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## Title

Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems

## Authors

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## Abstract

In a changing world, identifying the drivers of vulnerability, resilience and robustness (VRR) of agricultural systems has become a major issue. We developed and applied a generic analytical framework to perform a systematic review of studies that quantitatively assess VRR of agricultural systems in temperate climate zones. After a thorough selection process based on visualizing bibliometric networks in the Web of Science database of peer-reviewed articles in English, we show that the core set of the 37 selected studies addressed mainly the effect of climate change on the yield of grassland and crop systems. Synthesis of the studies' results yields some main conclusions, but also reveals differences in the influence of diversity and intensification level. First, the synthesis shows that diversity enhances (i) resilient crop yield dynamics and (ii) levels of grassland biomass, but (iii) its effect on grassland biomass dynamics is unclear. In addition, the effect of crop intensification on yield dynamics depends on (iv) the intensification practice considered (e.g. irrigation, fertilisation), (v) its combination with other practices and (vi) the soil and climate. Transversally, the synthesis reveals that (vii) the nature of species in grasslands or crop rotations (e.g. presence of a legume) and (viii) the nature of farms in a region (e.g. economic size distribution) are strong drivers of VRR, i.e. composition has a strong effect. Furthermore,

(ix) the frequency of climate events, (x) short- vs. long-term analysis, (xi) nonlinear effects and (xii) the relative impact of disturbances in comparison with the impact of agricultural practices are all elements that make it difficult to draw clear conclusions about the influence of diversity and intensification. Finally, our results highlight that a functional approach should be used to decipher diversity-productivity relationships, and that agricultural practices and their appropriateness to the pedoclimatic context and local resources must be characterised finely when analysing drivers of VRR.

## **Keywords**

dynamics; farming system; climate change; yield; composition effect; diversification

### **1. Introduction**

Agricultural systems increasingly experience climatic and economic disturbances, and at the same time must address issues such as food security, economic viability and the quality of the environment (Coumou and Rahmstorf, 2012; Dessai and van der Sluijs, 2007). Identifying drivers that determine the ability of agricultural systems to continue to achieve these goals despite the occurrence of disturbances remains an operational and research issue (Tendall et al., 2015).

According to Mumby et al. (2014), three key conceptual frameworks are relevant and commonly used to analyse the ability of a managed ecosystem, such as an agricultural system, to maintain performances when disturbances occur:

- Resilience, which has received wide research interest in agriculture (Peterson et al., 2018) and is based mainly on Holling's ecological definition: the ability to withstand a shock and recover from adverse disturbances (Gunderson, 2000; Holling, 1973). Most recently, it has been defined as the ability to absorb disturbances and to benefit from the resulting changes to generate

opportunities that increase adaptive capacity (Engle, 2011; Resilience Alliance, 2010; Walker and Salt, 2012).

- Vulnerability, which is inversely related, is interdependent or intersects with resilience (Engle, 2011; Gallopín, 2006; Turner, 2010). It is defined as the degree to which a system is harmed due to disturbances or stress (Turner et al., 2003). Most studies present vulnerability as a function of the system's exposure to disturbances, its sensitivity and its adaptive capacity (Adger, 2006).
- Robustness, which is the ability to maintain desired levels of system outputs, especially agricultural, despite the occurrence of disturbances (Urruty et al., 2016).

These three conceptual frameworks are used to analyse dynamics (i.e. changes over time) of the structure or functions of a system to describe its behaviour when it experiences disturbances (Martin et al., 2011; Perrings, 1998; Urruty et al., 2016). The research community attempts to standardise definitions to provide common vocabulary and generic tools (from theoretical uses to quantification). However, debate continues about the differences and overlap among these three concepts (Miller et al., 2010; Mumby et al., 2014; Turner, 2010; Urruty et al., 2016; Wu, 2013). They are non-normative, as they do not specify, per se, structural characteristics or functions that should be maintained (Elmqvist et al., 2019). Because maintaining certain performances can be undesirable, "resilience is not always a good thing" (Gallopín, 2006; Walker and Meyers, 2004). Accordingly, vulnerability, resilience and robustness (VRR) frameworks may be considered as system properties, or the "tools" to achieve a "goal", which may be sustainability (a normative concept) (Elmqvist et al., 2019; Turner, 2010). Applying VRR frameworks to a system, such as an agricultural system, can identify the key functions to maintain. For example, Meuwissen et al. (2018) established a list of functions ("resilience for what purpose?") that farming systems provide that ensure sustainable development. For each function, they developed specific associated performance attributes (e.g. yield as an attribute of the function "agronomic performance").

While theoretical aspects have been discussed widely and qualitative assessments have been performed, fewer studies seem to have assessed VRR quantitatively (Douxchamps et al., 2017; Gillespie-Marthaler et al., 2019; Martin et al., 2017; Oliver et al., 2015). We assume that such studies exist, but that they are scattered over conceptual frameworks, disciplines and journals. To our knowledge, there is no synthesis of these scientific studies that quantitatively addresses the VRR of agricultural systems.

To address this lack, we performed a systematic review of such studies to summarise characteristics of the systems studied, available knowledge about the sensitivity of agricultural production and key explanatory factors of VRR. For this last objective, we first focussed on effects of diversity in its various forms, as diversity is commonly accepted to be a strong driver of dynamics of agricultural systems (Altieri et al., 2015; Biggs et al., 2012; Cabell and Oelofse, 2012; Lin, 2011; Oliver et al., 2015; Wiréhn et al., 2015), even though empirical evidence of its influence is scarce and debated (Ge et al., 2016; Gil et al., 2017; Prieto et al., 2015; Wang et al., 2019). Second, as discussed by others (Renard and Timan, 2019; Stampfli et al., 2018; Wang et al., 2019), we also investigated whether the intensification/production level of agroecosystems is a key driver of dynamics of these systems' performances.

## 2. Generic analytical framework

Due to the diversity and ambiguity of the VRR frameworks, we developed an analytical framework that enabled us to perform a systematic review of studies regardless of the conceptual framework used (Table 1). Based on the frameworks of Allen et al. (2016), Carpenter et al. (2001), Meuwissen et al. (2019) and Müller et al. (2016), we characterised each study in terms of:

- *what agricultural system* is potentially harmed: We considered the entire range of organisation levels (from plot to region) to provide a structured overview of VRR issues of the corresponding agricultural systems, as suggested by Therond et al. (2017).

- *which performance attribute(s)* to maintain: Investigated attributes can be agronomic (e.g. production level), economic (e.g. income), social (e.g. workload) or ecological (e.g. ecosystem services). We also classified the criterion used to describe dynamics of the performance attribute (e.g. variability, trend, recovery, resistance).
- *what disturbances*: Agricultural systems can experience many biophysical and socioeconomic disturbances, corresponding to shock(s) (e.g. extreme events) or long-term pressure(s) (e.g. increase in temperature due to climate change) (Carpenter et al., 2001; Müller et al., 2016; Scoones et al., 2007).
- *when and where* analysis was performed: The spatial and temporal extent and resolution of studies, which are key drivers of their results (Allen et al., 2016; Müller et al., 2016).
- *which explanatory factors*: Investigated factors may be endogenous (e.g. internal system characteristics such as diversity) or exogenous (e.g. external environment, insurance) (Meuwissen et al., 2019).

<b>VRR study characteristics</b>	<b>Description</b>	<b>Caution about</b>	<b>Categories</b>	<b>Examples</b>	<b>Reference</b>
<b><i>what agricultural system</i></b>	<b>Agricultural system studied and harmed by the disturbance</b>	Nature and level of the system investigated	Plot/field, farming system, region, food system	Plot/field level: grassland Farm level: mixed production	Carpenter et al., 2001
<b><i>which performance attribute(s)</i></b>	<b>Performance attribute of the system whose dynamics are disturbed, and associated criteria used to describe the dynamics</b>	Temporal extent of dynamics of the <i>attribute</i> and threshold of desired dynamics	Agronomic, economic, ecological	Yield, economic net return, ecosystem services provided to the population	Meuwissen et al., 2019; Müller et al., 2016
<b><i>what disturbance</i></b>	<b>Disturbance that occurred</b>	How disturbance is measured and threshold values	Shocks or long-term pressure	Shock: drought Long-term Pressure: climate change	Carpenter et al., 2001; Müller et al., 2016; Scoones et al., 2007
<b><i>when and where</i></b>	<b>Spatial and temporal resolution and extent of the study</b>	-	-	Monthly over 3 years Country level over Europe	Allen et al., 2016; Müller et al., 2016
<b><i>which explanatory factors</i></b>	<b>Potential explanatory factor of the VRR tested</b>	-	Endogenous or exogenous	Diversity, agricultural practices, subsidies	Meuwissen et al., 2019

Table 1. Analytical framework used for the systematic review, regardless of the conceptual framework used in the study (vulnerability, resilience and robustness (VRR)), inspired by Allen et al. (2016), Carpenter et al. (2001), Meuwissen et al. (2019) and Müller et al. (2016).

### 3. Method and study selection

To identify studies that quantitatively assessed VRR of agricultural systems, we performed an advanced search on the ISI Web of Science Core Collection (WoS, <http://www.isiknowledge.com>) for peer-reviewed articles in English for all available years (1956-July 2018). Our review focussed on studies that analysed dynamics of agricultural systems from the plot/field to regional levels. Studies that addressed

dynamics of organism communities and the biology and genetics of organisms (animals and crops) were excluded from the study.

As VRR are related to other key concepts used in agricultural research, in order not to miss an important article, we considered three key related concepts in the WOS query: (i) adaptive capacity, because it is a key sub-concept of vulnerability (Adger, 2006) but also can be considered an independent concept (Engle, 2011; Gallopín, 2006); (ii) viability theory and (iii) ecological integrity, of which the latter two are traditionally used to analyse dynamics of agricultural systems (Aubin, 2009; Müller et al., 2000). Accordingly, our WOS query was the following:

*TS = ((vulnerabilit\* OR resilien\* OR robustness\* OR "adaptive capacity" OR "ecological integrit\*" OR (viabilit\* AND theory)) AND (agri\* OR agro\* OR crop\* OR farm\* OR grass\* OR pastor\*) AND (indicator\* OR evaluat\* OR quantitativ\* OR quantif\* OR model\* OR simulat\* OR decrease OR increase OR assess\*))*

This query identified 9,807 articles. We first identified the relevant journals and WOS categories (6,451 articles remained) and then restricted the list to temperate climate zones (Kottek et al., 2006) to focus on similar agricultural systems, disturbances and ecological functioning, based on recommendations of Gil et al. (2017), who highlighted the inconsistency in generalising results from around the world, as their ecological and socio-economic functioning differ (3,399 articles remained). We used VOSviewer software to perform co-occurrence analysis (n=10 terms) of titles and abstracts to identify fields of study that lay outside our scope (e.g. genetics, glyphosate). We then used EndNote x9 software to search articles with a combination of terms to identify studies related to previously identified fields (with titles manually verified before exclusion) (1,409 articles remained). Then, titles and abstracts were read manually to select 231 potential articles. In this step, a second reader manually sorted a 10% random sample to test the influence of reader selection. This double-checking yielded 100% agreement between the two



readers. Finally, full reading of the 231 articles identified 37 that fell within the scope of the study (Supplementary material 1).

Our selection process showed that including adaptive capacity, viability theory and ecological integrity in the query did not add articles to the final selection of 37 articles (Supplementary material 2). Indeed, articles that mention these three concepts always mentioned VRR in their abstract. Accordingly, these additional concepts were not considered in our subsequent analysis.

Results of these 37 articles were extracted according to our analytical framework. Each result (combination of a *system – disturbance – performance attribute – dynamics criterion – explanatory factor*) was saved on one line of a database. Terminology was standardised, and each result was associated with its corresponding study, and results of statistical tests, if performed, were noted. This step enabled identification of similar systems and thus comparison of results.

## 4. Results

### 4.1. General studies' characteristics

We draw two main conclusions from analysis of these articles. First, the few quantitative studies identified (Supplementary material 1) confirms that quantitative assessment of agricultural system VRR remains rare. Second, most studies focus on certain systems, disturbances and *performance attributes* (Figure 1). Overall, 65% of the articles address climate change, while the main systems studied are grassland (35%) and crop (40%) systems, at the plot/field (38%), farm (35%) and regional (27%) levels. Studies focus mainly on the impact of disturbances on yield (72% of articles) and economic net return (16% of articles). Overall, 13% of the studies only analyse the sensitivity of dynamics of system *attribute(s)*, while 86% of them seek to determine the main factors that explain the behaviour studied. Diversity and intensification levels are the *explanatory factors* tested most, confirming their interest to the scientific community.

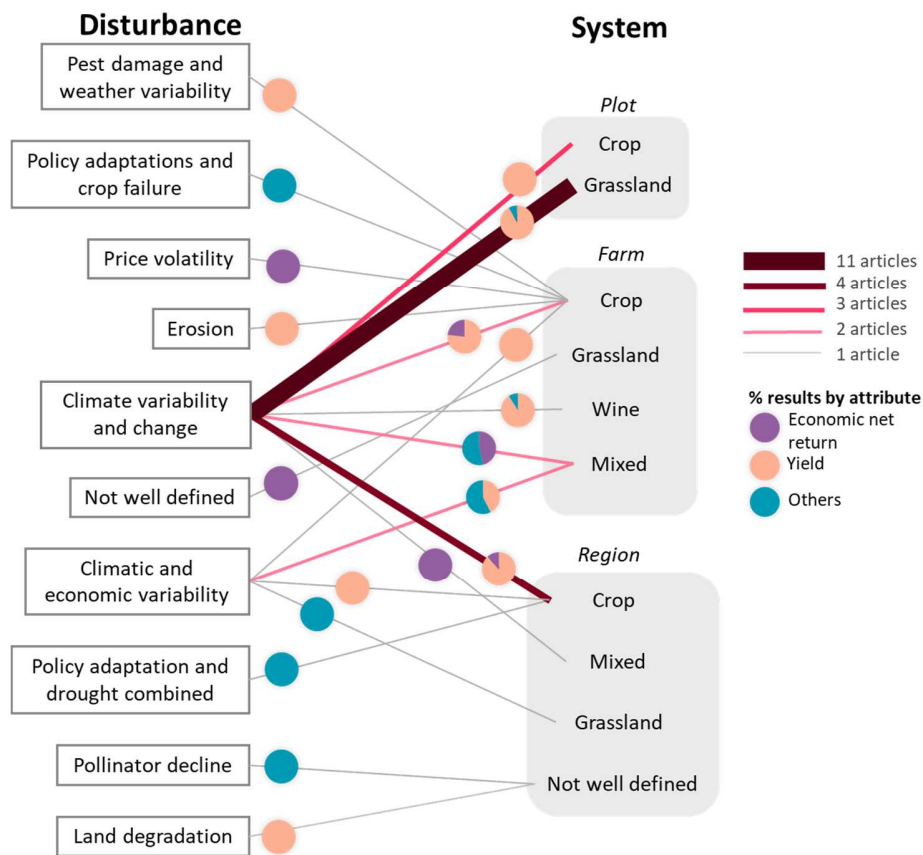


Figure 1. Overview of the main characteristics of the 37 articles selected that address the vulnerability, resilience and robustness of agricultural systems.

The 37 articles reviewed provide 506 individual “results”, that is, a direction of effect (negative, neutral, positive) of one *explanatory factor* on one performance *attribute*, described through one *criterion of dynamics* of one agricultural system experiencing one *disturbance*. To summarise, one result corresponds to a unique combination of *explanatory factor* - *performance attribute* - *criterion of dynamics* - *system* - *disturbance*. The number of results per article varies greatly (1-80) because several studies test many *explanatory factors* or use multiple *criteria of dynamics*. Some studies test results statistically, while others do not due to the mathematical method used.

To avoid presenting results based on only one study, we summarise results only when at least two studies analyse the same combination of *system* - *disturbance* - *performance attribute*. This approach

reduces the range of *attributes*, systems and disturbances reviewed to yield of grassland and crop systems to climate variability and change (combining interannual variability in temperature, drought) (Figure 1). Studies use different *performance attributes* to assess mixed systems, which hinders synthesis. For grassland studies, as suggested by Stampfli et al. (2018) and Wang et al. (2019), we distinguish grasslands by annual productivity level (high (> 20 t/ha), medium (5-20 t/ha) or low (< 5 t/ha)) to assess whether it influences their VRR to climate variability and change (Supplementary material 2). Nine *criteria of dynamics* are used to describe dynamics of the *performance attributes* studied (Supplementary material 4): level, variability, trend, resistance, recovery ratio or time, probability and frequency of exceeding a threshold, elasticity and distance from a stable state. Level corresponds to the mean of attribute values over the period investigated. Resistance is the difference in attribute values between pre-disturbance and post-disturbance levels. The recovery ratio is the ratio of the post-disturbance to pre-disturbance level, while the recovery time is the time required to recover to the initial level after disturbance. The probability of exceeding a threshold can be, for example, the probability of high yielding. The frequency of exceeding a threshold can be, for example, the number of times there are overgrazing. Elasticity is the intensity and direction of change. The distance from a stable state can be, for example, the eigenvalues of a variance-covariance matrix. Most of these *criteria of dynamics* are described in the review of indicators of resilience used in ecology by Scheffer et al. (2015). A summary of the number of uses of each criterion is presented in Supplementary material 4.

#### 4.2. Sensitivity of agricultural systems experiencing climatic disturbances

Before analysing effects of diversity and intensification level on the VRR of agricultural systems, we first summarise results of studies that analyse the sensitivity (Adger, 2006) of the yield of grassland and crop systems to climate change. Nine articles explicitly provide 76 results of such analysis (Di Falco and Chavas, 2008; Ferreyra et al., 2001; Hoover et al., 2014; Mäkinen et al., 2015; Prieto et al., 2015; Reidsma

et al., 2009a; Reidsma and Ewert, 2008; Stampfli et al., 2018; Zavalloni et al., 2008). The *criteria of dynamics* they used to analyse sensitivity of yield to climate change are level, variability, trend, resistance and probability of exceeding a threshold. Results by study are detailed in Supplementary material 5.

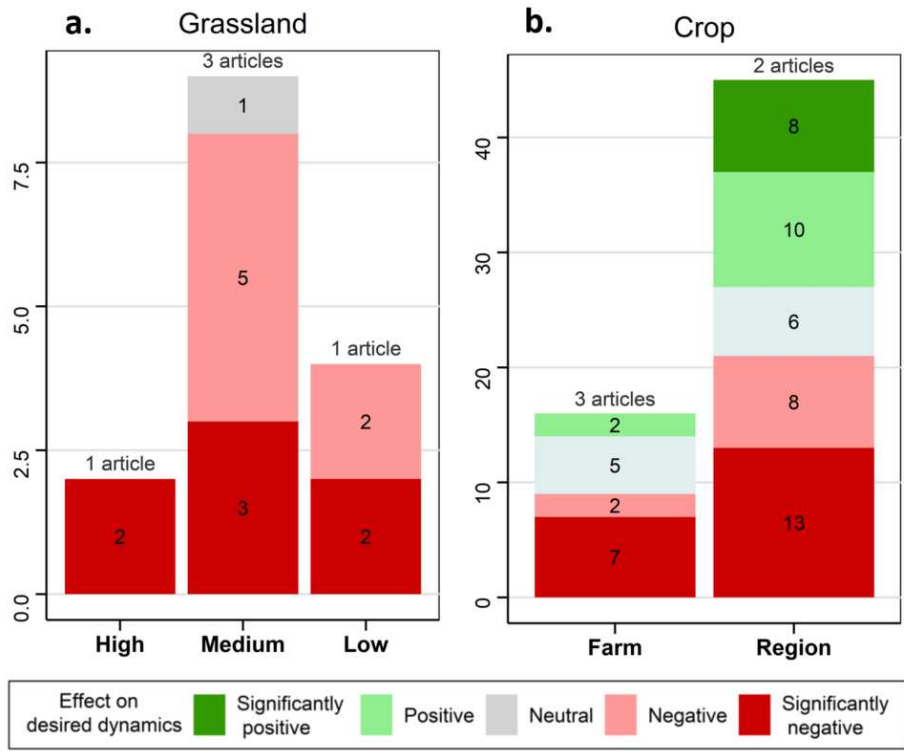


Figure 2. Number of results (and associated number of articles) indicating a direction and degree of effect of climate variability and change on desired (resilient) dynamics of yield, by (a) level of production (i.e. yield) at the plot/field level for grassland systems and (b) organisation level for crop systems. For grassland studies, we distinguish grasslands by annual productivity level (high (> 20 t/ha), medium (5-20 t/ha) or low (< 5 t/ha)). The desired direction of *criteria of dynamics* is described in the text. Significant effects are those that could be tested statistically and were found significantly different ( $p < 0.05$ ).

#### 4.2.1. Grassland systems

Climate change (higher temperatures and lower precipitation) has mostly negative effects on grassland yield at the plot/field level (Figure 2a). The effect of climatic disturbance is mainly negative, resulting in lower productivity (Zavalloni et al., 2008), high variability (Mäkinen et al., 2015; Prieto et al., 2015) and, during drought, low resistance of yield (Hoover et al., 2014; Stampfli et al., 2018; Zavalloni et al., 2008). High temperatures do not seem to induce low resistance of grassland yield, but their effect could vary according to their duration, magnitude or timing (Hoover et al., 2014). Plants sown during high temperatures (“heated plants”) do not develop benefits such as resistance of yield to hydrological stress (Zavalloni et al., 2008). In addition, “heated plants” transpire more than unheated plants during drought (De Boeck et al., 2011; Zavalloni et al., 2008). Combined drought and high temperatures can have either non additional negative effect on above-ground biomass (Hoover et al., 2014; Zavalloni et al., 2008) or either additional negative one (De Boeck et al., 2011). The productivity level of grassland systems does not seem to influence the negative effect of climatic disturbances. Grassland systems are more sensitive to drought than to high temperatures, regardless of productivity level. Stampfli et al. (2018) conclude that high productivity increases negative effects of drought on forb biomass only, not grass biomass.

#### 4.2.2. Crop systems

Negative effects of climate on crop systems are less clear than those on grasslands (Figure 2b). Most results (91%) are from Reidsma and Ewert (2008) and Reidsma et al. (2008a). Temperature (high, increasing and/or variable) and precipitation (low, decreasing and/or variable) have negative effects on crop yield for 55% of results (Reidsma et al., 2009a). Interestingly, some studies identify positive effects of an increase in temperature and decrease in precipitation (Ferreyra et al., 2001; Reidsma et al., 2009a; Reidsma and Ewert, 2008). This could be due to irrigation, which is a safeguard management practice during increased temperature (Ferreyra et al., 2001; Reidsma et al., 2008a) and decreased precipitation (Reidsma et al., 2008a), but the positive effect can decrease over time and be limited at high fertilisation

rates (Reidsma et al., 2009a). Extremely negative effects are observed in certain irrigated regions, such as Italy, and could be due to insufficient irrigation for crops that require large amounts of water, such as rice (Reidsma et al., 2009a).

In their study on policy adaptations and the effect of drought on crops at the regional level, Bitterman and Bennett (2016) show that crop yields in regions with larger disturbances are less sensitive to climate change. They conclude that this relation could be related to the adaptability of farmers and varies by region. Although crop systems remain sensitive in most regions, farmers in more exposed regions adapt crop species and management practices. Reidsma et al. (2008a) indicate that while yield is lower in warmer regions, climatic disturbances there harm crops less.

#### 4.3. Diversity, a driver of yield resilience for crops but not necessarily for grasslands

Twelve articles assess the extent to which diversity explains the VRR of the yield performance of crops and grasslands when experiencing climate variability and change, yielding 38 results (Barkaoui et al., 2016; Carlsson et al., 2017; Gaudin et al., 2015; Isbell et al., 2015; Matsushita et al., 2016; Pfisterer and Schmid, 2002; Prieto et al., 2015; Reidsma and Ewert, 2008; Urruty et al., 2017; Zavalloni et al., 2008; Reidsma et al., 2010; Carter and Blair, 2012). The *criteria of dynamics* they use are level, variability, trend, resistance, recovery and probability of exceeding a threshold. Results by study are detailed in Supplementary material 5.

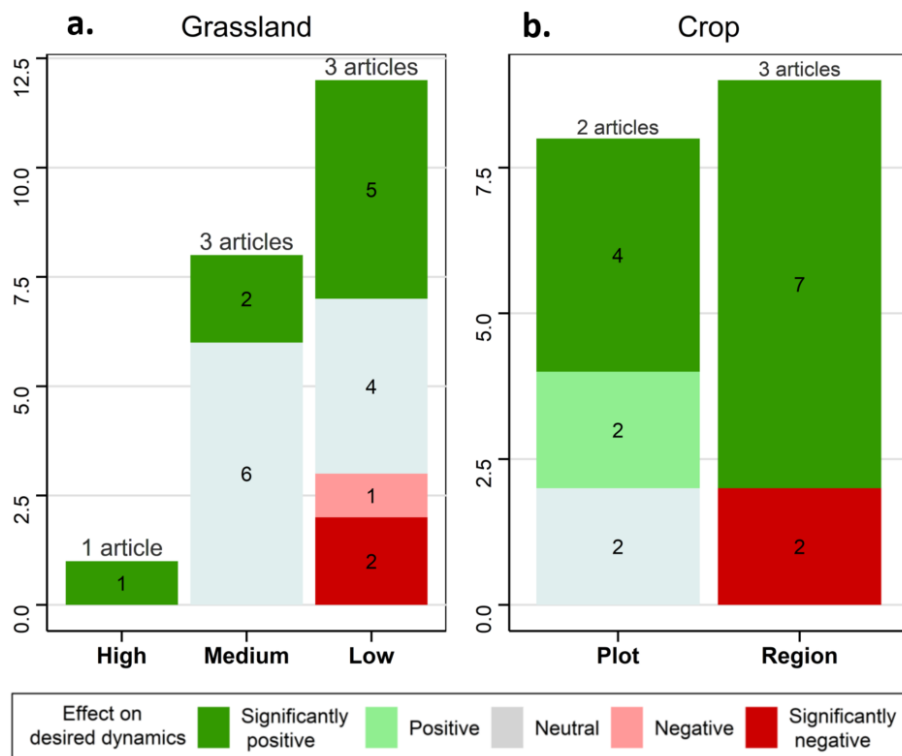


Figure 3. Number of results (and associated number of articles) indicating a direction and degree of effect of diversity on the effect of climate variability and change on desired (resilient) dynamics of yield, by (a) level of production (i.e. yield) at the plot/field level for grassland systems and (b) organisation level for crop systems. For grassland studies, we distinguish grasslands by annual productivity level (high (> 20 t/ha), medium (5-20 t/ha) or low (< 5 t/ha)). The desired direction of *criteria of dynamics* is described in the text. Significant effects are those that could be tested statistically and were found significantly different ( $p < 0.05$ ).

#### 4.3.1. Grassland diversity

To quantify plant diversity in grasslands at the plot level, 86% of results use species richness, 9% genetic richness and 5% (one result) functional description of plant diversity. Generally, diversity is not always related to the desired dynamics of yield (i.e. high level, low variability, increasing trend, high resistance and rapid recovery). The 48% of grassland results that are neutral (Figure 3a) corroborate the

assumption that the relation between diversity and grassland's yield resilience is not well established and requires additional study. However, results differ according to the *criteria of dynamics* used.

For the production level, species richness definitely increases the level of above-ground biomass produced during drought and climate variability (Isbell et al., 2015; Pfisterer and Schmid, 2002; Prieto et al., 2015; Zavalloni et al., 2008). In total, 80% of results indicate a positive effect of diversity on yield level, with no clear difference among annual production levels (high, medium or low). However, the effect of species richness on resistance (vs. level) of yield due to climate events depends on the study. Isbell et al. (2015) show higher resistance of yield of species-rich grasslands regardless of the direction and intensity of events, whereas Pfisterer and Schmid (2002) describe lower resistance of yield of species-rich grasslands under climatic disturbance. The frequency of climate events (Isbell et al., 2015) and the "composition effect" due to the presence of certain species (Pfisterer and Schmid, 2002) are considered explanatory factors. These results show that (i) biodiversity increases resistance to climate events that are preceded by other climate events and (ii) legumes decrease, but *Poa pratensis* increases, the resistance of yield of grasslands. Zavalloni et al. (2008) test whether complementarity and the selection effects (i.e. the probability of highly productive species) can explain low resistance of yield of species-rich grasslands. They determined that resistance to hydrological stress decreased due to the niche complementarity effect, since it increased plant water uptake and, in turn, subsequent soil water availability.

Species richness and root functional diversity have no impact (6 results, Barkaoui et al., 2016; Carter and Blair, 2012; Isbell et al., 2015) or negative impact on the recovery ratio of yield (1 result, Pfisterer and Schmid, 2002), which is surprising, because diversity is often associated with resilience, commonly assessed as a recovery time or ratio (Pimm, 1984). In tests of potential composition effects, Pfisterer and Schmid (2002) show that the presence of species particularly resistant to drought that are also highly



productive (*P. pratensis*, *Dactylis glomerata* and *Arrhenatherum elatius*) may determine the direction of observed results. Important results are that recovery of biomass production can be temporary, and so the temporal extent of observations influences the results (Pfisterer and Schmid, 2002). When considering the production trend, Prieto et al. (2015) show that during drought, multispecies grasslands grow an average of 10% faster than monocultures do. Furthermore, diversity in grassland species influences variability in yield both positively and negatively, depending on the frequency and direction of climatic disturbances (Isbell et al., 2015; Prieto et al., 2015). Finally, regardless of the level of intensification, effects of diversity on yield dynamics of grasslands experiencing climate change are not obvious and seem to depend on grassland composition, which indicators are used to assess yield dynamics and the temporal extent of observation.

#### 4.3.2. Crop diversity

For crop systems at the plot/field level, studies quantify biodiversity as species diversity in rotations. At the regional level, studies investigate diversity in farm types (size, land-cover richness and equity), taxonomic diversity of cultivars and diversity of responses (e.g. variability in yield by region). Again, results for crop systems are clearer than those for grasslands. For most results (76%), diversity has a positive effect on desired dynamics (high level, low variability, increasing trend, rapid recovery and a high probability of exceeding a threshold) when disturbance occurs (Figure 3b).

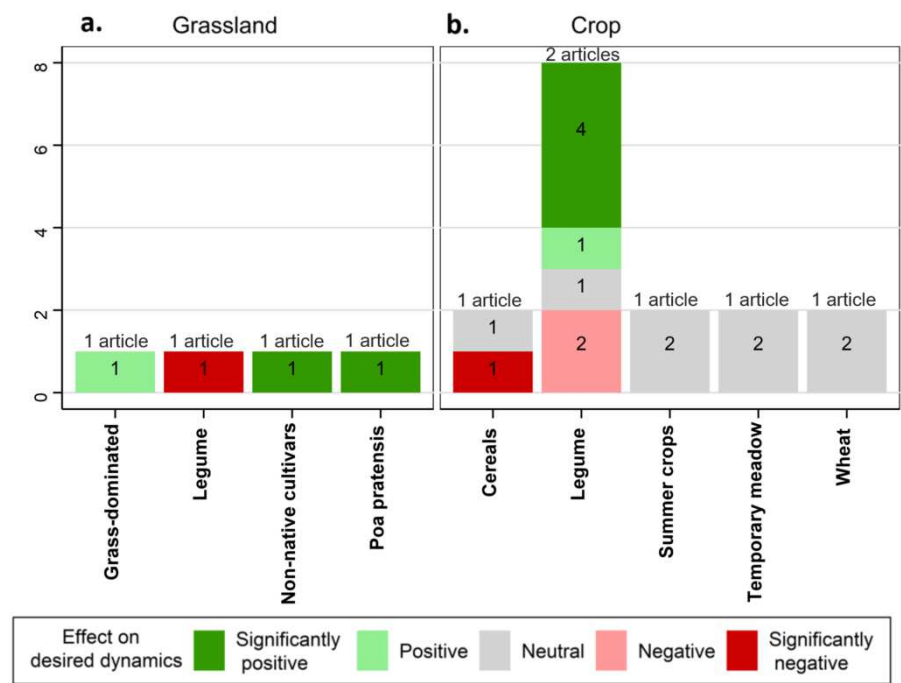
At the plot/field level, diversity in crop rotations always has a positive effect on the level of production and negative effect on its variability when soya bean is present (Gaudin et al., 2015; Urruty et al., 2017). Furthermore, diversity does influence the trend for yield. At plot and regional levels, within-farm diversity (crop species, varieties and rotations) has a positive effect on the desired dynamics of yield: high level, low variability, positive trend, resistance of yield, rapid recovery time and probability of exceeding a threshold (Di Falco and Chavas, 2008; Gaudin et al., 2015; Matsushita et al., 2016; Urruty et

al., 2017). A single negative effect (Matsushita et al., 2016) is explained as being due to specific characteristics of rice production (a composition effect).

At the regional level, Reidsma and Ewert (2008) show that diversity in farm type, size and intensity of production have a positive effect on decreasing yield variability under high temperatures. They also show that diversity in land use can increase negative effects of high temperatures on the variability in regional yield. Reidsma et al. (2008b) show that the negative effect of high temperatures increased for the largest farms, which they assume could be due to farmers on large farms having less aversion to risk.

#### 4.4. Major composition effects

Previous results tend to highlight the importance of considering the composition effect on the dynamics of system performances. Accordingly, we summarise results of the reviewed studies for the effect of a particular species or species group (Figure 4). Cereals, summer crops, temporary meadows, the proportion of grass/forbs, native cultivars and *P. pratensis* are tested for their effect on levels, variability, trend, resistance, recovery and probability of exceeding a threshold of yield of grassland and crop systems (Barkaoui et al., 2016; Carlsson et al., 2017; Gaudin et al., 2015; Pfisterer and Schmid, 2002; Urruty et al., 2017).



318 Figure 4. Number of results (and associated number of studies) indicating a direction and degree of  
319 effect of species composition on the effect of climate variability and change on desired (resilient)  
320 dynamics of yield by type of production for (a) grassland and (b) crops. The desired direction of *criteria of*  
321 *dynamics* is described in the text. Significant effects are those that could be tested statistically and were  
322 found significantly different ( $p<0.05$ ).

323

324 Barkaoui et al. (2016) show that the composition of Mediterranean grassland species has more effect  
325 than species diversity during drought. They emphasise root functional identity rather than root  
326 functional diversity as a key factor of resilience of the plant community, since root-depth distribution  
327 and root morphology determine the volume of soil water extracted and the ability to use it (additional  
328 reference in Nippert and Knapp, 2007). For example, deep-rooted plant communities resist more during  
329 summer drought and thus recover faster (Lopez-Iglesias et al., 2014; Padilla and Pugnaire, 2007).

Similarly, Carlsson et al. (2017) show that a single dominant functional group can resist drought more than several functional groups. Their study also shows that grassland systems with a high proportion of grass have higher resistance of yield than those with high proportion of forbs or legumes. Pfisterer and Schmid (2002) observed a positive correlation between *P. pratensis* abundance and the resistance of grassland yield. They also specify that resistant species can be selected and in turn induce rapid recovery following disturbances. Carlsson et al. (2017) suggest that the composition effect must be considered as a function of fertilisation rate because the latter can increase the abundance of certain species, such as grasses.

Specific effects of legumes have also been identified (Supplementary material 7). Carlsson et al. (2017) and Pfisterer and Schmid (2002) show that the abundance of legumes in grasslands can decrease resistance of yield during drought ( $p < 0.05$ ). In contrast, crop rotations that include legumes as a catch or cover crop improve the yield level and stability (Gaudin et al., 2015; Urruty et al., 2017), but the probability of exceeding the threshold of a high yield level depends on the legume species (Gaudin et al., 2015). For example, relay cropping with red clover more than doubled the likelihood of yield exceeding the 90<sup>th</sup> percentile ( $p < 0.05$ ), while alfalfa decreased the probability of exceeding a threshold of high yield (Gaudin et al., 2015).

#### 4.5. Intensifying inputs is not necessarily related to better yield dynamics

We summarised results of the reviewed studies for the effect of the level of input use intensification on the VRR of crop systems to climate change (temperature and drought) at the plot/field (2 articles) and regional (2 articles) levels (Figure 5). These studies focussed on the effect of intensification level on the dynamics of yield of crop systems. Intensification levels are described by fertilisation, soil improvement, tillage, irrigation, pesticide use and farm size. Results by study are detailed in Supplementary material 8.

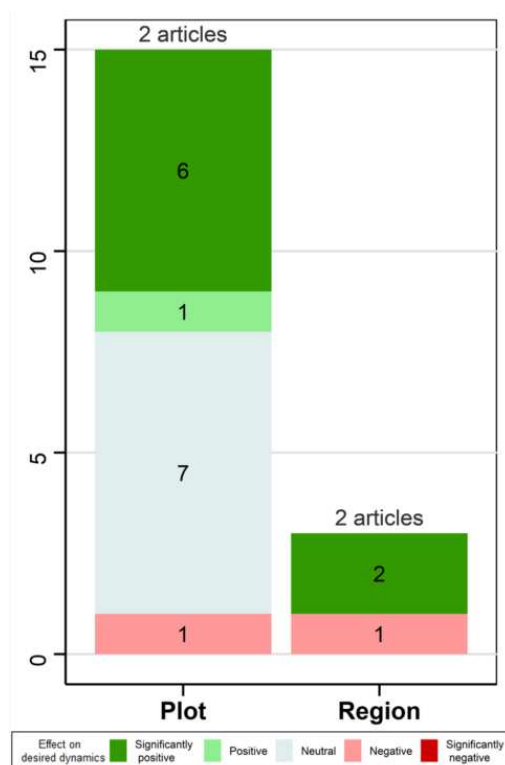


Figure 5. Number of results (and associated number of studies) indicating a direction and degree of effect of crop intensification (fertilisation, soil improvement, tillage, irrigation, pesticide use, farm size) on the effect of climate variability and change on desired (resilient) dynamics of yield, by organisation level (plot/field or region). The desired direction of *criteria of dynamics* is described in the text. Significant effects are those that could be tested statistically and were found significantly different ( $p < 0.05$ ).

Nitrogen fertilisation, fungicide use, tillage and pesticide use are related to higher levels and the probability of exceeding a high yield, but their effect on variability and trends of yield is unclear (Gaudin et al., 2015; Urruty et al., 2017). Gaudin et al. (2015) show that reducing tillage can decrease yield variability in favourable years but does not influence yield when extreme events occur. Urruty et al. (2017) show that intensive management (fertiliser use, soil improvement, pesticide use, tillage) in France has no significant effect on the trend for wheat yield, whereas at the regional level, the study of Matsushita et al. (2016) in Japan indicates that chemical fertiliser use significantly improves the short-term trend for yield.

Results of Reidsma et al. (2008b) at the farm level (the only study at this level) show that the effect of fertilisation on the trend for yield (positive or negative) depends on the country and when low precipitation or high temperatures occur. They explain this effect by the ability of fertilisation and water availability to meet crop nitrogen and water demand, respectively. Their study also shows that irrigation

can increase the negative effect of high temperatures in certain countries due to the higher water demand of irrigated crops and can improve yield when water is available, such as in non-water-limited irrigated systems. They observe a combined non-linear effect of temperature and irrigation, with a threshold above which effects of fertilisation and irrigation change from positive to negative.

#### 4.6. General drivers of agricultural system dynamics

The scarcity of articles that address similar combinations of *system - disturbance* (Figure 1) preclude further transversal analysis of drivers of agricultural systems. However, to provide a general overview of effects of the *explanatory factors* tested, we consider all systems and all disturbances for the two *performance attributes* used most: yield (Figure 6) and economic net return (Figure 7). These summary results must be used with caution since they are based on a wide diversity of studies, but they may provide insights into effects of *explanatory factors* on these two key *attributes* of agricultural systems. Results are detailed by study in Supplementary material 8 and Supplementary material 9.

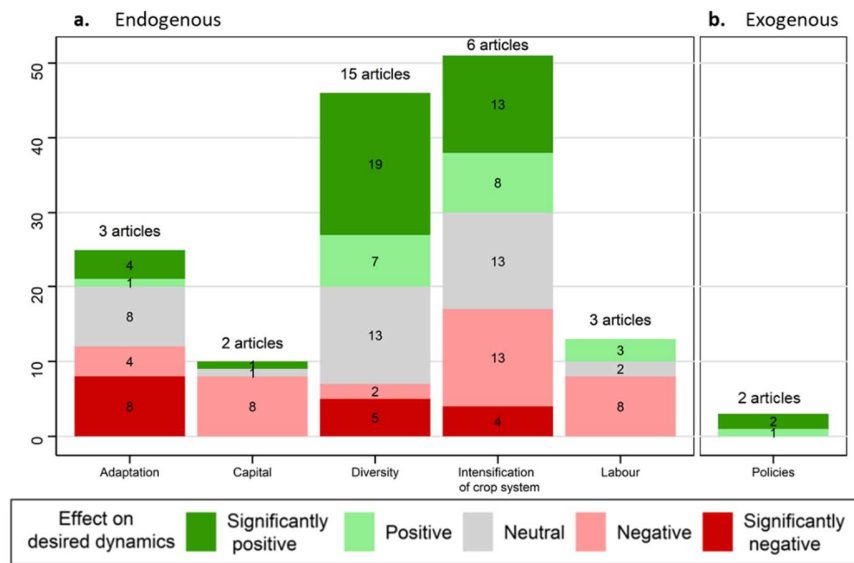


Figure 6. Number of results (and associated number of studies) indicating a direction and degree of effect on the effect of climate variability and change on desired (resilient) dynamics of yield, by type of explanatory factor (endogenous or exogenous) for all systems. The desired direction of criteria of dynamics is described in the text. Significant effects are those that could be tested statistically and were found significantly different ( $p < 0.05$ ).

For both attributes, exogenous factors (policies, a positive economic market or insurance) mitigate the effect of disturbance, indicating that these factors have real potential to improve the resilience of farming systems (Castañeda-Vera and Garrido, 2017; Ferreyra et al., 2001; Matsushita et al., 2016; Reidsma et al., 2009b).

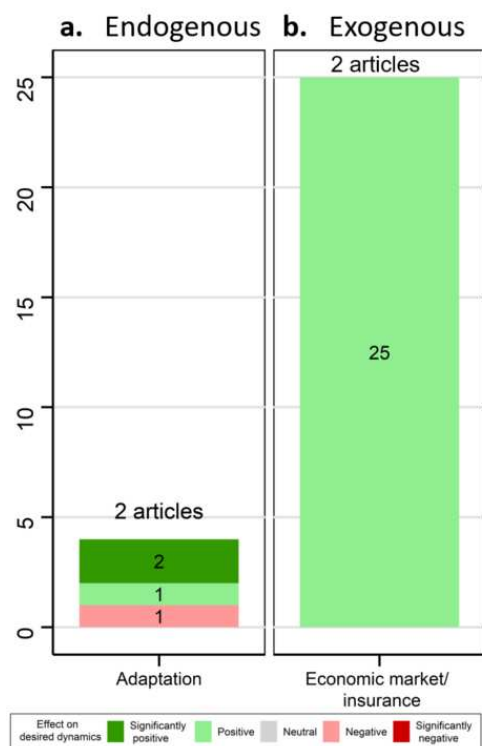


Figure 7. Number of results (and associated number of studies) indicating a direction and degree of effect on the effect of climate variability and change on desired (resilient) dynamics of economic net return, by type of *explanatory factor* (endogenous or exogenous) for all systems. The desired direction of *criteria of dynamics* is described in the text. Significant effects are those that could be tested statistically and were found significantly different ( $p < 0.05$ ).

408

409 Results are scattered for other potential *explanatory factors*, and no consistent effect emerges. For  
 410 example, while some studies observed that high levels of labour and capital can have a negative impact  
 411 on yield dynamics at the farm level (Bardaji and Iraizoz, 2015), others observed they can have a positive  
 412 effect at the regional level (Matsushita et al., 2016; Salvati, 2010). Bardaji and Iraizoz (2015) explain that  
 413 both labour (annual work units) and capital (fixed assets) can be considered as proxies of intensification  
 414 level.

415 Combining the results of all studies that address the effect of diversity and intensification on the yield of  
 416 all systems confirms that these effects are less clear, as only 43% and 41% of the results, respectively,  
 417 indicate a positive effect (Supplementary material 1).

418 The studies reviewed show no clear effect of adaptation on yield. Three forms of adaptation are  
 419 considered in these studies: adapting crop management each year (Urruty et al., 2017), adapting the



farming strategy (e.g. "changing to mixed or specialised systems"; Fletcher and Hilbert, 2007; Martin and Magne, 2015; Seo, 2010) and technological progress over the duration of the study (Bardaji and Iraizoz, 2015; Reidsma et al., 2009b). Negative effects of adaptation concern mainly the limited ability of technological progress to mitigate the effects of disturbances that can result in a decreasing trend for yield. These effects depend on the European region (some exceptions are mentioned by Reidsma et al. 2008b) for arable crops, but not for wine production (Bardaji and Iraizoz, 2015). Although based on the results of only two studies, adaptation also has a mostly positive effect on the dynamics of economic net return (Fletcher and Hilbert, 2007; Seo, 2010).

## 5. Discussion and conclusion

In this review, we highlight that most studies that quantified dynamics of agricultural system performances in temperate climates focussed on effects of climate change on dynamics of yield of grassland systems at the plot/field level and crop systems at the plot/field, farm and regional levels. Other studies are scattered over other combinations of the *systems - disturbances - performance attributes* investigated (Figure 1). The wide variety of the studies reviewed strongly limited our ability to generalise their results, restricting us to summarising mainly those that address the effect of climate change on yield dynamics. Another key methodological challenge of our review was to summarise the results of studies that address the same combination of *system - disturbance - performance attribute* but that use different *criteria of dynamics* and associated indicators to analyse performance dynamics (Supplementary material 3). While the diversity of indicators enables researchers to analyse different characteristics of dynamics, it makes studies much more difficult to compare and summarise. Thus, we aggregate results regardless of the *criterion/indicator* used in order to determine general trends among studies but highlight differences in the results according to the *criterion* used for analysis.

## 5.1. Diversity effects

The studies reviewed indicate that biodiversity has a positive influence on the (mean) level of yield of grasslands and crop systems. For grasslands, this influence is observed regardless of production level. These results do not converge fully with those of Wang et al. (2019) that confirm the stress-gradient hypothesis: “facilitative interactions amongst plant species dominate under harsh environments, whereas competitive interactions dominate under more favourable conditions”. In their study on the effect of diversity on natural grassland yields over space, these authors highlight the strong effect of the stress gradient in biodiversity-productivity (i.e. production) relationships, with a shift from a strongly positive effect in low-productivity communities to a strongly negative effect in high-productivity communities. We do not observe this difference in effect as a function of productivity level in our results. To explain their results relative to plot-level experiments, Wang et al. (2019) claim that they explore a large gradient of productivity (30-1382 g/m<sup>2</sup> at peak biomass). However, the studies we reviewed explored an even larger gradient, as Zavalloni et al. (2008) show a positive effect of high functional diversity on a more productive grassland (500-2500 g/m<sup>2</sup> at peak biomass) with a mixture of species from three functional groups (grasses, N-fixing dicots and non-N-fixing dicots). Differences between results of our study and those of Wang et al. (2019) may be explained by the fact that diversity can be characterised using different indicators/approaches (e.g. functional or taxonomic) and that a functional approach may be necessary to disentangle diversity-productivity relationships (see below). Like for grasslands, but in only two studies, diversity in crop rotations is positively related to yield level (Gaudin et al. 2015; Urruty et al., 2017). To our knowledge, the positive effect of diversified rotations, which provide nutrients and biological regulation services, is debated less, as recent studies confirm that they are strong positive effects of rotation diversity on crop yield level (Bowles et al., 2020; Duru et al., 2015; Kleijn et al., 2019; Kremen and Miles, 2012; Lin, 2011; Palomo-Campesino et al., 2018).

These results for grassland and crop systems based on yield level as an indicator of yield dynamics seem debatable, as a level is more a static indicator of state. When using an indicator more adapted for analysing yield dynamics, our review shows that diversity is not always a strong positive driver of yield resilience, low vulnerability or high robustness. For grasslands, the effect of biodiversity varies among studies when using *criteria* such as resistance or the recovery ratio. Isbell et al. (2015) identify that diversity increases yield resistance in grasslands mainly when they experience frequent *disturbances*, while Pfisterer and Schmid (2002) show the importance of composition effects (facilitative/competitive interaction). In contrast to grasslands, our review shows that diversity has a clearer positive effect on crop yield dynamics, from plot/field to regional levels. Within-farm diversity over space and time (rotation) usually has a positive effect on yield dynamics (76% of results are positive) regardless of the indicator used. Only a few results show negative effects, due to specific composition effects (e.g. rice, in Matsushita et al. 2016). Our results are similar to those of Renard and Tilman (2019), who show that crop diversity has a strong effect on the temporal stability of countries' total yield (in kcal), and of Bowles et al. (2020), who show that trend of yield increases and risk of crop failure decreases over time as the diversity of maize rotations in North America increases.

Diversity in farm economic size and production intensity also has a positive effect on yield variability (Reidsma et al. 2008a). Although based on few studies, our results seem to confirm the strategy of not putting all eggs in one basket: diversification of farm production may provide economic security at farm and regional levels (Abson et al., 2013).

Our review highlights that composition effects, rather than a species-diversity effect per se, can have a strong effect on yield dynamics in agricultural systems. Functional diversity, as discussed by Barkaoui et al. (2016) and Zavalloni et al. (2008), seems to be key in explaining the relationships between diversity and the dynamics observed. However, although ecology and agroecology now usually use the functional

approach, few of the articles reviewed (n= 6/37) use a functional description of plant diversity to address effects of species characteristics (traits) on ecosystem functioning. Thus, the community that studies agricultural *system* dynamics seems to be poorly connected to the one that uses functional approaches, although functional characterisation of species is a recognised way to support the design of planned biodiversity to develop sustainable agricultural systems (Duru et al., 2015; Wood et al., 2015).

## 5.2. Effects of agricultural system intensification

Our results show that yield of grassland systems seems more sensitive to climate variability and change than that of crop systems. This difference may be due mainly to the management adaptations available to the crop systems studied, especially irrigation, in the face of higher temperatures and drought. From a methodological viewpoint, crop/grassland management needs to be described accurately when comparing the sensitivity of different agricultural systems.

While intensification has a major effect on yield levels, we find no clear trend in its effect on yield dynamics (55% of results are neutral). Rather than intensification level, the appropriateness of the combination of crop, management and pedoclimatic context (i.e. production situation, Aubertot and Robin (2013)) plays an important role. For example, Reidsma et al. (2008a) highlight that the positive effect of irrigation depends on water availability and fertilisation level, which later drives crop water demand. They also suggest that lower yields (and thus, less intensive crop systems) in warm climates are less sensitive to climate change because crop management there already seems adapted to the climate. More generally, Reidsma et al. (2008b, 2008a) show that farm characteristics (e.g. size, diversity of land use) can have a stronger influence on yield variability than climate change, whose impacts are perceived more at larger levels (e.g. regional).

Our results for the effect of intensification are consistent with those of Renard and Tilman (2019), who show that irrigation, and thus adaptation to water scarcity, is an important mechanism to improve

national yield stability, whereas nitrogen-use intensity (intensification level) has no significant impact. They also show that effects of diversity and irrigation on total yield stability are approximately equal to those of precipitation and temperature instability.

As discussed in the studies reviewed (Bitterman and Bennett, 2016; Hoover et al., 2014; Pfisterer and Schmid, 2002; Isbell et al., 2015) and shown by Müller et al. (2016), results from analysing system *performance* dynamics can depend strongly on the temporal extent of the studies. Study duration is crucial when analysing (i) climatic and economic trends or rupture scenarios and (ii) effects of resource availability (e.g. water, phosphorus). For example, the frequency of climate events can explain the effect of diversity on yield resistance (Isbell et al., 2015). More generally, showing that increasing irrigation or fertilisation improves resilience in the short term can mask the more long-term scarcity effects of local water resources, finite resources (e.g. phosphorus, petroleum) and negative feedback loops (e.g. pollution). Accordingly, studies that investigate the VRR of agricultural systems while considering effects of intensification should assess middle- and long-term effects on natural and fossil resources and the environment.

Finally, our transversal analysis of studies (regardless of the *system - disturbance* combination) highlights potential negative effects of intensification of labour, capital and machinery on yield dynamics at the farm level (Bardaji and Iraizoz, 2015), while positive effects are observed at the regional level (Matsushita et al., 2016; Salvati, 2010). These results are similar to those of Reidsma et al. (2008b) at the farm level, suggesting that the largest farms (economically) are less resilient.

### 5.3. Concluding remarks

In addition to increasing functional diversity, ensuring that the level of intensification is appropriate for the production situation seems the best way to ensure the resilience/robustness of yields to climate change. Farm diversity in economic size and intensity (of economic outputs) at the regional level also

535 seems a way to improve the VRR of agricultural production at the local/regional level. In addition, our  
536 transversal analysis suggests that policies (e.g. income-stabilisation tools, direct payments, subsidies,  
537 government investment in agricultural infrastructure) and insurance are effective external factors,  
538 complementary to internal ones, for improving the resilience of economic net return of farming systems.

539 Contributions

540 M.D and O.T. developed the conceptual framework with guidance and contributions from all other co-  
541 authors; M.D. performed the literature review with the help of N.U. for reviewing; M.D. and O.T. wrote  
542 the manuscript; and C.B. and N.U. proofread the manuscript.

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