



HAL
open science

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

Manon Dardonville, Christian Bockstaller, Olivier Therond

► To cite this version:

Manon Dardonville, Christian Bockstaller, Olivier Therond. Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive capacity of temperate agricultural systems. *Journal of Cleaner Production*, 2021, 286, pp.125456. 10.1016/j.jclepro.2020.125456 . hal-03150196

HAL Id: hal-03150196

<https://hal.science/hal-03150196>

Submitted on 2 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

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

3

4 **Authors**

5 Manon DARDONVILLE^{1, 2*}, Christian BOCKSTALLER¹, Olivier THEROND¹

6 ¹ Université de Lorraine, INRAE, LAE, F-68000 Colmar, France

7 ²Agrosolutions, 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.

Concepts	Definitions	Reference
Resilience	<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)
Vulnerability	<i>“the degree to which a system is harmed due to disturbances or stress”</i>	Turner et al. (2003)
Robustness	<i>“the ability to maintain desired levels of system outputs, [...] despite the occurrence of disturbances”</i>	Urruty et al. (2016)
Adaptive capacity	<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*).

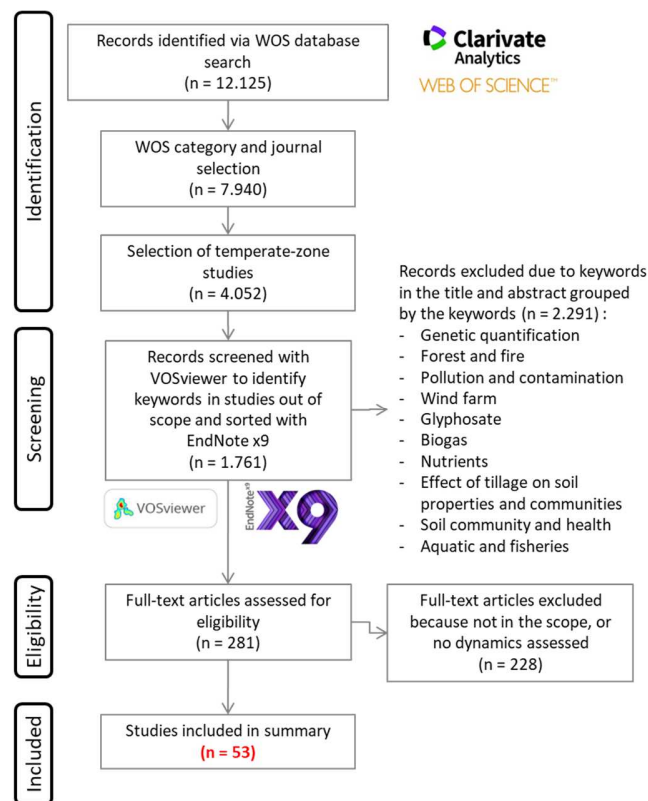
127 Hereafter, we present the methodology used to select the studies reviewed, the results that
128 answer the research questions and the discussion, which provides recommendations to other
129 researchers.

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).

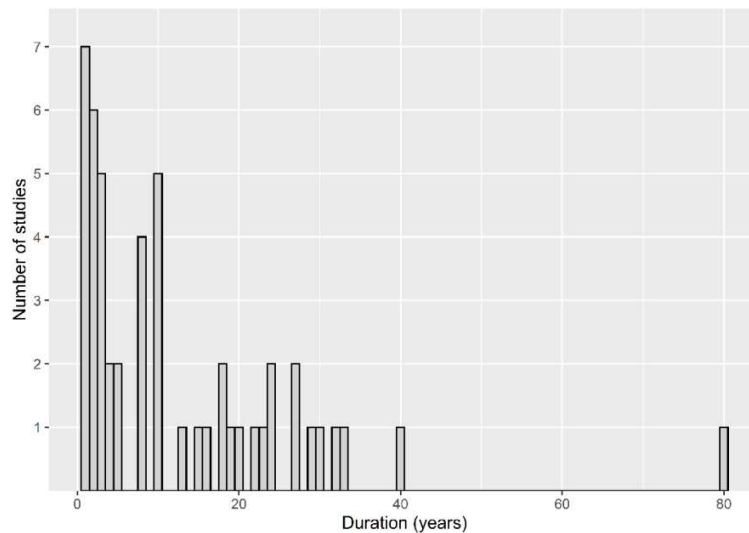
215 Here, “resistance” refers to a concept and not to a criterion that describes the dynamics of the
216 attribute. The concepts of vulnerability, resilience and robustness are rarely combined; for
217 example, only one article combines vulnerability and resilience (Figure 4), confirming that they
218 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 m² 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).



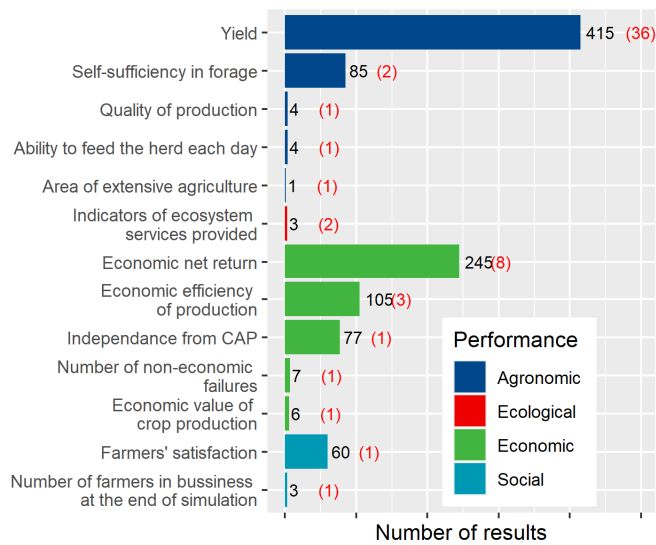
240
241 *Figure 2. Temporal extent (duration) of analysis in each study reviewed (years).*

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)
Level	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)
Variability	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)
Trend	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)
Resistance	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)
Recovery	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)
Distance to a stable state	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)
Distance to a threshold	Difference between a desired level and actual level	-	Sneessens et al., 2019	1 (19)
Probability of exceeding a threshold	-	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)
Frequency that threshold was exceeded	-	Walker et al. (2004)	Bitterman and Bennett, 2016; Lien et al., 2007; Sabatier et al., 2015; Sneessens et al., 2019	4 (33)
Elasticity	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.*

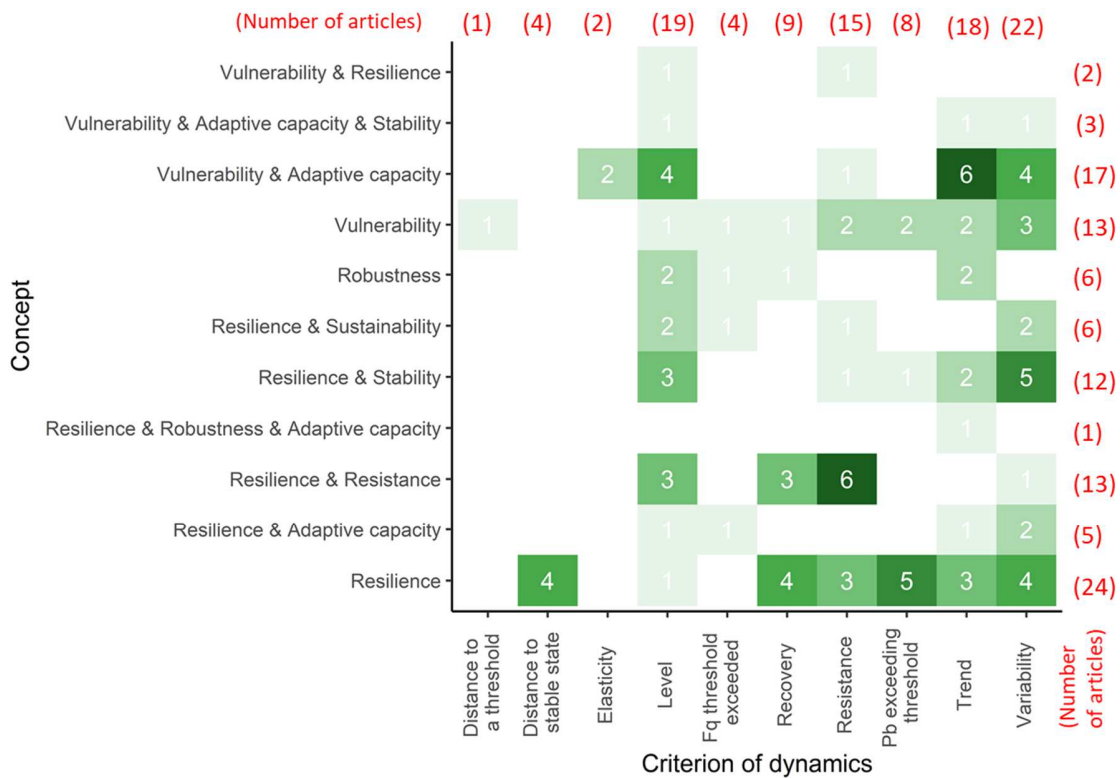
Criteria	Attributes			
	One	Two	Four	Five
One	25	0	0	0
Two	11	3	1	0
Three	7	2	0	0
Four	2	0	0	1
Eight	1	0	0	0

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.*

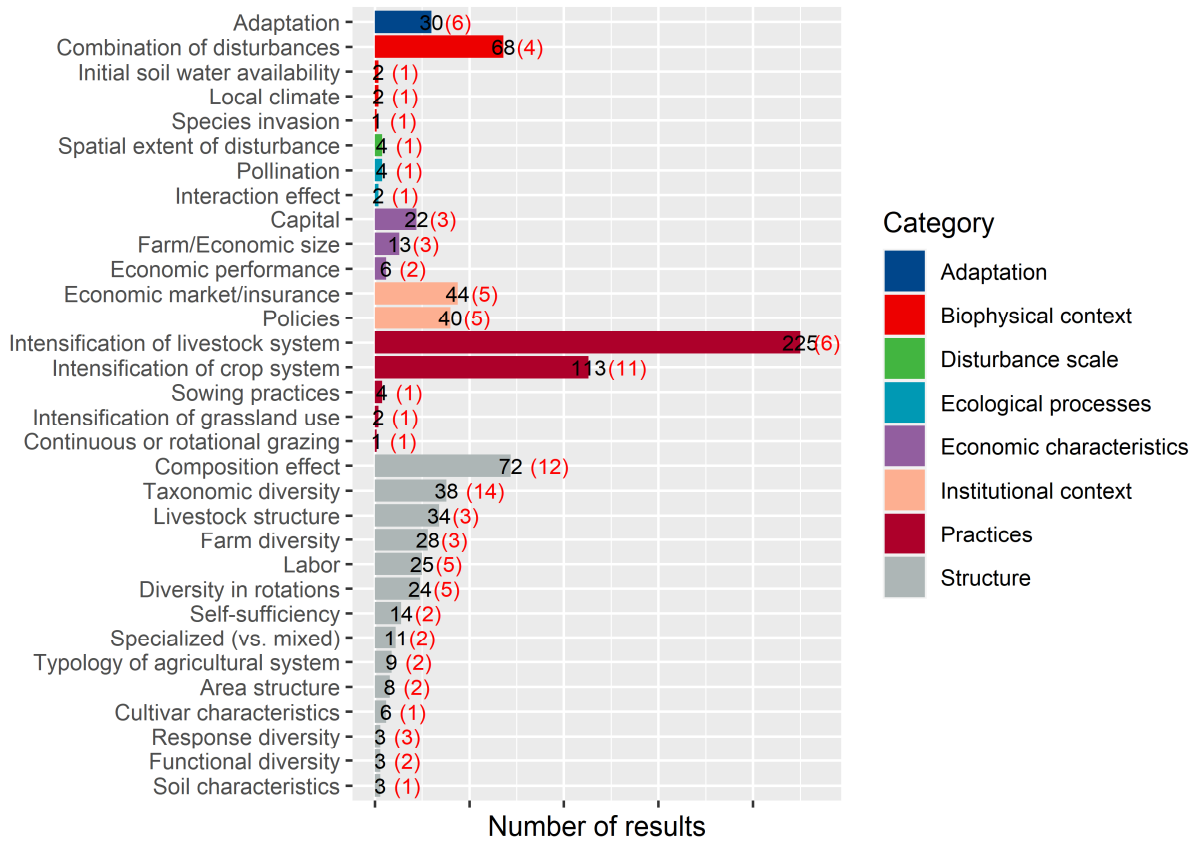
310 **3.6. Explanatory factors tested**

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.*

RESILIENCE PROPERTY (CABELL AND OELOFSE, 2012)	“WHAT TO LOOK FOR” (TABLE 1 OF CABELL AND OELOFSE, 2012)	POTENTIAL EXPLANATORY FACTORS REVIEWED
SOCIALLY SELF- ORGANIZED	“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”	-
ECOLOGICALLY SELF- REGULATED	“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
APPROPRIATELY CONNECTED	“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
HIGH DEGREE OF	“Heterogeneity of features within the landscape and	Functional diversity, response

FUNCTIONAL AND RESPONSE DIVERSITY	on the farm; diversity of inputs, outputs, income sources, markets, pest controls, etc.”	diversity
OPTIMALLY REDUNDANT	“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
HIGH DEGREE OF SPATIAL AND TEMPORAL HETEROGENEITY	“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
CAREFULLY EXPOSED TO DISTURBANCE	“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
RESPONSIBLY COUPLED WITH LOCAL NATURAL CAPITAL	“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)
REFLECTIVE AND SHARED LEARNING	“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”	-
 Globally Autonomous and Locally Interdependent	“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
HONORS LEGACY	“Maintenance of heirloom seeds and engagement of elders, incorporation of traditional cultivation techniques with modern knowledge”	-
BUILDS HUMAN CAPITAL	“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
REASONABLY PROFITABLE	“Farmers and farm workers earn a livable wage; agriculture sector does not rely on distortionary	Economic performances, economic market/insurance,

subsidies”

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

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.

559 **Acknowledgements**

560 We thank Agrosolutions, the agricultural consulting firm that supported and funded the project.
561 The funder played no role in the decision to publish. We thank Michelle and Michael Corson for
562 proofreading. We also thank Guy Richard, Michel Duru and Jean-Roger Estrade for providing
563 general guidance and discussion.

564 **Bibliography**

- 565 Adger, W.N., 2006. Vulnerability. *Glob. Environ. Change* 16, 268–281.
566 <https://doi.org/10.1016/j.gloenvcha.2006.02.006>
- 567 Allen, C., Birge, H., Angeler, D., Arnold, C., Chaffin, B., DeCaro, D., Garmestani, A., Gunderson, L., 2018.
568 Quantifying uncertainty and trade-offs in resilience assessments. *Ecol. Soc.* 23.
569 <https://doi.org/10.5751/ES-09920-230103>
- 570 Allen, C.R., Angeler, D.G., Chaffin, B.C., Twidwell, D., Garmestani, A., 2019. Resilience reconciled. *Nat.*
571 *Sustain.* 2, 898–900. <https://doi.org/10.1038/s41893-019-0401-4>
- 572 Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-
573 resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890. [https://doi.org/10.1007/s13593-](https://doi.org/10.1007/s13593-015-0285-2)
574 [015-0285-2](https://doi.org/10.1007/s13593-015-0285-2)
- 575 AminShokravi, A., Heravi, G., 2020. Developing the framework for evaluation of the inherent static
576 resilience of the access to care network. *J. Clean. Prod.* 267, 122123.
577 <https://doi.org/10.1016/j.jclepro.2020.122123>
- 578 Bardaji, I., Iraizoz, B., 2015. Uneven responses to climate and market influencing the geography of high-
579 quality wine production in Europe. *Reg. Environ. Change* 15, 79–92.
580 <https://doi.org/10.1007/s10113-014-0623-y>
- 581 Barkaoui, K., Roumet, C., Volaire, F., 2016. Mean root trait more than root trait diversity determines
582 drought resilience in native and cultivated Mediterranean grass mixtures. *Agric. Ecosyst. Environ.*
583 231, 122–132. <https://doi.org/10.1016/j.agee.2016.06.035>

584 Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., Burnsilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans,
585 L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D.,
586 Schoon, M.L., Schultz, L., West, P.C., 2012. Toward principles for enhancing the resilience of
587 ecosystem services. *Annu. Rev. Environ. Resour.* 37, 421–448. [https://doi.org/10.1146/annurev-
589 environ-051211-123836](https://doi.org/10.1146/annurev-
588 environ-051211-123836)

589 Bitterman, P., Bennett, D.A., 2016. Constructing stability landscapes to identify alternative states in
590 coupled social-ecological agent-based models. *Ecol. Soc.* 21, 21. [https://doi.org/10.5751/ES-
592 08677-210321](https://doi.org/10.5751/ES-
591 08677-210321)

592 Bonisoli, L., Galdeano-Gómez, E., Piedra-Muñoz, L., 2018. Deconstructing criteria and assessment tools to
593 build agri-sustainability indicators and support farmers' decision-making process. *J. Clean. Prod.*
594 182, 1080–1094. <https://doi.org/10.1016/j.jclepro.2018.02.055>

595 Bouttes, M., Bize, N., Maréchal, G., Michel, G., Cristobal, M.S., Martin, G., 2019. Conversion to organic
596 farming decreases the vulnerability of dairy farms. *Agron. Sustain. Dev.* 39, 19.
597 <https://doi.org/10.1007/s13593-019-0565-3>

598 Bouttes, M., San Cristobal, M., Martin, G., 2018. Vulnerability to climatic and economic variability is
599 mainly driven by farmers' practices on French organic dairy farms. *Eur. J. Agron.* 94, 89–97.
600 <https://doi.org/10.1016/j.eja.2018.01.013>

601 Brooks, N., Neil Adger, W., Mick Kelly, P., 2005. The determinants of vulnerability and adaptive capacity
602 at the national level and the implications for adaptation. *Glob. Environ. Change* 15, 151–163.
603 <https://doi.org/10.1016/j.gloenvcha.2004.12.006>

604 Brunner, S.H., Grêt-Regamey, A., 2016. Policy strategies to foster the resilience of mountain social-
605 ecological systems under uncertain global change. *Environ. Sci. Policy* 66, 129–139.
606 <https://doi.org/10.1016/j.envsci.2016.09.003>

607 Brzezina, N., Kopainsky, B., Mathijs, E., 2016. Can Organic Farming Reduce Vulnerabilities and Enhance
608 the Resilience of the European Food System? A Critical Assessment Using System Dynamics
609 Structural Thinking Tools. *Sustainability* 8, 971. <https://doi.org/10.3390/su8100971>

610 Cabell, J.F., Oelofse, M., 2012. An Indicator Framework for Assessing Agroecosystem Resilience. *Ecol.*
611 *Soc.* 17. <https://doi.org/10.5751/ES-04666-170118>

612 Callo-Concha, D., Ewert, F., 2014. Using the Concepts of Resilience, Vulnerability and Adaptability for the
613 Assessment and Analysis of Agricultural Systems. *Change Adapt. Socio-Ecol. Syst.* 1.
614 <https://doi.org/10.2478/cass-2014-0001>

615 Carlsson, M., Merten, M., Kayser, M., Isselstein, J., Wrage-Mönnig, N., 2017. Drought stress resistance
616 and resilience of permanent grasslands are shaped by functional group composition and N
617 fertilization. *Agric. Ecosyst. Environ.* 236, 52–60. <https://doi.org/10.1016/j.agee.2016.11.009>

618 Carter, D.L., Blair, J.M., 2012. High richness and dense seeding enhance grassland restoration
619 establishment but have little effect on drought response. *Ecol. Appl.* 22, 1308–1319.
620 <https://doi.org/10.1890/11-1970.1>

621 Castañeda-Vera, A., Garrido, A., 2017. Evaluation of risk management tools for stabilising farm income
622 under CAP 2014-2020. *Econ. Agrar. Recur. Nat.* 17, 3. <https://doi.org/10.7201/earn.2017.01.01>

623 Chavas, J.-P., Di Falco, S., 2017. Resilience, Weather and Dynamic Adjustments in Agroecosystems: The
624 Case of Wheat Yield in England. *Environ. Resour. Econ.* 67, 297–320.
625 <https://doi.org/10.1007/s10640-015-9987-9>

626 Cinner, J.E., Barnes, M.L., 2019. Social Dimensions of Resilience in Social-Ecological Systems. *One Earth* 1,
627 51–56. <https://doi.org/10.1016/j.oneear.2019.08.003>

628 Cociu, A., Cizma, G.D., 2015. Maize yield and its stability as affected by tillage and crop residue
629 management. *AgroLife Sci. J.* 4, 46–51.

630 Coomes, O.T., Barham, B.L., MacDonald, G.K., Ramankutty, N., Chavas, J.-P., 2019. Leveraging total factor
631 productivity growth for sustainable and resilient farming. *Nat. Sustain.* 2, 22–28.
632 <https://doi.org/10.1038/s41893-018-0200-3>

633 Córdoba Vargas, C.A., Hortúa Romero, S., León Sicard, T., 2019. Key points of resilience to climate
634 change: a necessary debate from agroecological systems. *Clim. Dev.* 1–11.
635 <https://doi.org/10.1080/17565529.2019.1664376>

636 Corobov, R., Sîrodov, I., Koepfel, S., Denisov, N., Sîrodov, G., 2013. Assessment of Climate Change
637 Vulnerability at the Local Level: A Case Study on the Dniester River Basin (Moldova). *Sci. World J.*
638 2013, 1–13. <https://doi.org/10.1155/2013/173794>

639 Craven, D., Eisenhauer, N., Pearce, W.D., Hautier, Y., Isbell, F., Roscher, C., Bahn, M., Beierkuhnlein, C.,
640 Bönisch, G., Buchmann, N., Byun, C., Catford, J.A., Cerabolini, B.E.L., Cornelissen, J.H.C., Craine,
641 J.M., De Luca, E., Ebeling, A., Griffin, J.N., Hector, A., Hines, J., Jentsch, A., Kattge, J., Kreyling, J.,
642 Lanta, V., Lemoine, N., Meyer, S.T., Minden, V., Onipchenko, V., Polley, H.W., Reich, P.B., van
643 Ruijven, J., Schamp, B., Smith, M.D., Soudzilovskaia, N.A., Tilman, D., Weigelt, A., Wilsey, B.,
644 Manning, P., 2018. Multiple facets of biodiversity drive the diversity–stability relationship. *Nat.*
645 *Ecol. Evol.* 2, 1579–1587. <https://doi.org/10.1038/s41559-018-0647-7>

646 Dalsgaard, J.P.T., Lightfoot, C., Christensen, V., 1995. Towards quantification of ecological sustainability
647 in farming systems analysis. *Ecol. Eng.* 4, 181–189. [https://doi.org/10.1016/0925-](https://doi.org/10.1016/0925-8574(94)00057-C)
648 [8574\(94\)00057-C](https://doi.org/10.1016/0925-8574(94)00057-C)

649 Dardonville, M., Urruty, N., Bockstaller, C., Therond, O., 2020. Influence of diversity and intensification
650 level on vulnerability, resilience and robustness of agricultural systems. *Agric. Syst.* 184, 102913.
651 <https://doi.org/10.1016/j.agsy.2020.102913>

652 Darnhofer, I., Fairweather, J., Moller, H., 2010. Assessing a farm’s sustainability: insights from resilience
653 thinking. *Int. J. Agric. Sustain.* 8, 186–198. <https://doi.org/10.3763/ijas.2010.0480>

654 de la Rosa, D., Moreno, J.A., Mayol, F., Bonsón, T., 2000. Assessment of soil erosion vulnerability in
655 western Europe and potential impact on crop productivity due to loss of soil depth using the
656 ImpelERO model. *Agric. Ecosyst. Environ.* 81, 179–190. [https://doi.org/10.1016/S0167-](https://doi.org/10.1016/S0167-8809(00)00161-4)
657 [8809\(00\)00161-4](https://doi.org/10.1016/S0167-8809(00)00161-4)

658 Di Falco, S., Chavas, J.-P., 2008. Rainfall Shocks, Resilience, and the Effects of Crop Biodiversity on
659 Agroecosystem Productivity. *Land Econ.* 84, 83–96. <https://doi.org/10.3368/le.84.1.83>

660 Diserens, F., Choptiany, J., Barjolle, D., Graeub, B., Durand, C., Six, J., 2018. Resilience Assessment of
661 Swiss Farming Systems: Piloting the SHARP-Tool in Vaud. *Sustainability* 10, 4435.
662 <https://doi.org/10.3390/su10124435>

663 Donohue, I., Hillebrand, H., Montoya, J.M., Petchey, O.L., Pimm, S.L., Fowler, M.S., Healy, K., Jackson,
664 A.L., Lurgi, M., McClean, D., O’Connor, N.E., O’Gorman, E.J., Yang, Q., 2016. Navigating the
665 complexity of ecological stability. *Ecol. Lett.* 19, 1172–1185. <https://doi.org/10.1111/ele.12648>

666 Douchamps, S., Debevec, L., Giordano, M., Barron, J., 2017. Monitoring and evaluation of climate
667 resilience for agricultural development – A review of currently available tools. *World Dev.*
668 *Perspect.* 5, 10–23. <https://doi.org/10.1016/j.wdp.2017.02.001>

669 Enfors-Kautsky, E., Järnberg, L., Quinlan, A., Ryan, P., 2018. Wayfinder: a resilience guide for navigating
670 towards sustainable futures. GRAID Program Stock Resil Cent <https://wayfinder.earthaccess.org/> Accessed 31.

671 Ferreyra, R.A., Podesta, G.P., Messina, C.D., Letson, D., Dardanelli, J., Guevara, E., Meira, S., 2001. A
672 linked-modeling framework to estimate maize production risk associated with ENSO-related
673 climate variability in Argentina. *Agric. For. Meteorol.* 107, 177–192.

674 Fletcher, C.S., Hilbert, D.W., 2007. Resilience in landscape exploitation systems. *Ecol. Model.* 201, 440–
675 452. <https://doi.org/10.1016/j.ecolmodel.2006.10.011>

676 Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob.*
677 *Environ. Change* 16, 253–267. <https://doi.org/10.1016/j.gloenvcha.2006.04.002>

678 Gallopín, G.C., 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Glob. Environ.*
679 *Change* 16, 293–303. <https://doi.org/10.1016/j.gloenvcha.2006.02.004>

680 Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015.
681 Increasing Crop Diversity Mitigates Weather Variations and Improves Yield Stability. *PLOS ONE*
682 10, e0113261. <https://doi.org/10.1371/journal.pone.0113261>

683 Ge, L., Anten, N.P., van Dixhoorn, I.D., Feindt, P.H., Kramer, K., Leemans, R., Meuwissen, M.P., Spoolder,
684 H., Sukkel, W., 2016. Why we need resilience thinking to meet societal challenges in bio-based
685 production systems. *Curr. Opin. Environ. Sustain.*, Open Issue, part I 23, 17–27.
686 <https://doi.org/10.1016/j.cosust.2016.11.009>

687 Gil, J., Cohn, A.S., Duncan, J., Newton, P., Vermeulen, S., 2017. The resilience of integrated agricultural
688 systems to climate change. *WIREs Clim. Change* 8, e461. <https://doi.org/10.1002/wcc.461>

689 Gillespie-Marthaler, L., Nelson, K., Baroud, H., Abkowitz, M., 2019. Selecting Indicators for Assessing
690 Community Sustainable Resilience. *Risk Anal.* risa.13344. <https://doi.org/10.1111/risa.13344>

691 Gillespie-Marthaler, L., Nelson, K.S., Baroud, H., Kosson, D.S., Abkowitz, M., 2019. An integrative
692 approach to conceptualizing sustainable resilience. *Sustain. Resilient Infrastruct.* 4, 66–81.
693 <https://doi.org/10.1080/23789689.2018.1497880>

694 Grafton, R.Q., Doyen, L., Béné, C., Borgomeo, E., Brooks, K., Chu, L., Cumming, G.S., Dixon, J., Dovers, S.,
695 Garrick, D., Helfgott, A., Jiang, Q., Katic, P., Kompas, T., Little, L.R., Matthews, N., Ringler, C.,
696 Squires, D., Steinshamn, S.I., Villasante, S., Wheeler, S., Williams, J., Wyrwoll, P.R., 2019.
697 Realizing resilience for decision-making. *Nat. Sustain.* 2, 907–913.
698 <https://doi.org/10.1038/s41893-019-0376-1>

699 Grêt-Regamey, A., Huber, S.H., Huber, R., 2019. Actors’ diversity and the resilience of social-ecological
700 systems to global change. *Nat. Sustain.* <https://doi.org/10.1038/s41893-019-0236-z>

701 Hodbod, J., Barreteau, O., Allen, C., Magda, D., 2016. Managing adaptively for multifunctionality in
702 agricultural systems. *J. Environ. Manage.* 183, 379–388.
703 <https://doi.org/10.1016/j.jenvman.2016.05.064>

704 Holling, C.S., 1973. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* 4, 1–23.
705 <https://doi.org/10.1146/annurev.es.04.110173.000245>

706 Holling, C.S., Gunderson, L., Light, S., 1995. *Barriers and Bridges to the Renewal of Ecosystems*. New York:
707 Columbia University Press.

708 Hoover, D.L., Knapp, A.K., Smith, M.D., 2014. Resistance and resilience of a grassland ecosystem to
709 climate extremes. *Ecology* 95, 2646–2656. <https://doi.org/10.1890/13-2186.1>

710 Ingrisich, J., Bahn, M., 2018. Towards a Comparable Quantification of Resilience. *Trends Ecol. Evol.* 33,
711 251–259. <https://doi.org/10.1016/j.tree.2018.01.013>

712 IPCC, Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y.,
713 Bex, V., Midgley, P.M., 2013. Working Group I Contribution to the Fifth Assessment Report of the
714 Intergovernmental Panel on Climate Change 14.

715 Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T.M., Bonin, C.,
716 Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J.N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A.,
717 Kreyling, J., Lanta, V., Manning, P., Meyer, S.T., Mori, A.S., Naeem, S., Niklaus, P.A., Polley, H.W.,
718 Reich, P.B., Roscher, C., Seabloom, E.W., Smith, M.D., Thakur, M.P., Tilman, D., Tracy, B.F., van
719 der Putten, W.H., van Ruijven, J., Weigelt, A., Weisser, W.W., Wilsey, B., Eisenhauer, N., 2015.
720 Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526,
721 574–577. <https://doi.org/10.1038/nature15374>

722 Kahiluoto, H., Kaseva, J., Hakala, K., Himanen, S.J., Jauhiainen, L., Rötter, R.P., Salo, T., Trnka, M., 2014.
723 Cultivating resilience by empirically revealing response diversity. *Glob. Environ. Change* 25, 186–
724 193. <https://doi.org/10.1016/j.gloenvcha.2014.02.002>

725 Khumairoh, U., Lantinga, E.A., Schulte, R.P.O., Suprayogo, D., Groot, J.C.J., 2018. Complex rice systems to
726 improve rice yield and yield stability in the face of variable weather conditions. *Sci. Rep.* 8,
727 14746. <https://doi.org/10.1038/s41598-018-32915-z>

728 Lake, P.S., 2013. Resistance, Resilience and Restoration. *Ecol. Manag. Restor.* 14, 20–24.
729 <https://doi.org/10.1111/emr.12016>

730 Leonhardt, S.D., Gallai, N., Garibaldi, L.A., Kuhlmann, M., Klein, A.-M., 2013. Economic gain, stability of
731 pollination and bee diversity decrease from southern to northern Europe. *Basic Appl. Ecol.* 14,
732 461–471. <https://doi.org/10.1016/j.baae.2013.06.003>

733 Li, J., Huang, L., Zhang, J., Coulter, J.A., Li, L., Gan, Y., 2019. Diversifying crop rotation improves system
734 robustness. *Agron. Sustain. Dev.* 39, 38. <https://doi.org/10.1007/s13593-019-0584-0>

735 Li, M., Peterson, C.A., Tautges, N.E., Scow, K.M., Gaudin, A.C.M., 2019. Yields and resilience outcomes of
736 organic, cover crop, and conventional practices in a Mediterranean climate. *Sci. Rep.* 9, 12283.
737 <https://doi.org/10.1038/s41598-019-48747-4>

738 Lien, G., Hardaker, J.B., Flaten, O., 2007. Risk and economic sustainability of crop farming systems. *Agric.*
739 *Syst.* 94, 541–552. <https://doi.org/10.1016/j.agsy.2007.01.006>

740 Ludwig, D., Walker, B., Holling, C.S., 1997. Sustainability, Stability, and Resilience. *Conserv. Ecol.* 1.

741 Macholdt, J., Styczen, M.E., Macdonald, A., Piepho, H.-P., Honermeier, B., 2020. Long-term analysis from
742 a cropping system perspective: Yield stability, environmental adaptability, and production risk of
743 winter barley. *Eur. J. Agron.* 117, 126056. <https://doi.org/10.1016/j.eja.2020.126056>

744 Mäkinen, H., Kaseva, J., Virkajärvi, P., Kahiluoto, H., 2015. Managing resilience of forage crops to climate
745 change through response diversity. *Field Crops Res.* 183, 23–30.
746 <https://doi.org/10.1016/j.fcr.2015.07.006>

747 Martin, E.A., Feit, B., Requier, F., Friberg, H., Jonsson, M., 2019. Assessing the resilience of biodiversity-
748 driven functions in agroecosystems under environmental change, in: *Advances in Ecological*
749 *Research*. Elsevier, pp. 59–123. <https://doi.org/10.1016/bs.aecr.2019.02.003>

750 Martin, G., Magne, M.A., 2015. Agricultural diversity to increase adaptive capacity and reduce
751 vulnerability of livestock systems against weather variability – A farm-scale simulation study.
752 *Agric. Ecosyst. Environ.* 199, 301–311. <https://doi.org/10.1016/j.agee.2014.10.006>

753 Martin, G., Magne, M.-A., Cristobal, M.S., 2017. An Integrated Method to Analyze Farm Vulnerability to
754 Climatic and Economic Variability According to Farm Configurations and Farmers' Adaptations.
755 *Front. Plant Sci.* 8, 1483. <https://doi.org/10.3389/fpls.2017.01483>

756 Matsushita, K., Yamane, F., Asano, K., 2016. Linkage between crop diversity and agro-ecosystem
757 resilience: Nonmonotonic agricultural response under alternate regimes. *Ecol. Econ.* 126, 23–31.
758 <https://doi.org/10.1016/j.ecolecon.2016.03.006>

759 May, R.M., 1975. Stability in ecosystems: some comments, in: *Unifying Concepts in Ecology*. Springer, pp.
760 161–168.

761 McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S., 2001. Climate change 2001: impacts,
762 adaptation, and vulnerability: contribution of Working Group II to the third assessment report of
763 the Intergovernmental Panel on Climate Change. Cambridge University Press.

764 Mechler, R., Hochrainer, S., Aaheim, A., Salen, H., Wreford, A., 2010. Modelling economic impacts and
765 adaptation to extreme events: Insights from European case studies. *Mitig. Adapt. Strateg. Glob.*
766 *Change* 15, 737–762. <https://doi.org/10.1007/s11027-010-9249-7>

767 Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., Mey, Y. de, Finger, R.,
768 Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P.,
769 Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciecchomska, A., Accatino, F.,
770 Kopainsky, B., Poortvliet, P.M., Candel, J.J.L., Maye, D., Severini, S., Senni, S., Soriano, B.,
771 Lagerkvist, C.-J., Peneva, M., Gavrilescu, C., Reidsma, P., 2019. A framework to assess the

772 resilience of farming systems. *Agric. Syst.* 176, 102656.
773 <https://doi.org/10.1016/j.agsy.2019.102656>

774 Meyer, K., Hoyer-Leitzel, A., Iams, S., Klasky, I., Lee, V., Ligtenberg, S., Bussmann, E., Zeeman, M.L., 2018.
775 Quantifying resilience to recurrent ecosystem disturbances using flow–kick dynamics. *Nat.*
776 *Sustain.* 1, 671–678. <https://doi.org/10.1038/s41893-018-0168-z>

777 Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der
778 Leeuw, S., Rockström, J., Hinkel, J., Downing, T., Folke, C., Nelson, D., 2010. Resilience and
779 Vulnerability: Complementary or Conflicting Concepts? *Ecol. Soc.* 15, 11.
780 <https://doi.org/10.5751/ES-03378-150311>

781 Müller, F., 2005. Indicating ecosystem and landscape organisation. *Ecol. Indic.* 5, 280–294.
782 <https://doi.org/10.1016/j.ecolind.2005.03.017>

783 Müller, F., Bergmann, M., Dannowski, R., Dippner, J.W., Gnauck, A., Haase, P., Jochimsen, M.C., Kasprzak,
784 P., Kröncke, I., Kümmerlin, R., Küster, M., Lischeid, G., Meesenburg, H., Merz, C., Millat, G.,
785 Müller, J., Padisák, J., Schimming, C.G., Schubert, H., Schult, M., Selmečzy, G., Shatwell, T., Stoll,
786 S., Schwabe, M., Soltwedel, T., Straile, D., Theuerkauf, M., 2016. Assessing resilience in long-term
787 ecological data sets. *Ecol. Indic.* 65, 10–43. <https://doi.org/10.1016/j.ecolind.2015.10.066>

788 Mumby, P.J., Chollett, I., Bozec, Y.-M., Wolff, N.H., 2014. Ecological resilience, robustness and
789 vulnerability: how do these concepts benefit ecosystem management? *Curr. Opin. Environ.*
790 *Sustain.* 7, 22–27. <https://doi.org/10.1016/j.cosust.2013.11.021>

791 Nelson, K., Gillespie-Marthaler, L., Baroud, H., Abkowitz, M., Kosson, D., 2019. An integrated and
792 dynamic framework for assessing sustainable resilience in complex adaptive systems. *Sustain.*
793 *Resilient Infrastruct.* 1–19. <https://doi.org/10.1080/23789689.2019.1578165>

794 Nyström, M., Jouffray, J.-B., Norström, A.V., Crona, B., Søgaard Jørgensen, P., Carpenter, S.R., Bodin, Ö.,
795 Galaz, V., Folke, C., 2019. Anatomy and resilience of the global production ecosystem. *Nature*
796 575, 98–108. <https://doi.org/10.1038/s41586-019-1712-3>

797 Oram, N.J., De Deyn, G.B., Bodelier, P.L.E., Cornelissen, J.H.C., Groenigen, J.W., Abalos, D., 2020. Plant
798 community flood resilience in intensively managed grasslands and the role of the plant economic
799 spectrum. *J. Appl. Ecol.* 57, 1524–1534. <https://doi.org/10.1111/1365-2664.13667>

800 Parry, M., Parry, M.L., Canziani, O., Palutikof, J., Van der Linden, P., Hanson, C., others, 2007. Climate
801 change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth
802 assessment report of the IPCC. Cambridge University Press.

803 Perrin, A., Cristobal, M.S., Milestad, R., Martin, G., 2020. Identification of resilience factors of organic
804 dairy cattle farms. *Agric. Syst.* 183, 102875. <https://doi.org/10.1016/j.agsy.2020.102875>

805 Peterson, C.A., Eviner, V.T., Gaudin, A.C.M., 2018. Ways forward for resilience research in
806 agroecosystems. *Agric. Syst.* 162, 19–27. <https://doi.org/10.1016/j.agsy.2018.01.011>

807 Pfisterer, A.B., Schmid, B., 2002. Diversity-dependent production can decrease the stability of ecosystem
808 functioning. *Nature* 416, 84–86. <https://doi.org/10.1038/416084a>

809 Piedra-Bonilla, E.B., da Cunha, D.A., Braga, M.J., 2020. Climate variability and crop diversification in
810 Brazil: An ordered probit analysis. *J. Clean. Prod.* 256, 120252.
811 <https://doi.org/10.1016/j.jclepro.2020.120252>

812 Pimm, S.L., 1984. The complexity and stability of ecosystems. *Nature* 307, 321–326.

813 Pimm, S.L., Donohue, I., Montoya, J.M., Loreau, M., 2019. Measuring resilience is essential to understand
814 it. *Nat. Sustain.* 2, 895–897. <https://doi.org/10.1038/s41893-019-0399-7>

815 Prieto, I., Violle, C., Barre, P., Durand, J.-L., Ghesquiere, M., Litrico, I., 2015. Complementary effects of
816 species and genetic diversity on productivity and stability of sown grasslands. *Nat. Plants* 1,
817 15033. <https://doi.org/10.1038/nplants.2015.33>

818 Prosperi, P., Allen, T., Cogill, B., Padilla, M., Peri, I., 2016. Towards metrics of sustainable food systems: a
819 review of the resilience and vulnerability literature. *Environ. Syst. Decis.* 36, 3–19.
820 <https://doi.org/10.1007/s10669-016-9584-7>

821 Quinlan, A.E., Berbés-Blázquez, M., Haider, L.J., Peterson, G.D., 2016. Measuring and assessing resilience:
822 broadening understanding through multiple disciplinary perspectives. *J. Appl. Ecol.* 53, 677–687.
823 <https://doi.org/10.1111/1365-2664.12550>

824 Redhead, J.W., Oliver, T.H., Woodcock, B.A., Pywell, R.F., 2020. The influence of landscape composition
825 and configuration on crop yield resilience. *J. Appl. Ecol.* 1365-2664.13722.
826 <https://doi.org/10.1111/1365-2664.13722>

827 Reidsma, P., Ewert, F., 2008. Regional Farm Diversity Can Reduce Vulnerability of Food Production to
828 Climate Change. *Ecol. Soc.* 13. <https://doi.org/10.5751/ES-02476-130138>

829 Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate
830 variability in European agriculture: The importance of farm level responses. *Eur. J. Agron.* 32, 91–
831 102. <https://doi.org/10.1016/j.eja.2009.06.003>

832 Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2009a. Vulnerability and adaptation of European
833 farmers: a multi-level analysis of yield and income responses to climate variability. *Reg. Environ.*
834 *Change* 9, 25. <https://doi.org/10.1007/s10113-008-0059-3>

835 Reidsma, P., Oude Lansink, A., Ewert, F., 2009b. Economic impacts of climatic variability and subsidies on
836 European agriculture and observed adaptation strategies. *Mitig. Adapt. Strateg. Glob. Change*
837 14, 35–59. <https://doi.org/10.1007/s11027-008-9149-2>

838 Rist, L., Felton, A., Nyström, M., Troell, M., Sponseller, R.A., Bengtsson, J., Österblom, H., Lindborg, R.,
839 Tidåker, P., Angeler, D.G., Milestad, R., Moen, J., 2014. Applying resilience thinking to production
840 ecosystems. *Ecosphere* 5, art73. <https://doi.org/10.1890/ES13-00330.1>

841 Sabatier, R., Oates, L.G., Brink, G.E., Bleier, J., Jackson, R.D., 2015. Grazing in an Uncertain Environment:
842 Modeling the Trade-Off between Production and Robustness. *Agron. J.* 107, 257.
843 <https://doi.org/10.2134/agronj14.0357>

844 Salvati, L., 2010. Exploring the Relationship between Agricultural Productivity and Land Degradation in a
845 Dry Region of Southern Europe. *New Medit* 35.

846 Scheffer, M., Carpenter, S.R., Dakos, V., van Nes, E.H., 2015. Generic Indicators of Ecological Resilience:
847 Inferring the Chance of a Critical Transition. *Annu. Rev. Ecol. Evol. Syst.* 46, 145–167.
848 <https://doi.org/10.1146/annurev-ecolsys-112414-054242>

849 Schmitt, E., Galli, F., Menozzi, D., Maye, D., Touzard, J.-M., Marescotti, A., Six, J., Brunori, G., 2017.
850 Comparing the sustainability of local and global food products in Europe. *J. Clean. Prod.* 165,
851 346–359. <https://doi.org/10.1016/j.jclepro.2017.07.039>

852 Seo, S.N., 2010. A Microeconometric Analysis of Adapting Portfolios to Climate Change: Adoption of
853 Agricultural Systems in Latin America. *Appl. Econ. Perspect. Policy* 32, 489–514.
854 <https://doi.org/10.1093/aep/32.3.489>

855 Singh, A.P., Dhadse, K., 2021. Economic evaluation of crop production in the Ganges region under
856 climate change: A sustainable policy framework. *J. Clean. Prod.* 278, 123413.
857 <https://doi.org/10.1016/j.jclepro.2020.123413>

858 Smit, B., Pilifosova, O., 2003. Adaptation to climate change in the context of sustainable development
859 and equity. *Sustain. Dev.* 8, 9.

860 Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. *Glob. Environ. Change* 16,
861 282–292. <https://doi.org/10.1016/j.gloenvcha.2006.03.008>

862 Sneessens, I., Sauvé, L., Randrianasolo-Rakotobe, H., Ingrand, S., 2019. A framework to assess the
863 economic vulnerability of farming systems: Application to mixed crop-livestock systems. *Agric.*
864 *Syst.* 176, 102658. <https://doi.org/10.1016/j.agsy.2019.102658>

865 Stampfli, A., Bloor, J.M.G., Fischer, M., Zeiter, M., 2018. High land-use intensity exacerbates shifts in
866 grassland vegetation composition after severe experimental drought. *Glob. Change Biol.* 24,
867 2021–2034. <https://doi.org/10.1111/gcb.14046>

868 Stelling, J., Sauer, U., Szallasi, Z., Doyle, F.J., Doyle, J., 2004. Robustness of Cellular Functions. *Cell* 118,
869 675–685. <https://doi.org/10.1016/j.cell.2004.09.008>

870 Stockholm Resilience Center, 2015. What Is Resilience? An Introduction to a Popular yet Often
871 Misunderstood Concept.

872 Tendall, D.M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q.B., Kruetli, P., Grant, M., Six, J., 2015.
873 Food system resilience: Defining the concept. *Glob. Food Secur.* 6, 17–23.
874 <https://doi.org/10.1016/j.gfs.2015.08.001>

875 Turner, B.L., 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability
876 science? *Glob. Environ. Change* 20, 570–576. <https://doi.org/10.1016/j.gloenvcha.2010.07.003>

877 Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N.,
878 Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework
879 for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci.* 100, 8074–8079.
880 <https://doi.org/10.1073/pnas.1231335100>

881 Urruty, N., Guyomard, H., Tailliez-Lefebvre, D., Huyghe, C., 2017. Factors of winter wheat yield
882 robustness in France under unfavourable weather conditions. *Eur. J. Agron.* 90, 174–183.
883 <https://doi.org/10.1016/j.eja.2017.08.002>

884 Urruty, N., Tailliez-Lefebvre, D., Huyghe, C., 2016. Stability, robustness, vulnerability and resilience of
885 agricultural systems. A review. *Agron. Sustain. Dev.* 36, 15. [https://doi.org/10.1007/s13593-015-](https://doi.org/10.1007/s13593-015-0347-5)
886 0347-5

887 van Strien, M.J., Huber, S.H., Anderies, J.M., Grêt-Regamey, A., 2019. Resilience in social-ecological
888 systems: identifying stable and unstable equilibria with agent-based models. *Ecol. Soc.* 24, art8.
889 <https://doi.org/10.5751/ES-10899-240208>

890 Vetter, V.M.S., Kreyling, J., Dengler, J., Apostolova, I., Arfin-Khan, M.A.S., Berauer, B.J., Berwaers, S., De
891 Boeck, H.J., Nijs, I., Schuchardt, M.A., Sopotlieva, D., Gillhausen, P., Wilfahrt, P.A., Zimmermann,
892 M., Jentsch, A., 2020. Invader presence disrupts the stabilizing effect of species richness in plant
893 community recovery after drought. *Glob. Change Biol.* 26, 3539–3551.
894 <https://doi.org/10.1111/gcb.15025>

895 Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A.P., 2004. Resilience, Adaptability and Transformability
896 in Social-ecological Systems. *Ecol. Soc.* 9, art5. <https://doi.org/10.5751/ES-00650-090205>

897 Walker, B., Meyers, J.A., 2004. Thresholds in Ecological and Social Ecological Systems: a Developing
898 Database. *Ecol. Soc.* 9, 3. <https://doi.org/10.5751/ES-00664-090203>

899 Wiréhn, L., Danielsson, Å., Neset, T.-S.S., 2015. Assessment of composite index methods for agricultural
900 vulnerability to climate change. *J. Environ. Manage.* 156, 70–80.
901 <https://doi.org/10.1016/j.jenvman.2015.03.020>

902 Wright, B.D., 2011. The Economics of Grain Price Volatility. *Appl. Econ. Perspect. Policy* 33, 32–58.
903 <https://doi.org/10.1093/aep/ppq033>

904 Wu, J., 2013. Landscape sustainability science: ecosystem services and human well-being in changing
905 landscapes. *Landsc. Ecol.* 28, 999–1023. <https://doi.org/10.1007/s10980-013-9894-9>

906 Yang, L.-N., Pan, Z.-C., Zhu, W., Wu, E.-J., He, D.-C., Yuan, X., Qin, Y.-Y., Wang, Y., Chen, R.-S., Thrall, P.H.,
907 Burdon, J.J., Shang, L.-P., Sui, Q.-J., Zhan, J., 2019. Enhanced agricultural sustainability through
908 within-species diversification. *Nat. Sustain.* 2, 46–52. [https://doi.org/10.1038/s41893-018-0201-](https://doi.org/10.1038/s41893-018-0201-2)
909 2

910 Zampieri, M., Toreti, A., Ceglar, A., Naumann, G., Turco, M., Tebaldi, C., 2020a. Climate resilience of the
911 top ten wheat producers in the Mediterranean and the Middle East. *Reg. Environ. Change* 20, 41.
912 <https://doi.org/10.1007/s10113-020-01622-9>

913 Zampieri, M., Weissteiner, C.J., Grizzetti, B., Toreti, A., van den Berg, M., Dentener, F., 2020b. Estimating
914 resilience of crop production systems: From theory to practice. *Sci. Total Environ.* 735, 139378.
915 <https://doi.org/10.1016/j.scitotenv.2020.139378>
916 Zavalloni, C., Gielen, B., Lemmens, C.M.H.M., Boeck, H.J.D., Blasi, S., Bergh, S.V. den, Nijs, I., Ceulemans,
917 R., 2008. Does a warmer climate with frequent mild water shortages protect grassland
918 communities against a prolonged drought? *Plant Soil* 308, 119–130.
919 <https://doi.org/10.1007/s11104-008-9612-6>
920 Zhang, F., Chen, Y., Zhang, J., Guo, E., Wang, R., Li, D., 2019. Dynamic drought risk assessment for maize
921 based on crop simulation model and multi-source drought indices. *J. Clean. Prod.* 233, 100–114.
922 <https://doi.org/10.1016/j.jclepro.2019.06.051>
923 Žurovec, O., Čadro, S., Sitaula, B., 2017. Quantitative Assessment of Vulnerability to Climate Change in
924 Rural Municipalities of Bosnia and Herzegovina. *Sustainability* 9, 1208.
925 <https://doi.org/10.3390/su9071208>
926