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

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Abstract

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

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

1. Introduction

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

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

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 Pilifosova (2003)

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

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

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

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

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

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

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

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

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

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

2. Methodology

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

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

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

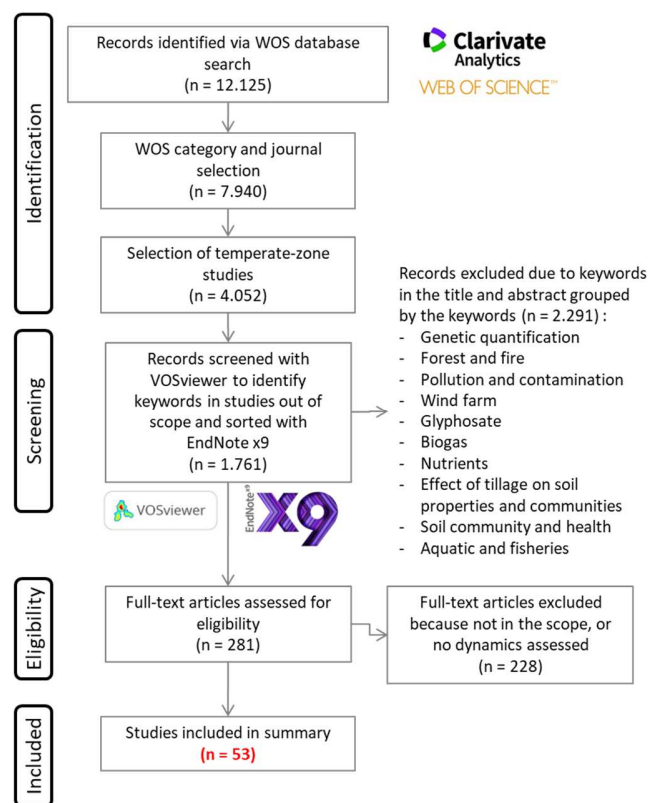


Figure 1. Description of the method used to select and sort articles according to the PRISMA protocol for a systematic review (Moher et al., 2015).

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

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

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

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

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

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

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

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

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

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

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

3. Results

3.1. Scope, farming systems and organization level

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

The articles reviewed focus mainly on the effect of climate disturbance (79% of articles) on agronomic yield (67% of articles) and economic attribute performances (net return in 15% of articles) of grasslands (30% of articles) and crop systems (43% of articles) at field (45% of articles), farm (33% of articles) and regional (18% of articles) levels (Supplementary material 4). Although these articles are relatively focused on climate disturbance and yields, they consider a variety of organization levels and types of production.

3.2. Concepts used

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

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

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

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

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

year time step. The spatial extents of the studies cannot be compared because they range from 1 m² plots at several sites in the world to a few dozen farms within a European Union NUTS2 region. Only one article studies the impact of the spatial extent of a disturbance (Mechler et al., 2010).

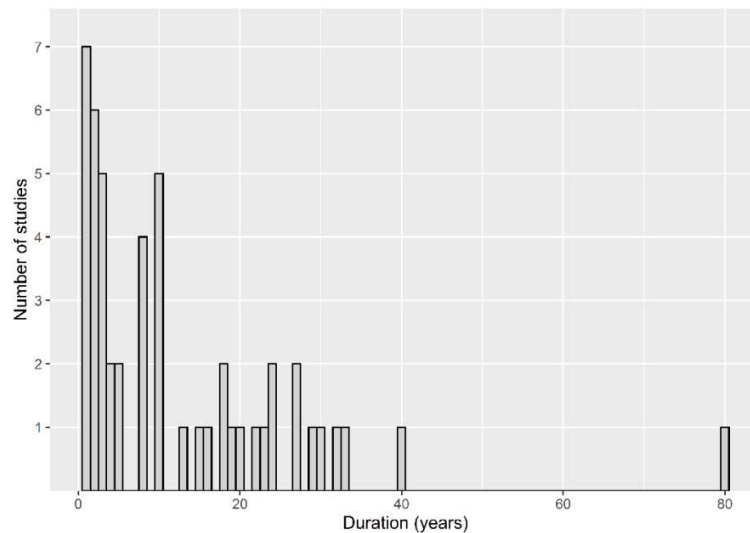


Figure 2. Temporal extent (duration) of analysis in each study reviewed (years).

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

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

3.4. Performance attributes and criteria to describe their dynamics

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

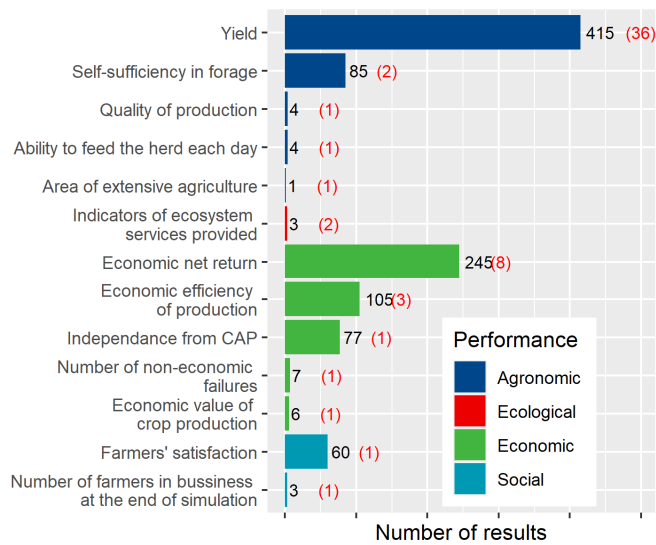


Figure 3. Number of results (in black) and articles (in red) by performance attribute whose dynamics are studied when disturbance occurs.

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

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

Table 3. Distribution of the 53 articles reviewed as a function of the number of performance 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

3.5. Combinations of concepts and criteria of dynamics

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

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

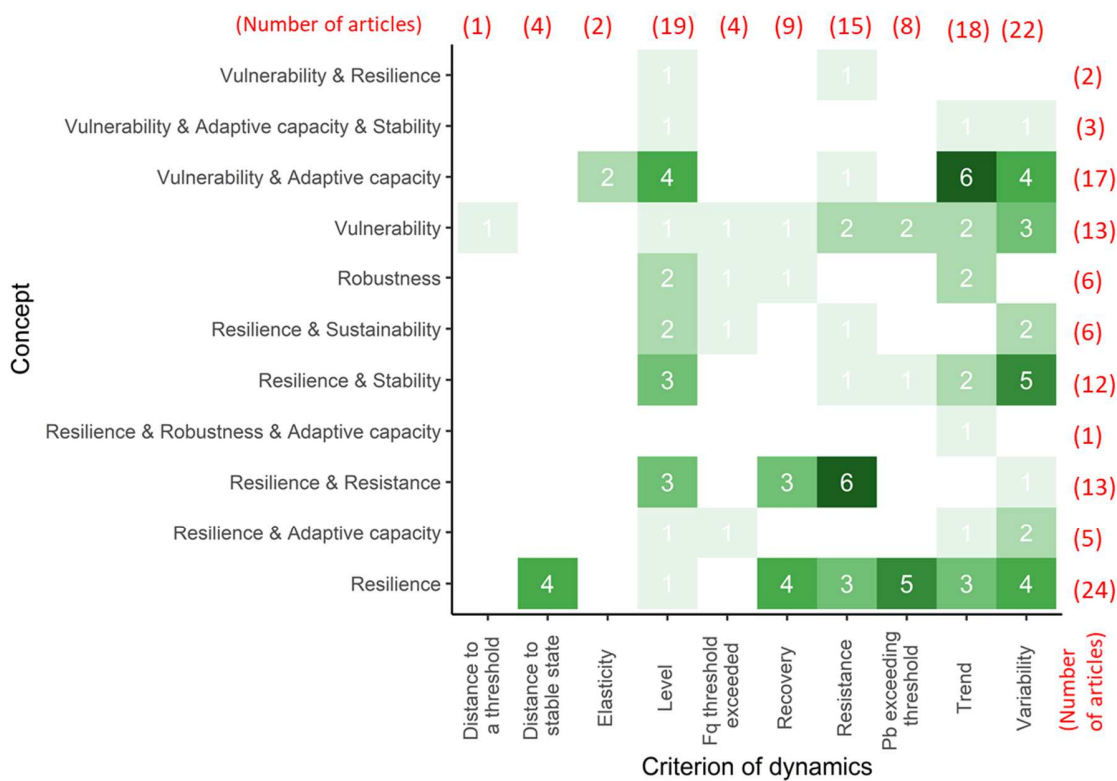


Figure 4. Number of articles reviewed as a function of concept(s) and criterion of dynamics of performance attribute. A given article can mention several concepts and/or criteria.

3.6. Explanatory factors tested

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

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

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

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

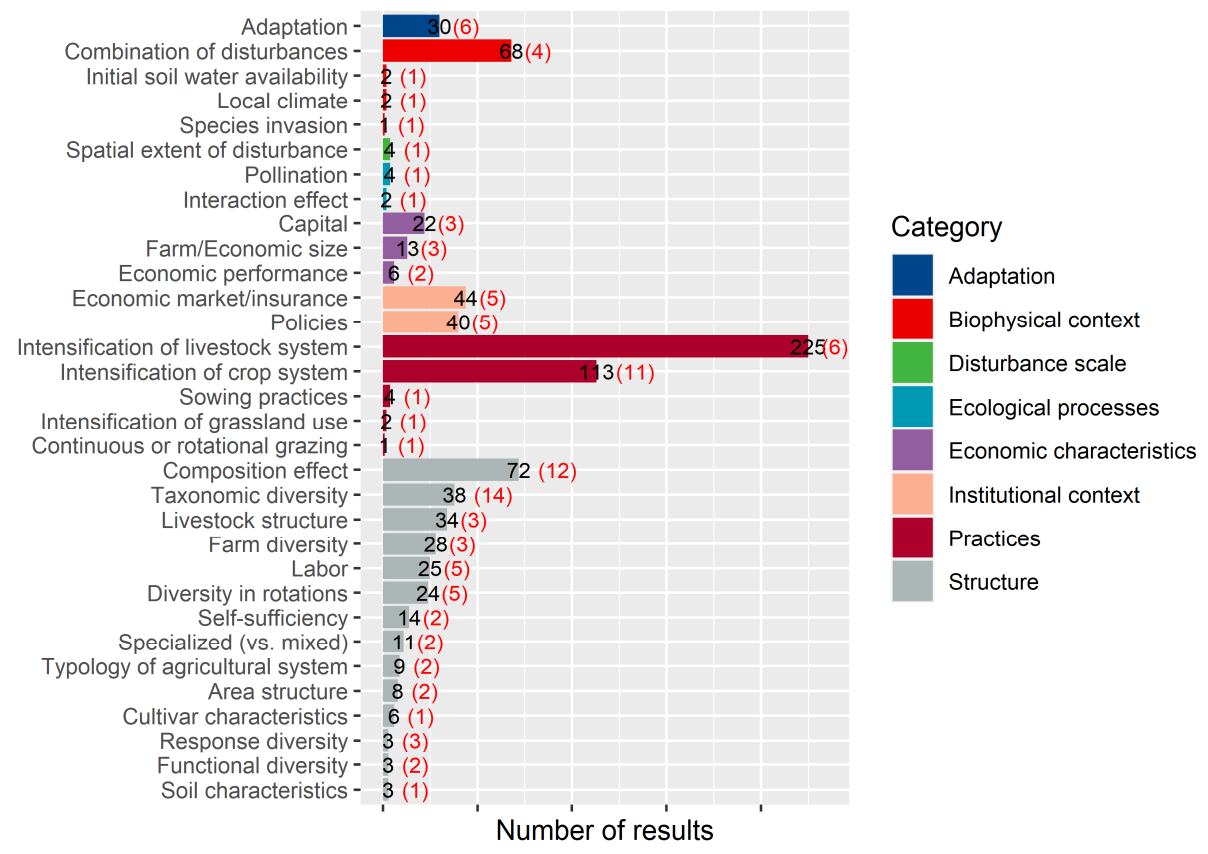


Figure 5. Number of results (in black) and articles (in red) by explanatory factor and its category.

4. Discussion

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

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

4.1. Relationships between VRRAC concepts and criteria of dynamics

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

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

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

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

4.2. Adaptive capacity

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

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

4.3. Temporal-scale effects

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

4.4. Multi-performance of agricultural systems

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

4.5. Multiplicity, complementarity and selection of criteria of dynamics

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

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

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

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

4.6. Multiplicity, complementarity and selection of explanatory factors

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

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

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

Table 4. Resilience properties described by Cabell and Oelofse (2012) and potential explanatory 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).

5. Conclusion

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

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

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

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

Contributions

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

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