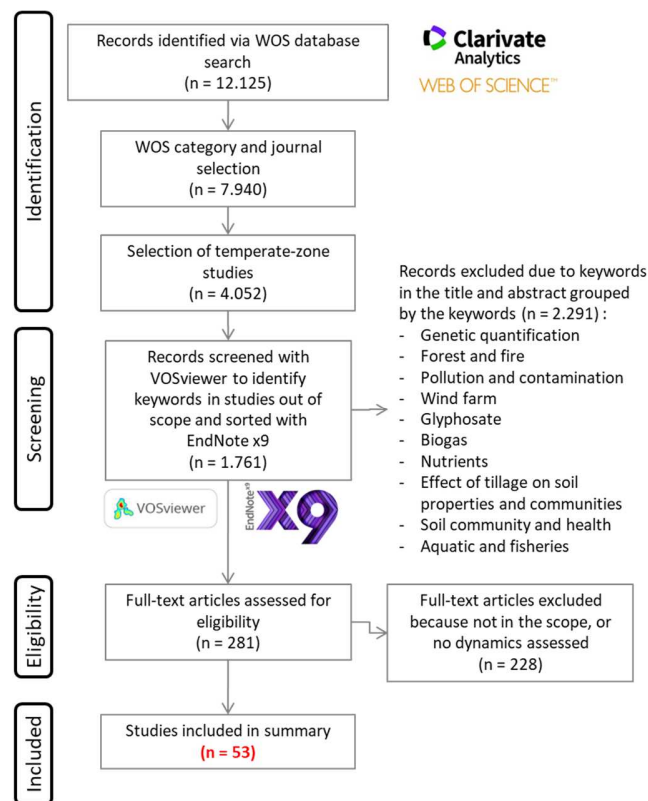
## 130 **2. Methodology**

131 To select scientific articles that quantitatively analyzed dynamics of the VRAAC of agricultural  
132 systems, we followed the PRISMA protocol for systematic review (Moher et al., 2015). We ran  
133 the query in the ISI Web of Science Core Collection database (WoS,  
134 <http://www.isiknowledge.com>) to identify peer-reviewed English articles and reviews published  
135 from 1956 (the beginning of the collection) to September 2020. We focused on temperate  
136 studies that analyzed agricultural system dynamics from field to regional levels without  
137 considering dynamics of communities of organisms. The query was organized in three sections  
138 to select articles that addressed at least one of the VRRAC concepts, agricultural crop and  
139 livestock systems and quantitative assessment. Accordingly, the query was:

140 *Topic = ((vulnerabilit\* OR resilien\* OR robustness OR "adaptive capacity") AND (agri\* OR agro\**  
141 *OR crop\* OR farm\* OR grass\* OR pastor\*) AND (indicator\* OR evaluat\* OR assess\* OR*  
142 *quantitativ\* OR quantif\* OR model\* OR simulat\* OR decrease OR increase))*



143 The WoS Core Collection database was chosen because it encompasses a variety of research  
 144 fields, such as those in the natural sciences, but also in the social sciences, which could have  
 145 performed the studies we sought.



146

147 *Figure 1. Description of the method used to select and sort articles according to the PRISMA protocol for*  
 148 *a systematic review (Moher et al., 2015).*

149 The query identified 12,125 articles (Figure 1). Then, using the advanced search function of the  
 150 WoS, we excluded off-topic journals, WoS categories and articles that involved non-temperate  
 151 zones, based on mapping by Kottek et al. (2006). Since the remaining corpus was still large  
 152 (7940 articles), we performed bibliometric analysis to detect off-topic articles semi-  
 153 automatically based on their lexical fields. To do this, like Wang et al. (2020) and Obiang Ndong  
 154 et al. (2020), we first used the bibliometric analysis and mapping software VOSviewer to

155 visualize the co-occurrence of terms (at least  $n = 10$  times) in the title and abstract of all the  
156 articles (Supplementary material 1). From the resulting bibliometric network, we identified  
157 potential off-topic lexical fields, such as soil community dynamics, soil health, plant or animal  
158 genetics, fisheries and obvious non-agricultural production (i.e. forests) (Figure 1). Keywords in  
159 these off-topic lexical fields were then used in the bibliographical management software  
160 EndNote X9 to select potential off-topic articles. Next, the title and abstract of these articles  
161 were read to identify which ones were truly off-topic and to ensure that relevant articles were  
162 not excluded. After this screening process, 1761 articles remained. One reviewer read all titles  
163 and abstracts of the articles and identified 281 articles within our study's scope. Finally, one  
164 reviewer read the 281 articles deeply and identified the final subset of 53 articles within the  
165 scope of the review. A second reviewer read a random sample of 10% of the 281 articles, and  
166 the result was 100% agreement between the two reviewers. Articles that did not assess  
167 temporal dynamics of an agricultural system quantitatively were excluded (e.g. those that  
168 assessed only one year of production).

169 We described each of the 53 studies using the analytical framework defined by Dardonville et al.  
170 (2020), which combined recommendations of Allen et al. (2016), Carpenter et al. (2001),  
171 Meuwissen et al. (2019), Müller et al. (2016) and Peterson et al. (2018). Thus, for each study, we  
172 specified:

173 1. The nature of the agricultural system studied (VRRAC "of what"): the type of production  
174 (e.g. annual crops, perennial crops) and the level of organization (e.g. field, farm, region)

175 2. The exogenous disturbance that affects the system (VRRAC "to what disturbance"),  
176 which corresponds to a shock or long-term pressure

177 3. The spatial and temporal extent and resolution of the disturbance (VRRAC "when and  
178 where")

179 4. The performance attribute (VRRAC "for which performance attribute(s)") that is  
180 important to maintain over time and whose dynamics are examined (e.g. yield, income)

181 5. The criterion that summarizes one aspect of the dynamics of the performance attribute  
182 (e.g. variability, recovery, resistance)

183 6. The explanatory factors tested that could explain the dynamics observed and thus the  
184 VRRAC (VRRAC "due to which explanatory factors")

185 The information collected was collated in a dedicated database. Terminology was standardized  
186 for each exogenous disturbance, performance attribute, criterion of dynamics and explanatory  
187 factor (see Supplementary material 2 for an aggregation tree of explanatory factors). The  
188 database contained 1016 individual results that correspond to a direction (positive, negative or  
189 neutral) of the effect of one explanatory factor on one performance attribute, described by one  
190 criterion of dynamics for one system experiencing one disturbance (explanatory factor ×  
191 performance attribute × criterion of dynamics × system × disturbance). The number of results  
192 per article varied greatly (1-80), since one study could test several explanatory factors for  
193 several performance attributes or criteria of dynamics. VRRAC concepts (e.g. "resilience" in

194 Lake (2013)) used in each article were classified, and when articles used multiple concepts (e.g.  
195 “resilience” and “resistance” in Isbell et al. (2015)), we recorded each specific combination.

### 196 **3. Results**

#### 197 **3.1. Scope, farming systems and organization level**

198 Only 53 articles from the WoS database were identified that had performed quantitative  
199 *dynamics analysis* of a temperate agricultural system in the field of VRRAC assessment. 66% of  
200 the articles have been published recently, since 2015 (Supplementary material 3).

201 The articles reviewed focus mainly on the effect of climate disturbance (79% of articles) on  
202 agronomic yield (67% of articles) and economic attribute performances (net return in 15% of  
203 articles) of grasslands (30% of articles) and crop systems (43% of articles) at field (45% of  
204 articles), farm (33% of articles) and regional (18% of articles) levels (Supplementary material 4).

205 Although these articles are relatively focused on climate disturbance and yields, they consider a  
206 variety of organization levels and types of production.

#### 207 **3.2. Concepts used**

208 The articles reviewed refer explicitly to the concepts of resilience (30 articles, as defined by  
209 Folke, (2006); Holling, (1973); Lake, (2013); Rist et al., (2014); Walker et al., (2004); Walker and  
210 Meyers, (2004); Ingrisich and Bahn, (2018)), vulnerability (16 articles, as defined by Adger,  
211 (2006); McCarthy et al., (2001); Smit and Wandel, (2006)), adaptive capacity (12 articles, as  
212 defined by McCarthy et al. (2001); Parry et al. (2007)) and/or robustness (3 articles, as defined  
213 by Stelling et al. (2004); Urruty et al. (2016)), but also, additionally, to stability (7 articles, May,  
214 (1975)), sustainability (3 article) and resistance (7 articles, as defined by Pimm (1984)) (Figure 4).

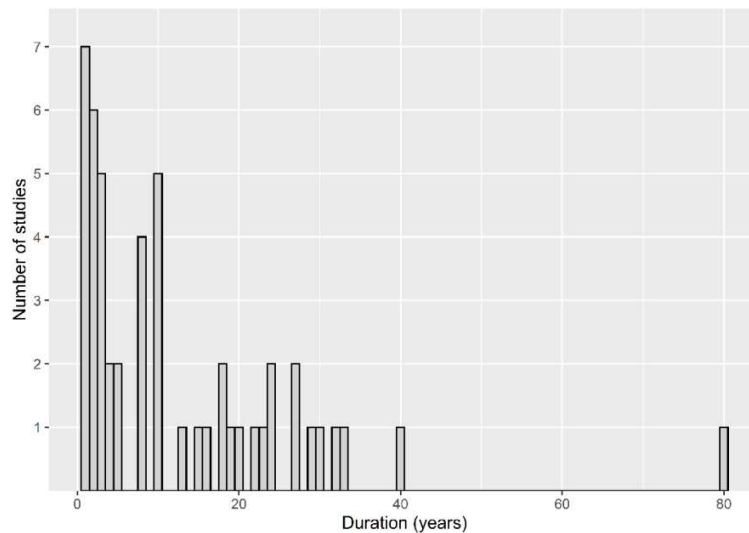
215 Here, “resistance” refers to a concept and not to a criterion that describes the dynamics of the  
216 attribute. The concepts of vulnerability, resilience and robustness are rarely combined; for  
217 example, only one article combines vulnerability and resilience (Figure 4), confirming that they  
218 are used by different scientific communities. However, resilience is often combined with the  
219 other concepts (16 out of 30 articles), mainly with resistance or stability. In contrast,  
220 vulnerability is often combined with adaptive capacity (9 out of 16 articles). Robustness is  
221 mentioned only alone (Figure 4).

### 222 3.3. Methods to measure and assess dynamics and test explanatory factors

223 Many methods are used to address the dynamics of agricultural systems and test potential  
224 explanatory factors. Methods can be distinguished by how they (i) measure dynamics (e.g.  
225 source of data, protocols), (ii) assess dynamics (criteria and mathematical indicators) and (iii)  
226 identify explanatory factors for these dynamics.

227 Dynamics are measured from experimental studies, existing observed data or simulations.  
228 Twenty articles are based on long-term field experiments (e.g. Barkaoui et al., 2016; Hoover et  
229 al., 2014; Macholdt et al., 2020; Mäkinen et al., 2015)), while 22 articles use an existing or  
230 constituted database (e.g. FADN in Bardaji and Iraizoz, (2015); Reidsma and Ewert, (2008);  
231 Zampieri et al., (2020a)). Eleven articles use observed data on disturbances (e.g. climate, prices)  
232 as input data for simulation models, such as a grassland model (Sabatier et al., 2015), a farming  
233 system model (Martin and Magne, 2015) and an agent-based model (Bitterman and Bennett,  
234 2016; Brunner and Grêt-Regamey, 2016; Grêt-Regamey et al., 2019; van Strien et al., 2019). The  
235 temporal extent and resolution of the studies range from 1-80 years (Figure 2) with a 1 day to 1-

236 year time step. The spatial extents of the studies cannot be compared because they range from  
237 1 m<sup>2</sup> plots at several sites in the world to a few dozen farms within a European Union NUTS2  
238 region. Only one article studies the impact of the spatial extent of a disturbance (Mechler et al.,  
239 2010).



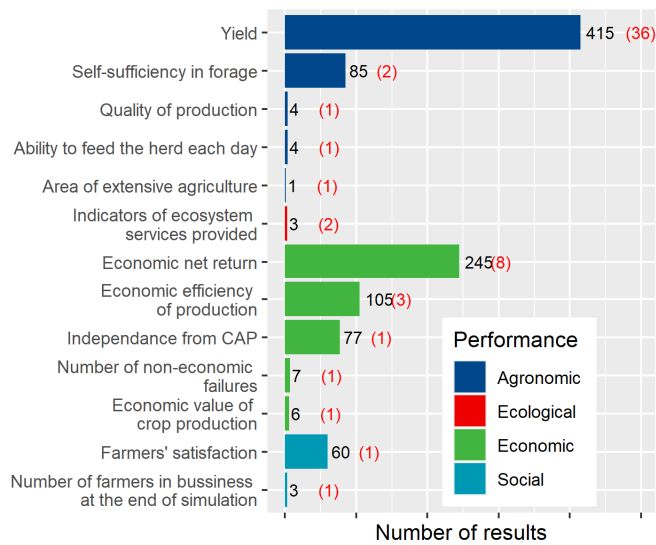
240  
241 *Figure 2. Temporal extent (duration) of analysis in each study reviewed (years).*

242 Dynamics are assessed using a variety of methods, such as de-trended time series criteria of  
243 dynamics (Craven et al., 2018; Zampieri et al., 2020b, 2020a), general linear regression models  
244 (Reidsma et al., 2009a), mixed linear or logit models (Bouttes et al., 2019; Macholdt et al., 2020;  
245 Martin et al., 2017; Perrin et al., 2020; Seo, 2010), marginal utility (Brunner and Grêt-Regamey,  
246 2016) and eigenvalues of the variance-covariance matrix (Fletcher and Hilbert, 2007). Some  
247 studies (5 out of 53) performed only a sensitivity analysis (i.e. they focus only on dynamics of  
248 system performance attribute(s) without analyzing explanatory factor(s)). The remaining articles  
249 use two main types of methods to identify explanatory factors. Twenty articles use statistical  
250 methods, such as linear mixed models, to estimate relationships between potential explanatory

251 factors and the criteria of dynamics (e.g. effect of intensification on productivity dynamics in  
252 Bouttes et al. (2018); Martin et al. (2017)). In contrast, 33 articles use methods allowing to  
253 estimate the effect of potential explanatory factors on the relation between criteria and  
254 disturbance variables (e.g. effect of intensification on the effect of climate change on yield  
255 dynamics in Bardaji and Iraizoz (2015); Reidsma et al. (2009b) or effect of species community  
256 changes on the effect of flooding on biomass level in Oram et al., (2020)).

#### 257 3.4. Performance attributes and criteria to describe their dynamics

258 As mentioned, the articles we reviewed focus mainly on analyzing dynamics of agronomic yield  
259 (67% of articles, 40% of results) and economic net return (15% of articles, 24% of results, *Figure*  
260 *3*). The remaining 16% of articles consider other attributes, such as agronomic (e.g. product  
261 quality) or ecological performance (3% of articles). Only 13% (n=7) of articles consider multiple  
262 attributes (usually agronomic and economic performance) in a multi-performance approach  
263 (Table 2). Two articles study social performance attribute as farmers' satisfaction or continuity  
264 of farming business (Bitterman and Bennett, 2016; Perrin et al., 2020). In an original approach,  
265 Brunner and Grêt-Regamey (2016) use an attribute that aggregates four ecosystem services, but  
266 they do not discuss them separately.



267

268 *Figure 3. Number of results (in black) and articles (in red) by performance attribute whose*  
 269 *dynamics are studied when disturbance occurs.*

270 We identify ten criteria of dynamics of performance attributes used in the articles reviewed:  
 271 trend (15 articles, 35% of results), level (19 articles, 27% of results), variability (as defined by  
 272 Pimm (1984), 17 articles, 16% of results), trend (14 articles, 35% of results), resistance  
 273 (difference between pre-disturbance and post-disturbance level, as defined by Pimm (1984), 15  
 274 articles, 5% of results), elasticity (intensity and direction of change, 2 articles, 3% of results),  
 275 frequency that a threshold was exceeded (as defined by Walker et al. (2004), 4 articles, 3% of  
 276 results), probability of exceeding a given threshold (as defined by Walker et al. (2004), 6 articles,  
 277 2% of results, e.g. high yield), time required to recover to the pre-disturbance level ('resilience'  
 278 of Pimm (1984), 5 articles, 2% of results), and distance to a stable state (as defined by Ludwig et  
 279 al. (1997), 4 articles, 1% of results, e.g. eigenvalues of the variance-covariance matrix), distance  
 280 to a threshold (1 article, 2% of results), (Table 1). Most of these criteria are described by Meyer  
 281 et al. (2018) and Scheffer et al. (2015).



Table 2. Summary of the criteria used to describe dynamics in the articles reviewed

Criterion	Example of indicator	Reference	Articles that use the criterion	Number of articles (and results)
<b>Level</b>	Mean	-	(Bouttes et al., 2018, 2019; Castañeda-Vera and Garrido, 2017; Ferreyra et al., 2001; Gaudin et al., 2015; Isbell et al., 2015; Leonhardt et al., 2013; J. Li et al., 2019; M. Li et al., 2019; Martin et al., 2017; Perrin et al., 2020; Pfisterer and Schmid, 2002; Prieto et al., 2015; Redhead et al., 2020; Reidsma and Ewert, 2008; Seo, 2010; Urruty et al., 2017; Yang et al., 2019; Zavalloni et al., 2008)	19 (284)
<b>Variability</b>	Residuals of linear regression	Pimm (1984)	Bouttes et al., 2018; Castañeda-Vera and Garrido, 2017; Cociu and Cizma, 2015; Craven et al., 2018; Gaudin et al., 2015; Isbell et al., 2015; Khumairoh et al., 2018; Leonhardt et al., 2013; M. Li et al., 2019; Macholdt et al., 2020; Mäkinen et al., 2015; Martin et al., 2017; Prieto et al., 2015; Redhead et al., 2020; Reidsma et al., 2009a; Reidsma and Ewert, 2008; Sneessens et al., 2019; Yang et al., 2019	17 (163)
<b>Trend</b>	Slope of linear regression	-	(Bardaji and Iraizoz, 2015; Bouttes et al., 2018, 2019; Cociu and Cizma, 2015; Di Falco and Chavas, 2008; Kahiluoto et al., 2014; Leonhardt et al., 2013; J. Li et al., 2019; Martin et al., 2017; Matsushita et al., 2016; Perrin et al., 2020; Prieto et al., 2015; Reidsma et al., 2009b, 2009a, 2010; Salvati, 2010; Urruty et al., 2017)	15 (365)
<b>Resistance</b>	Difference between pre-disturbance and post-disturbance	Pimm (1984)	Brunner and Grêt-Regamey, 2016; Carlsson et al., 2017; de la Rosa et al., 2000; Di Falco and Chavas, 2008; Hoover et al., 2014; Isbell et al., 2015; Martin and Magne, 2015; Mechler et al., 2010; Oram et al., 2020; Pfisterer and Schmid, 2002; Redhead et al., 2020; Seo, 2010; Stampfli et al., 2018; Vetter et al., 2020; Zavalloni et al., 2008	15 (51)
<b>Recovery</b>	Time or ratio (pre/post) to return to the pre-disturbance level	'resilience' of Pimm (1984)	Barkaoui et al., 2016; Carter and Blair, 2012; Di Falco and Chavas, 2008; Isbell et al., 2015; J. Li et al., 2019; Matsushita et al., 2016; Oram et al., 2020; Pfisterer and Schmid, 2002; Sneessens et al., 2019	9 (33)
<b>Distance to a stable state</b>	Eigenvalue of the variance-covariance matrix	Ludwig et al. (1997)	Chavas and Di Falco, 2017; Fletcher and Hilbert, 2007; Grêt-Regamey et al., 2019; van Strien et al., 2019	4 (5)
<b>Distance to a threshold</b>	Difference between a desired level and actual level	-	Sneessens et al., 2019	1 (19)
<b>Probability of exceeding a threshold</b>	-	Walker et al. (2004)	Ferreyra et al., 2001; Gaudin et al., 2015; M. Li et al., 2019; Macholdt et al., 2020; Zampieri et al., 2020b, 2020a	6 (26)
<b>Frequency that threshold was exceeded</b>	-	Walker et al. (2004)	Bitterman and Bennett, 2016; Lien et al., 2007; Sabatier et al., 2015; Sneessens et al., 2019	4 (33)
<b>Elasticity</b>	Intensity and direction of change	-	Bardaji and Iraizoz, 2015; Reidsma et al., 2009b	2 (36)

283 Among the criteria of dynamics used together (Supplementary material 5), level is used most  
284 often in combination with others (i.e. variability, trend, probability of exceeding a threshold,  
285 resistance and/or recovery). Level, distance to a threshold and elasticity are never used alone,

286 likely because they describe dynamics only partially. Distance to a stable state and the  
 287 frequency that a threshold was exceeded are always used alone, likely due to methodological  
 288 limitations (Bitterman and Bennett, 2016; Chavas and Di Falco, 2017; Fletcher and Hilbert, 2007;  
 289 Lien et al., 2007; Sabatier et al., 2015). Resistance is usually used alone (8 out of 21 articles) or  
 290 with recovery time (4 out of 21). The combination of level-trend-variability is the trio used most  
 291 often (4 articles, Bouttes et al. (2018); Leonhardt et al. (2013); Martin et al. (2017); Prieto et al.  
 292 (2015)). Multiple criteria are analyzed in 53% of studies, most of which use 2-3 criteria of  
 293 dynamics for each attribute (Table 3). Seven multi-performance studies use 2-5 criteria of  
 294 dynamics for each attribute investigated.

295 *Table 3. Distribution of the 53 articles reviewed as a function of the number of performance*  
 296 *attributes and criteria of dynamics of performance considered.*

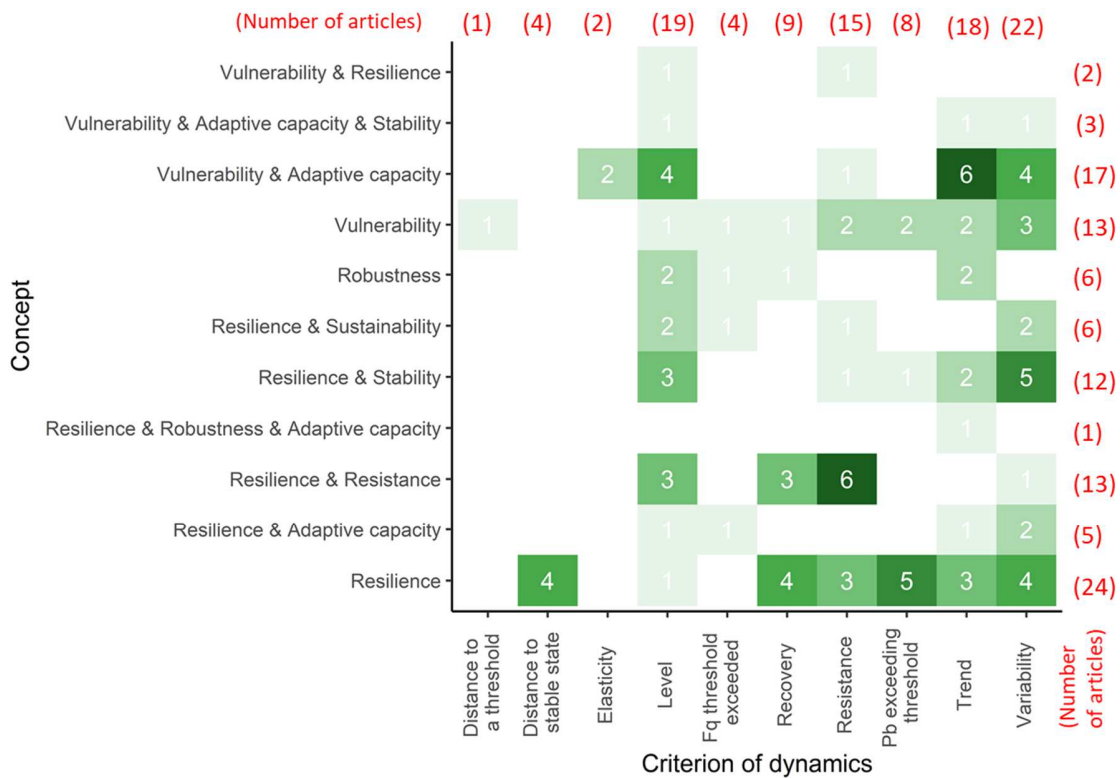
Criteria	Attributes			
	One	Two	Four	Five
One	25	0	0	0
Two	11	3	1	0
Three	7	2	0	0
Four	2	0	0	1
Eight	1	0	0	0

297

### 298 3.5. Combinations of concepts and criteria of dynamics

299 Most criteria of dynamics are associated with more than one of the four concepts investigated  
 300 (VRRAC). Criteria of level, trend and variability are associated with all four concepts, while  
 301 resistance, probability of exceeding a threshold and frequency that a threshold was exceeded  
 302 are associated only with resilience, vulnerability and adaptive capacity. However, since only six  
 303 of the articles reviewed refer to robustness, this concept is less common than the other two.

304 The criteria “recovery time/ratio” and “distance to a stable state” are associated in majority  
 305 with resilience. Elasticity is associated only with vulnerability and adaptive capacity (Bardaji and  
 306 Iraizoz, 2015; Reidsma et al., 2009b).



307  
 308 *Figure 4. Number of articles reviewed as a function of concept(s) and criterion of dynamics of*  
 309 *performance attribute. A given article can mention several concepts and/or criteria.*

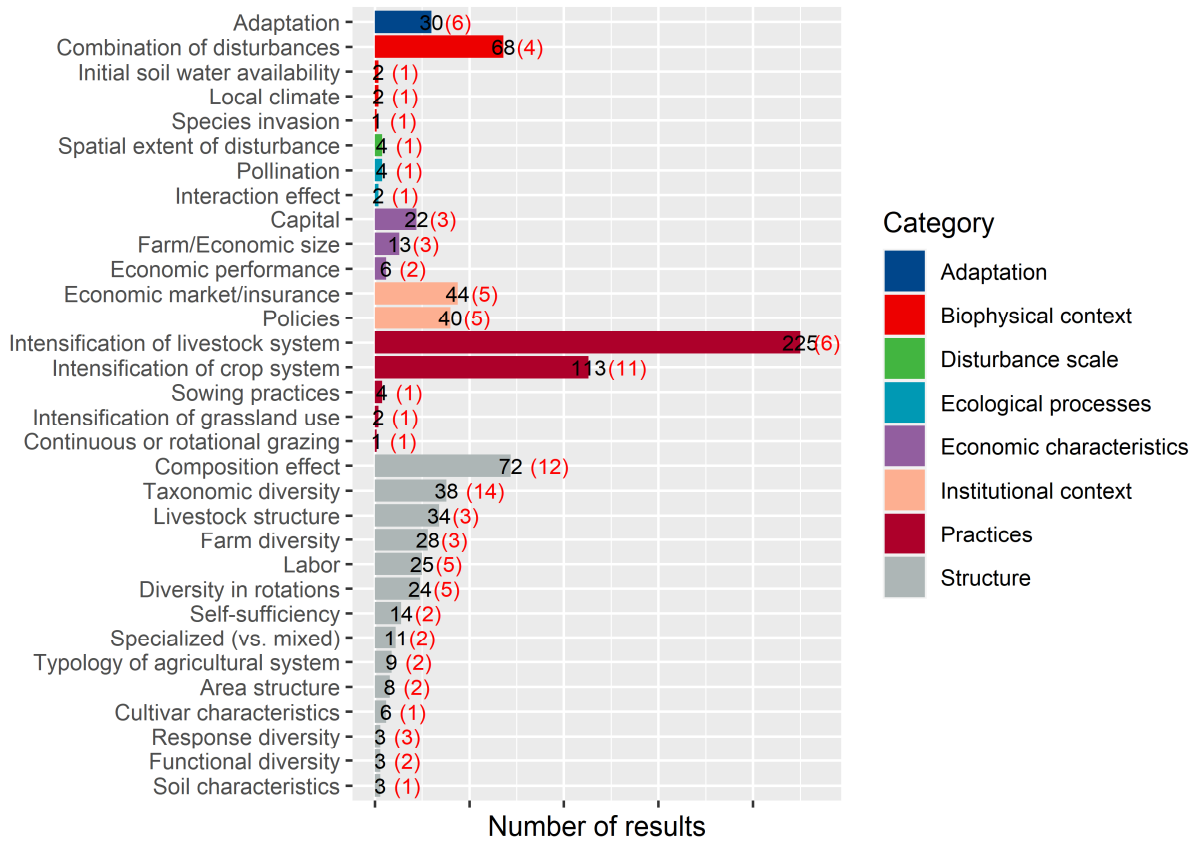
310 **3.6. Explanatory factors tested**

311 Most of the articles reviewed seek to determine explanatory factors of VRRAC (48 articles, 84%  
 312 of results). They tested 121 explanatory factors, which we categorized into 31 categories (Figure  
 313 5, Supplementary material 2) that correspond to descriptors of system structure (64% of  
 314 articles, 20% of results), agricultural practices (23% of articles, 34% of results), institutional  
 315 context (16% of articles, 8% of results), adaptation (11% of articles, 3% of results), economic

316 characteristics (11% of articles, 4% of results), biophysical context (13% of articles, 7% of  
317 results), ecological processes (2% of articles, 0.5% of results) and disturbance scale (2% of  
318 articles, 0.03% of results). Most factors studied (71%) are endogenous to the agricultural system  
319 (i.e. controllable by the farmer).

320 Although many explanatory factors are studied, articles address mainly effects of system  
321 structure, agricultural practices and institutional context, while economic characteristics are  
322 studied less, and ecological and biophysical factors are minors. The effect of system structure is  
323 studied by analyzing the effect of diversity, crop species surface areas, herd and farm labor  
324 structure, farm typologies (e.g. size, specialization), farm self-sufficiency and diversity. The  
325 effect of diversity is studied the most widely (27 articles) by analyzing effects of the spatial  
326 and/or temporal diversity of crops in rotations and mixtures or plants in grasslands, and the  
327 diversity of farm characteristics and response (see Dardonville et al., (2020) for more details).  
328 Agricultural practices are assessed mainly by considering input/practice intensification levels  
329 (e.g. pesticide, fertilization, irrigation, tillage) or ways to perform certain practices (e.g. sowing,  
330 grassland use). The institutional context is assessed to identify effects of policy or income  
331 stabilization measures. Adaptation is assessed by analyzing adaptations in crop management  
332 (Urruty et al., 2017), farm strategy (Fletcher and Hilbert, 2007; Martin and Magne, 2015; Seo,  
333 2010) or technological progress over time (Bardaji and Iraizoz, 2015; Reidsma et al., 2009b). The  
334 effect of ecological functioning is assessed only through the pollination service (Leonhardt et al.,  
335 2013) and the interaction effect (i.e. synergy or competition effects (Zavalloni et al., 2008)). The  
336 biophysical context category represents assessment of effects of a combination of disturbances

337 (e.g. heat and drought in Zavalloni et al., 2008), regional climate (Leonhardt et al., 2013), initial  
 338 soil water availability (Ferreyra et al. 2001) or invasion by other species (Vetter et al., 2020).



339

340 *Figure 5. Number of results (in black) and articles (in red) by explanatory factor and its category.*

341 **4. Discussion**

342 Our systematic review summarizes the system studied, methods, performance attributes used,  
 343 criteria of dynamics used and explanatory factors tested in the studies that quantitatively assess  
 344 the VRRAC of temperate agricultural systems. As shown, these studies use a variety of concepts,  
 345 methods and criteria. Based on results of our analysis and observations of other key  
 346 researchers, we discuss conceptual and methodological aspects of quantitative VRRAC

347 assessments. Consequently, we identify several points of vigilance and advice for future  
348 researchers.

#### 349 4.1. Relationships between VRRAC concepts and criteria of dynamics

350 The analysis of combinations of concepts and criteria in this review confirm that definitions of  
351 VRRAC concepts are fuzzy and highlight interchangeable use of criteria of dynamics. Many  
352 researchers have highlighted the redundancy, ambiguity and polysemy of VRRAC concepts  
353 (Callo-Concha and Ewert, 2014; Gallopín, 2006; Miller et al., 2010; Turner, 2010; Urruty et al.,  
354 2016), and Allen et al. (2019) does so recently for resilience. In the studies we reviewed, the  
355 concepts of vulnerability and resilience are used in combination with the one of adaptive  
356 capacity (25 out of 53 articles). In contrast, these concepts are less frequently combined in the  
357 review of Callo-Concha and Ewert (2014) covering qualitative and quantitative studies from  
358 2004 to 2013. Nonetheless, the dispersion of studies among VRRAC concepts that we observed  
359 confirms the conclusion of Callo-Concha and Ewert (2014) that operationalization of  
360 quantitative analysis of dynamics of agricultural systems is spread over the concepts. By  
361 focusing our query on the four VRRAC concepts, we may have missed articles that analyzed  
362 dynamics of agricultural systems in the face of disturbances but that did not mention one of  
363 these four concepts in their title, abstract or keywords. Our review of these four concepts could  
364 be widened by including studies of more distant concepts, such as stability or flexibility.

365 Because most studies defining VRRAC concepts do not explicitly develop operational criteria of  
366 dynamics (Grafton et al., 2019; Pimm et al., 2019), we show that most of these latter are  
367 developed by operational studies and are used interchangeably, regardless of the concept used.

368 The only exceptions are some resilience studies that focus on one criterion (e.g. “recovery  
369 time/ratio”, “distance to a stable state”) that translates the conceptual foundation of the  
370 resilience concept in the seminal article of Holling (1973). We can assume that researchers who  
371 assess dynamics of agricultural systems quantitatively would have less interest in using only one  
372 concept, because doing so would not help them choose criteria of dynamics.

373 This dispersion hides the fact that studies use same criteria and/or method to analyze dynamics,  
374 whatever the concept, which makes it more difficult to capitalize on knowledge. Our review,  
375 based on a generic analytical framework to analyze all studies that consider four key concepts,  
376 is one way to overcome this difficulty.

#### 377 4.2. Adaptive capacity

378 Although adaptive capacity is mentioned in 26% of the studies that we reviewed, and  
379 adaptation-related concepts are mentioned in 61% of the studies reviewed by Callo-Concha and  
380 Ewert (2014), only 6 articles reviewed in the present study test an explanatory factor related to  
381 adaptation, for example by analyzing the effect of management variability or scenarios on  
382 VRRAC. Thus, it seems that the bridge between theoretical/qualitative use of this concept and  
383 its use in quantitative assessment still remains to be built, perhaps due to difficulty in identifying  
384 tractable variables that represent adaptation. Following the same logic, no article reviewed  
385 analyzes the entire adaptive cycle introduced by Holling et al. (1995), probably due to the  
386 difficulty in developing quantitative criteria of dynamics in the four phases of the cycle  
387 (exploitation, conservation, release, reorganization). Only Fletcher and Hilbert (2007) study the

388 reorganization phase of the adaptive cycle by simulating the farmer's choice of strategy each  
389 year as a function of previous years.

#### 390 4.3. Temporal-scale effects

391 Our results show that many methods have been used to track dynamics when a shock (e.g.  
392 drought) or trend change (e.g. higher temperature, lower precipitation) occurs. The studies  
393 reviewed analyze short-term (58% of studies less than 11 years) and medium- to long-terms  
394 (more than 11 years) in relatively equal measure (Figure 2). The short-term studies correspond  
395 mainly to one- or two-year experimental plot studies of grassland dynamics with artificial  
396 disturbances (n=6, e.g. Barkaoui et al., 2016; Carter and Blair, 2012; Oram et al., 2020). We  
397 found only one study (Isbell et al., 2015) that addressed effects of recurring disturbance, unlike  
398 most of the experimental and observational studies in ecology reviewed by Donohue et al.  
399 (2016). This is surprising, since changes in climate (Meyer et al., 2018) and in the economic  
400 context can be considered as a succession of events. Furthermore, short and long temporal  
401 extents are not studied at the same time, which ignores recommendations of Bitterman and  
402 Bennett (2016), Hoover et al. (2014) and Pfisterer and Schmid (2002). Indeed, they argue that  
403 the temporal extent studied (VRRAC "when") can influence the results strongly: a system could  
404 be resilient in the short term but vulnerable in the longer term, and vice-versa (Donohue et al.,  
405 2016; Müller et al., 2016; Peterson et al., 2018). Considering long-term dynamics also allows  
406 long-term response variables to be assessed, such as resource depletion or the dynamics of  
407 natural capital (Dardonville et al., 2020; Peterson et al., 2018). However, addressing long-term  
408 dynamics is often resource-consuming since it requires long-term experimental studies and data  
409 sets or development of model-based approaches (Douxchamps et al., 2017).



#### 410 4.4. Multi-performance of agricultural systems

411 Most articles reviewed (86%) address only one performance attribute, mostly yield (67% of  
412 articles). Few articles reviewed address other attributes, such as ecological performance (3% of  
413 articles). This agrees with conclusions of the review by Donohue et al. (2016) of ecological  
414 studies, which focus mainly on the stability of biomass production. Studies that focus on only  
415 one performance attribute (or two, in 5 articles), particularly yield, overlook the  
416 multifunctionality of agricultural systems. Assessing the dynamics of agronomic (yield),  
417 ecological (e.g. ecosystem functions and services), social (e.g. work time) and economic  
418 attributes together is necessary to understand dynamics that underpin the behavior of  
419 agricultural systems in the framework of sustainability (Darnhofer et al., 2010). However,  
420 analyzing dynamics of several types of performance attributes (e.g. yield and quality of  
421 production by Bardaji and Iraizoz (2015), yield and economic net return by Ferreyra et al.  
422 (2001)) requires developing methods to aggregate and analyze dynamics of trade-offs and  
423 synergies between them (Hodbod et al., 2016).

#### 424 4.5. Multiplicity, complementarity and selection of criteria of dynamics

425 Unlike studies that focus on only one performance attribute, half of the articles (53%) reviewed  
426 use multiple criteria to analyze the dynamics of system attributes. In contrast, Donohue et al.  
427 (2016) indicated that 85-93% of studies in ecology used only one criterion, mainly variability  
428 (61% of experimental and 72% of observational studies). The multicriteria approach enables  
429 studies to provide complementarity points of view about the dynamics studied. Although level is  
430 the criterion combined most often with other criteria, it should obviously not be considered

431 alone as a criterion of dynamics due to its static nature. When combined with other criteria, it  
432 can provide key information that helps to put other criteria values into perspective. Indeed, it  
433 may be easier to show a positive trend when a performance level, such as yield, is low than  
434 when it is already high. For example, among the studies we reviewed, Martin et al. (2017)  
435 combine level, trend and variability to analyze how a given performance level is associated with  
436 a direction of trend and degree of variability. More recently, Sneessens et al. (2019) assess the  
437 economic vulnerability of farming systems using the relative standard deviation (i.e. variability),  
438 mean relative distance (i.e. distance to a threshold), number of disturbances (i.e. frequency of  
439 exceeding a threshold) and recovery time. Some studies take the multicriteria approach a step  
440 further by developing several indicators per criterion to cover different aspects of the criterion.  
441 For example, Li et al. (2019), while using an innovative combination of level, stability, resistance  
442 and maximum potential to analyze yield dynamics, use four and two indicators to estimate  
443 stability and resistance, respectively. In ecology research field, Ingrisich and Bahn (2018)  
444 compare several indicators of recovery: absolute recovery time, as well as baseline-normalized  
445 and impact-normalized indicators. Resistance is rarely combined with recovery time (4 articles),  
446 even though these dynamics are interdependent: comparing two recovery times requires  
447 knowing each fall in performance and thus the extent of the recovery required (like the “half-  
448 life” of radioactive decay, Pimm et al. (2019)).

449 Overall, there is a lack of justification for the criteria chosen. Donohue et al. (2016) claim that  
450 criteria should be chosen based on the nature of the disturbance observed. Recovery and  
451 resistance are suitable for a shock disturbance, while level, variability, elasticity and trend are  
452 suitable for a trend or for “noisy” disturbance. The decision to combine criteria also depends on

453 the conceptualization of the nature of system dynamics. Variability, trend, resistance, recovery  
454 and elasticity refer to the “engineering” vision of dynamics in the resilience framework  
455 (Donohue et al., 2016), while distance to a stable state and the probability and frequency of  
456 exceeding a threshold assume the existence of tipping points and different stability regimes, in  
457 reference to the “ecological” resilience framework (Holling, 1973). Accordingly, only one of the  
458 articles reviewed (Gaudin et al., 2015) combines an “engineering” criterion (variability) with an  
459 “ecological” criterion (probability of exceeding a threshold). This kind of study tries to reconcile  
460 the “engineering” and “ecological” dimensions of resilience (Allen et al., 2019). However, recent  
461 debate on the ability to reconcile them suggests that their differing conceptual positions on the  
462 existence of other states of stability remain far apart and may be unresolvable (Pimm et al.,  
463 2019).

#### 464 4.6. Multiplicity, complementarity and selection of explanatory factors

465 Many explanatory factors of VRRAC are explored in the articles reviewed. This dispersion can  
466 make it difficult to provide generic information about the main system properties that influence  
467 the VRRAC of agricultural systems. Developing a shared core set of explanatory factors that  
468 should always be investigated in VRAAC studies could help build generic knowledge. As Callo-  
469 Concha and Ewert (2014) recommend, doing so would allow for development of a more  
470 standardized analysis protocol. One strategy could be to test in *dynamics-analysis* studies the  
471 main properties used in *predefined-properties* studies. In this perspective, despite the greatly  
472 different terminologies used, we estimated the extent to which explanatory factors of VRRAC in  
473 the studies we reviewed corresponded to the resilience properties of agricultural systems  
474 identified by Cabell and Oelofse (2012) (Table 4). As expected, diversity (i.e. redundancy,

475 functional complementarity and heterogeneity) is investigated in the two approaches  
476 (*predefined-properties* and *dynamics-analysis*). As Dardonville et al. (2020) show, however, the  
477 effect of diversity depends on the nature of the agricultural system (crop vs. grassland) and is  
478 modulated by the system's composition (e.g. species, type of farm). Human capital and  
479 profitability are also well explored, showing appropriation and convergence of these objectives  
480 within research communities. Since articles reviewed ignore social explanatory factors, they do  
481 not consider the four social properties of resilience (i.e. socially self-organized, appropriately  
482 connected socially, reflective and shared learning, honors legacy) identified by Cabell and  
483 Oelofse (2012). Like them, Biggs et al. (2012), in their thorough review of principles of  
484 ecosystem service resilience in social-ecological systems, highlight the need to consider both  
485 ecological (biophysical) and social properties in such systems (see also Cinner and Barnes  
486 (2019)). The most surprising aspect of our analysis is that the two approaches yield opposite  
487 points of view of the effect of certain factors. For example, while exogenous supports of  
488 agricultural systems (e.g. policy and insurance) are identified as favorable explanatory factors of  
489 VRRAC in the articles reviewed, two resilience properties ("globally autonomous and locally  
490 interdependent" and "reasonably profitable" without "distortionary subsidies") highlight the  
491 importance for agricultural systems of remaining independent of such financial supports for  
492 their resilience. We assume that these two points of view could be related to the different  
493 temporal scales considered: exogenous supports can have a favorable effect in the short term  
494 but may make agricultural systems dependent on them, and thus sensitive to them, in the long  
495 term. To a lesser extent, the same holds true for the intensification of agricultural systems:  
496 some of the articles reviewed perceive it as a positive driver of VRRAC, while Cabell and Oelofse

497 (2012) consider it a negative property (“globally autonomous and locally interdependent”). In  
 498 their review of effects of intensification on the VRRAC of agricultural systems, Dardonville et al.  
 499 (2020) show, as discussed by Ge et al. (2016) and Peterson et al. (2018), that intensification can  
 500 have positive or negative effects depending on the initial level of production, temporal scale of  
 501 the study and availability of local resources (e.g. water for irrigation). As discussed, both points  
 502 of view highlight the influence of the temporal and spatial scales chosen on study results.  
 503 Finally, for the other resilience properties, the ambiguous definitions and terminologies used  
 504 make it difficult to relate the factors encountered to resilience properties. This highlights that  
 505 both research communities need to develop sound and clear assumptions and definitions  
 506 (including spatiotemporal scales) that underpin the selected or studied explanatory factors  
 507 (properties) of VRRAC in agricultural systems (Peterson et al., 2018).

508 *Table 4. Resilience properties described by Cabell and Oelofse (2012) and potential explanatory*  
 509 *factors encountered in the articles reviewed.*

<b>RESILIENCE PROPERTY (CABELL AND OELOFSE, 2012)</b>	<b>“WHAT TO LOOK FOR” (TABLE 1 OF CABELL AND OELOFSE, 2012)</b>	<b>POTENTIAL EXPLANATORY FACTORS REVIEWED</b>
<b>SOCIALLY SELF- ORGANIZED</b>	“Farmers and consumers are able to organize into grassroots networks and institutions, such as co-ops, farmer’s markets, community sustainability associations, community gardens, and advisory networks”	-
<b>ECOLOGICALLY SELF- REGULATED</b>	“Farms maintain plant cover and incorporate more perennials, provide habitat for predators and parasitoids, use ecosystem engineers, and align production with local ecological parameters”	Soil conservation agricultural practices
<b>APPROPRIATELY CONNECTED</b>	“Collaborating with multiple suppliers, outlets, and fellow farmers; crops planted in polycultures that encourage symbiosis and mutualism”	Interaction effect (competition or selection), specialized (vs. mixed) systems, self-sufficiency
<b>HIGH DEGREE OF</b>	“Heterogeneity of features within the landscape and	Functional diversity, response

<b>FUNCTIONAL AND RESPONSE DIVERSITY</b>	on the farm; diversity of inputs, outputs, income sources, markets, pest controls, etc.”	diversity
<b>OPTIMALLY REDUNDANT</b>	“Planting multiple varieties of crops rather than one, keeping equipment for various crops, getting nutrients from multiple sources, capturing water from multiple sources”	Taxonomic (genetic) diversity
<b>HIGH DEGREE OF SPATIAL AND TEMPORAL HETEROGENEITY</b>	“Patchiness on the farm and across the landscape, mosaic pattern of managed and unmanaged land, diverse cultivation practices, crop rotations”	Farm diversity, diversity in rotation, landscape composition and configuration
<b>CAREFULLY EXPOSED TO DISTURBANCE</b>	“Pest management that allows a certain controlled amount of invasion followed by selection of plants that fared well and exhibit signs of resistance”	Local climate, species invasion
<b>RESPONSIBLY COUPLED WITH LOCAL NATURAL CAPITAL</b>	“Builds (does not deplete) soil organic matter, recharges water, little need to import nutrients or export waste”	Soil conservation agricultural practices (as practices that maintain natural capital)
<b>REFLECTIVE AND SHARED LEARNING</b>	“Extension and advisory services for farmers; collaboration between universities, research centers, and farmers; cooperation and knowledge sharing between farmers; record keeping; baseline knowledge about the state of the agroecosystem”	-
<b>LOCALLY AUTONOMOUS AND GLOBALLY INTERDEPENDENT</b>	“Less reliance on commodity markets and reduced external inputs; more sales to local markets, reliance on local resources; existence of farmer co-ops, close relationships between producer and consumer, and shared resources such as equipment”	Policies (income stabilization tool, direct and greening payments, subsidies, government investment), intensification of crop and breeding system (different levels of dependence on external inputs), self-sufficiency
<b>HONORS LEGACY</b>	“Maintenance of heirloom seeds and engagement of elders, incorporation of traditional cultivation techniques with modern knowledge”	-
<b>BUILDS HUMAN CAPITAL</b>	“Investment in infrastructure and institutions for the education of children and adults, support for social events in farming communities, programs for preservation of local knowledge”	Capital, labor
<b>REASONABLY PROFITABLE</b>	“Farmers and farm workers earn a livable wage; agriculture sector does not rely on distortionary	Economic performances, economic market/insurance,

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subsidies”

policies (income stabilization tool, direct and greening payments, subsidies, government investment), capital (cash surplus, net cash, debt ratio), workload

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510

511 4.7. Normative vs. participatory approaches

512 Although the *dynamics-analysis approach* can be considered more objective than the  
513 *predefined-properties approach*, we agree with Córdoba Vargas et al. (2019), who highlight the a  
514 priori and subjective points of view, and especially the normativity of VRRAC, in studies that  
515 follow the former approach. Following these researchers, we highlight the importance of  
516 considering “who defines”, “for what purpose” and “according to what interests” the  
517 characteristics of VRRAC studies and analyzing the results in light of this key information. For  
518 example, researchers may argue and discuss the spatial and/or temporal extent of the study  
519 (e.g. local resource limitation or depletion), the performance attribute(s) to maintain (e.g.  
520 whether maintaining a high yield is relevant given potential environmental impacts) and the  
521 nature of the desired dynamics of the performance attribute (e.g. increasing the trend in yield  
522 or a high level of income is desired). To define these key characteristics in their studies,  
523 researchers could interact with the intended stakeholders, such as farmers, food-chain actors,  
524 policy-makers or researchers from another field (Callo-Concha and Ewert, 2014; Ge et al., 2016).  
525 This could result in considering multiple system characteristics, such as its structure (richness),  
526 performances (ecological, agronomic, economic and/or social) or key properties, such as the  
527 conservation of open spaces for potential futures (Enfors-Kautsky et al. 2018).

528 **5. Conclusion**

529 Our systematic review provides an original synthesis of the concepts, methods, performance  
530 attributes, criteria of dynamics and explanatory factors tested in studies that assess dynamics of  
531 agricultural systems quantitatively using the four key reference concepts of vulnerability,  
532 resilience, robustness or adaptive capacity. The weak conditionality between concepts and  
533 criteria of dynamics confirm both the fuzzy definitions of the former and the utility of our  
534 transversal review, based on a generic analytical framework, to collect knowledge spread over  
535 different conceptual fields of study. While operationalizing the assessment of VRRAC in  
536 agricultural systems remains a research challenge, this review describes potential methods and  
537 criteria of dynamics with which to analyze these dynamics.

538 Based on the results of this review, we recommend that future studies and users of these  
539 studies, such as policy-makers, pay attention to (i) the spatial and temporal scales of studies  
540 (VRRAC “*when and where*”) that determine their results (short vs. long term, field or farm vs.  
541 local (resource) level), (ii) the need to analyze more than yield dynamics alone to embrace the  
542 multifunctionality of agriculture (VRRAC “*for which performance attributes*”), (iii) the need to  
543 choose relevant and complementarity criteria of dynamics depending on the performance  
544 attributes analyzed and (iv) clarification and transparency of who defines, for what purpose and  
545 according to what interests the characteristics of VRRAC studies.

546 This review also shows that a wide range of agronomic and, to a lesser extent, economic and  
547 institutional explanatory factors are studied, but ecological and social aspects are rarely  
548 addressed. We claim that identifying the key system properties that determine the VRRAC of  
549 agricultural systems requires identifying a shared core set of potential explanatory factors,



550 including social and ecological factors, to consider systematically. Based on this review, this set  
551 could be identified through cross-sectional analysis of results of expert-based and quantitative  
552 analysis and updated in future studies based on new results. Identifying methods for assessing  
553 VRRAC should not stop there, and we expect a significant increase in the number of studies with  
554 a *dynamics-analysis* approach in the future.

### 555 **Contributions**

556 M.D and O.T developed the analytical framework with guidance and contributions from all co-  
557 authors; M.D performed the literature review; M.D and O.T wrote the manuscript; and C.B  
558 proofread the manuscript.

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