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1 **Title**

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

4 **Authors**

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9 **Abstract**

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

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

30 **Keywords**

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

32 1. Introduction

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

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

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

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

47 - Vulnerability, which is inversely related, is interdependent or intersects with resilience (Engle,
48 2011; Gallopín, 2006; Turner, 2010). It is defined as the degree to which a system is harmed due
49 to disturbances or stress (Turner et al., 2003). Most studies present vulnerability as a function of
50 the system's exposure to disturbances, its sensitivity and its adaptive capacity (Adger, 2006).

51 - Robustness, which is the ability to maintain desired levels of system outputs, especially
52 agricultural, despite the occurrence of disturbances (Urruty et al., 2016).

53 These three conceptual frameworks are used to analyse dynamics (i.e. changes over time) of the
54 structure or functions of a system to describe its behaviour when it experiences disturbances (Martin et
55 al., 2011; Perrings, 1998; Urruty et al., 2016). The research community attempts to standardise
56 definitions to provide common vocabulary and generic tools (from theoretical uses to quantification).
57 However, debate continues about the differences and overlap among these three concepts (Miller et al.,
58 2010; Mumby et al., 2014; Turner, 2010; Urruty et al., 2016; Wu, 2013). They are non-normative, as they
59 do not specify, per se, structural characteristics or functions that should be maintained (Elmqvist et al.,
60 2019). Because maintaining certain performances can be undesirable, "resilience is not always a good
61 thing" (Gallopín, 2006; Walker and Meyers, 2004). Accordingly, vulnerability, resilience and robustness
62 (VRR) frameworks may be considered as system properties, or the "tools" to achieve a "goal", which may
63 be sustainability (a normative concept) (Elmqvist et al., 2019; Turner, 2010). Applying VRR frameworks to
64 a system, such as an agricultural system, can identify the key functions to maintain. For example,
65 Meuwissen et al. (2018) established a list of functions ("resilience for what purpose?") that farming
66 systems provide that ensure sustainable development. For each function, they developed specific
67 associated performance attributes (e.g. yield as an attribute of the function "agronomic performance").

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

73 To address this lack, we performed a systematic review of such studies to summarise characteristics of
74 the systems studied, available knowledge about the sensitivity of agricultural production and key
75 explanatory factors of VRR. For this last objective, we first focussed on effects of diversity in its various
76 forms, as diversity is commonly accepted to be a strong driver of dynamics of agricultural systems (Altieri
77 et al., 2015; Biggs et al., 2012; Cabell and Oelofse, 2012; Lin, 2011; Oliver et al., 2015; Wiréhn et al.,
78 2015), even though empirical evidence of its influence is scarce and debated (Ge et al., 2016; Gil et al.,
79 2017; Prieto et al., 2015; Wang et al., 2019). Second, as discussed by others (Renard and Timan, 2019;
80 Stampfli et al., 2018; Wang et al., 2019), we also investigated whether the intensification/production
81 level of agroecosystems is a key driver of dynamics of these systems' performances.

82 2. Generic analytical framework

83 Due to the diversity and ambiguity of the VRR frameworks, we developed an analytical framework that
84 enabled us to perform a systematic review of studies regardless of the conceptual framework used
85 (Table 1). Based on the frameworks of Allen et al. (2016), Carpenter et al. (2001), Meuwissen et al.
86 (2019) and Müller et al. (2016), we characterised each study in terms of:

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

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

VRR study characteristics	Description	Caution about	Categories	Examples	Reference
<i>what agricultural system</i>	Agricultural system studied and harmed by the disturbance	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
<i>which performance attribute(s)</i>	Performance attribute of the system whose dynamics are disturbed, and associated criteria used to describe the dynamics	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
<i>what disturbance</i>	Disturbance that occurred	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
<i>when and where</i>	Spatial and temporal resolution and extent of the study	-	-	Monthly over 3 years Country level over Europe	Allen et al., 2016; Müller et al., 2016
<i>which explanatory factors</i>	Potential explanatory factor of the VRR tested	-	Endogenous or exogenous	Diversity, agricultural practices, subsidies	Meuwissen et al., 2019

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

106 3. Method and study selection

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

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

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

118 Accordingly, our WOS query was the following:

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

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

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

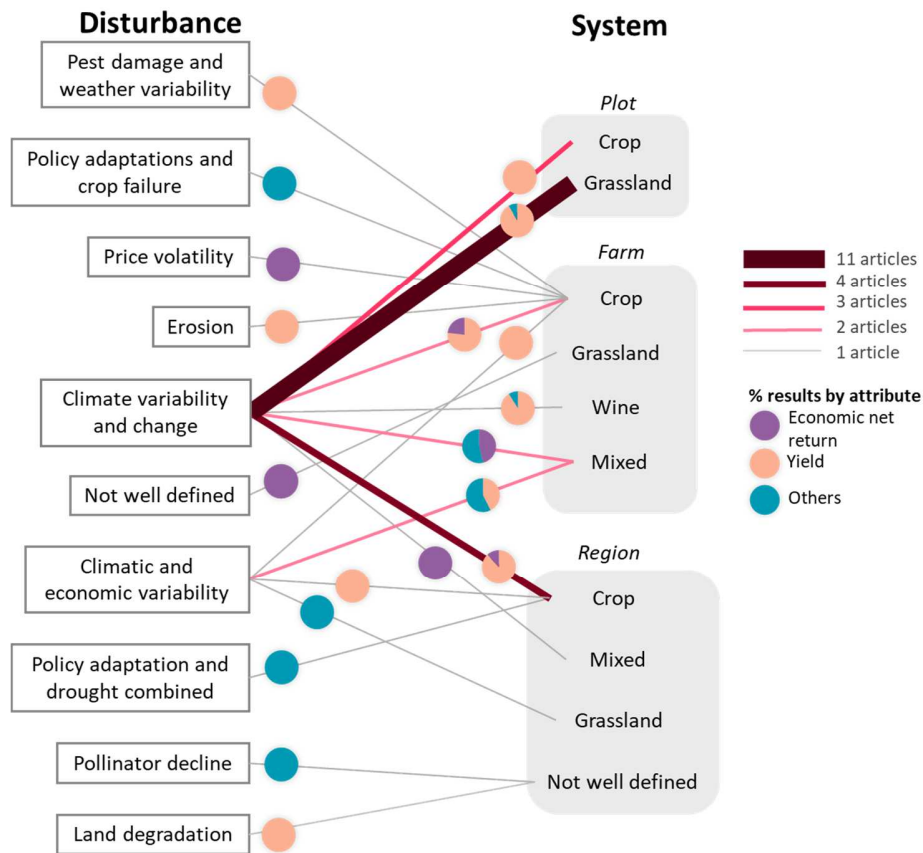
135 Our selection process showed that including adaptive capacity, viability theory and ecological integrity in
136 the query did not add articles to the final selection of 37 articles (Supplementary material 2). Indeed,
137 articles that mention these three concepts always mentioned VRR in their abstract.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

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

144 4. Results

145 4.1. General studies' characteristics

146 We draw two main conclusions from analysis of these articles. First, the few quantitative studies
147 identified (Supplementary material 1) confirms that quantitative assessment of agricultural system VRR
148 remains rare. Second, most studies focus on certain systems, disturbances and *performance attributes*
149 (Figure 1). Overall, 65% of the articles address climate change, while the main systems studied are
150 grassland (35%) and crop (40%) systems, at the plot/field (38%), farm (35%) and regional (27%) levels.
151 Studies focus mainly on the impact of disturbances on yield (72% of articles) and economic net return
152 (16% of articles). Overall, 13% of the studies only analyse the sensitivity of dynamics of system
153 *attribute(s)*, while 86% of them seek to determine the main factors that explain the behaviour studied.
154 Diversity and intensification levels are the *explanatory factors* tested most, confirming their interest to
155 the scientific community.



156
 157 Figure 1. Overview of the main characteristics of the 37 articles selected that address the vulnerability,
 158 resilience and robustness of agricultural systems.

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

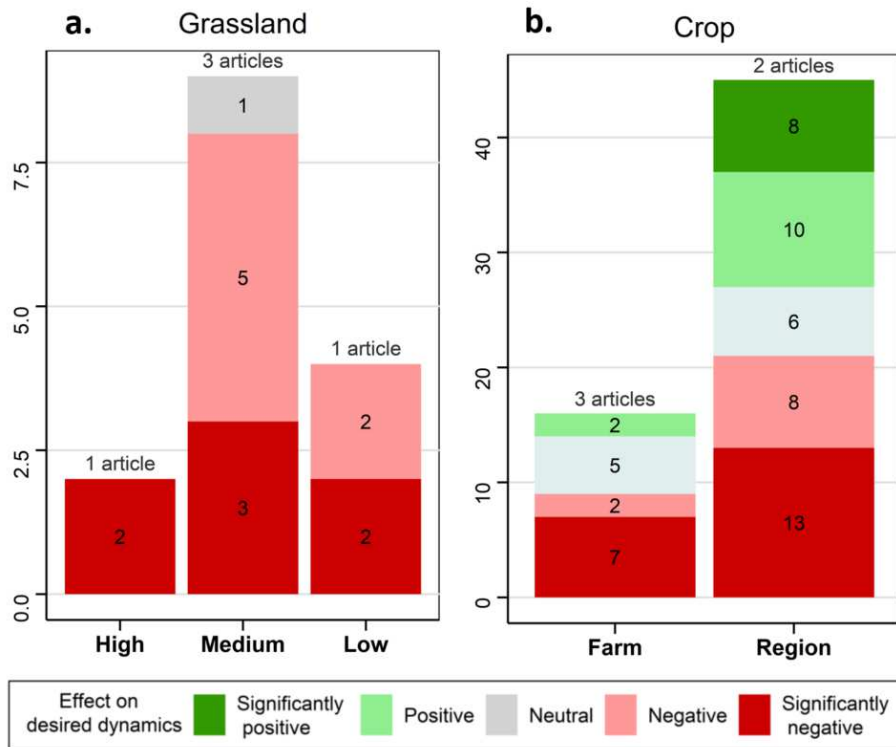
166 To avoid presenting results based on only one study, we summarise results only when at least two
 167 studies analyse the same combination of *system - disturbance - performance attribute*. This approach

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

186 4.2. Sensitivity of agricultural systems experiencing climatic disturbances

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

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



195
 196 Figure 2. Number of results (and associated number of articles) indicating a direction and degree of
 197 effect of climate variability and change on desired (resilient) dynamics of yield, by (a) level of production
 198 (i.e. yield) at the plot/field level for grassland systems and (b) organisation level for crop systems. For
 199 grassland studies, we distinguish grasslands by annual productivity level (high (> 20 t/ha), medium (5-20
 200 t/ha) or low (< 5 t/ha)). The desired direction of *criteria of dynamics* is described in the text. Significant
 201 effects are those that could be tested statistically and were found significantly different ($p < 0.05$).

202 4.2.1. Grassland systems

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

217 4.2.2. Crop systems

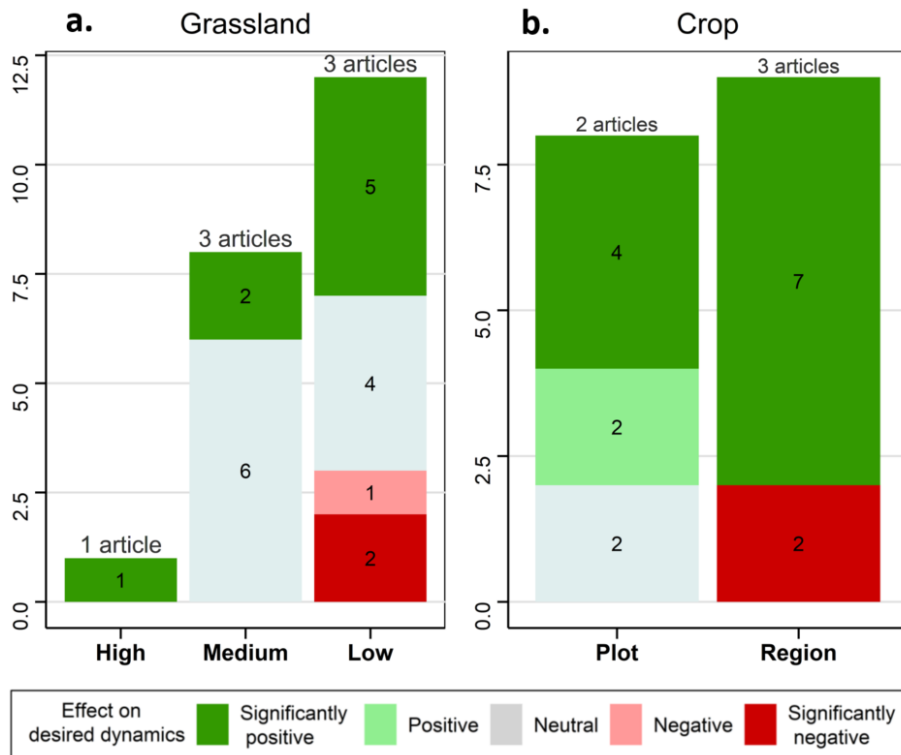
218 Negative effects of climate on crop systems are less clear than those on grasslands (Figure 2b). Most
219 results (91%) are from Reidsma and Ewert (2008) and Reidsma et al. (2008a). Temperature (high,
220 increasing and/or variable) and precipitation (low, decreasing and/or variable) have negative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

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

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

235 4.3. Diversity, a driver of yield resilience for crops but not necessarily for grasslands

236 Twelve articles assess the extent to which diversity explains the VRR of the yield performance of crops
237 and grasslands when experiencing climate variability and change, yielding 38 results (Barkaoui et al.,
238 2016; Carlsson et al., 2017; Gaudin et al., 2015; Isbell et al., 2015; Matsushita et al., 2016; Pfisterer and
239 Schmid, 2002; Prieto et al., 2015; Reidsma and Ewert, 2008; Urruty et al., 2017; Zavalloni et al., 2008;
240 Reidsma et al., 2010; Carter and Blair, 2012). The *criteria of dynamics* they use are level, variability,
241 trend, resistance, recovery and probability of exceeding a threshold. Results by study are detailed in
242 Supplementary material 5.



243
 244 Figure 3. Number of results (and associated number of articles) indicating a direction and degree of
 245 effect of diversity on the effect of climate variability and change on desired (resilient) dynamics of yield,
 246 by (a) level of production (i.e. yield) at the plot/field level for grassland systems and (b) organisation level
 247 for crop systems. For grassland studies, we distinguish grasslands by annual productivity level (high (> 20
 248 t/ha), medium (5-20 t/ha) or low (< 5 t/ha)). The desired direction of *criteria of dynamics* is described in
 249 the text. Significant effects are those that could be tested statistically and were found significantly
 250 different ($p < 0.05$).

251 4.3.1. Grassland diversity

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

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

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

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

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

289 4.3.2. Crop diversity

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

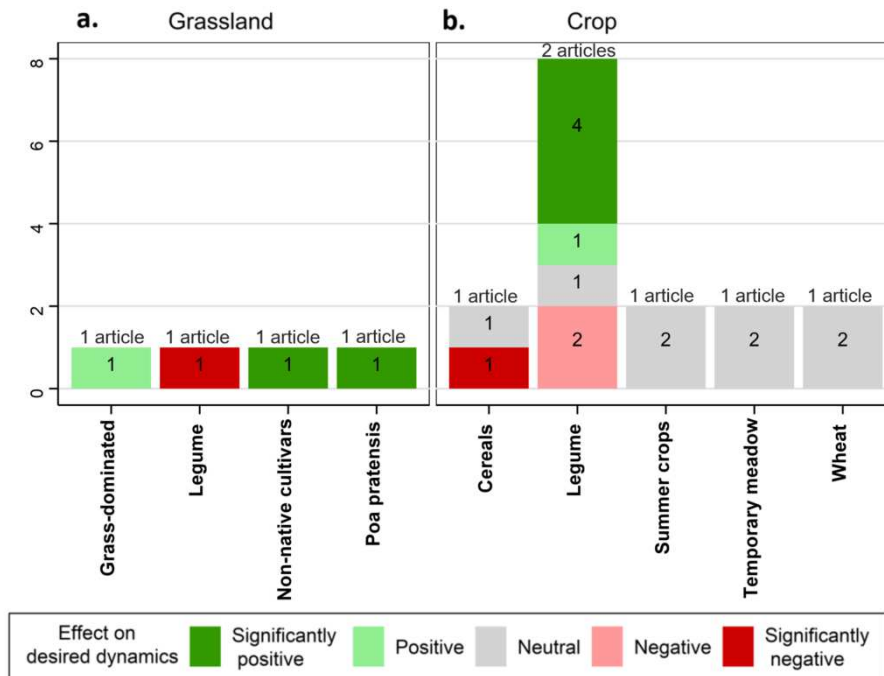
296 At the plot/field level, diversity in crop rotations always has a positive effect on the level of production
297 and negative effect on its variability when soya bean is present (Gaudin et al., 2015; Urruty et al., 2017).
298 Furthermore, diversity does influence the trend for yield. At plot and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

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

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

309 4.4. Major composition effects

310 Previous results tend to highlight the importance of considering the composition effect on the dynamics
311 of system performances. Accordingly, we summarise results of the reviewed studies for the effect of a
312 particular species or species group (Figure 4). Cereals, summer crops, temporary meadows, the
313 proportion of grass/forbs, native cultivars and *P. pratensis* are tested for their effect on levels, variability,
314 trend, resistance, recovery and probability of exceeding a threshold of yield of grassland and crop
315 systems (Barkaoui et al., 2016; Carlsson et al., 2017; Gaudin et al., 2015; Pfisterer and Schmid, 2002;
316 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).

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

338 Specific effects of legumes have also been identified (Supplementary material 7). Carlsson et al. (2017)
339 and Pfisterer and Schmid (2002) show that the abundance of legumes in grasslands can decrease
340 resistance of yield during drought ($p < 0.05$). In contrast, crop rotations that include legumes as a catch or
341 cover crop improve the yield level and stability (Gaudin et al., 2015; Urruty et al., 2017), but the
342 probability of exceeding the threshold of a high yield level depends on the legume species (Gaudin et al.,
343 2015). For example, relay cropping with red clover more than doubled the likelihood of yield exceeding
344 the 90th percentile ($p < 0.05$), while alfalfa decreased the probability of exceeding a threshold of high yield
345 (Gaudin et al., 2015).

346 4.5. Intensifying inputs is not necessarily related to better yield dynamics

347 We summarised results of the reviewed studies for the effect of the level of input use intensification on
348 the VRR of crop systems to climate change (temperature and drought) at the plot/field (2 articles) and
349 regional (2 articles) levels (Figure 5). These studies focussed on the effect of intensification level on the
350 dynamics of yield of crop systems. Intensification levels are described by fertilisation, soil improvement,
351 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 ($p < 0.05$).

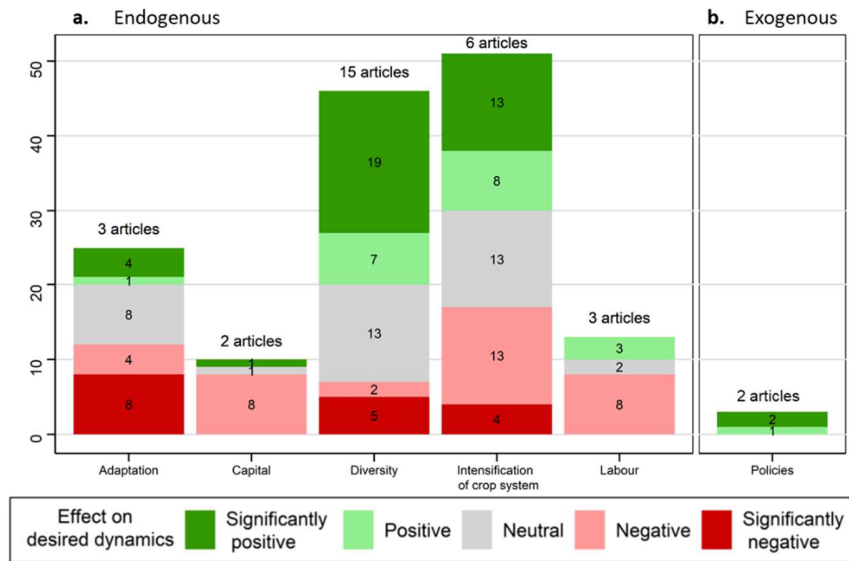
363 Nitrogen fertilisation, fungicide use, tillage and pesticide use are related to higher levels and the
 364 probability of exceeding a high yield, but their effect on variability and trends of yield is unclear (Gaudin
 365 et al., 2015; Urruty et al., 2017). Gaudin et al. (2015) show that reducing tillage can decrease yield
 366 variability in favourable years but does not influence yield when extreme events occur. Urruty et al.
 367 (2017) show that intensive management (fertiliser use, soil improvement, pesticide use, tillage) in France
 368 has no significant effect on the trend for wheat yield, whereas at the regional level, the study of
 369 Matsushita et al. (2016) in Japan indicates that chemical fertiliser use significantly improves the short-
 370 term trend for yield.

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

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

379 4.6. General drivers of agricultural system dynamics

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



387

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

393

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

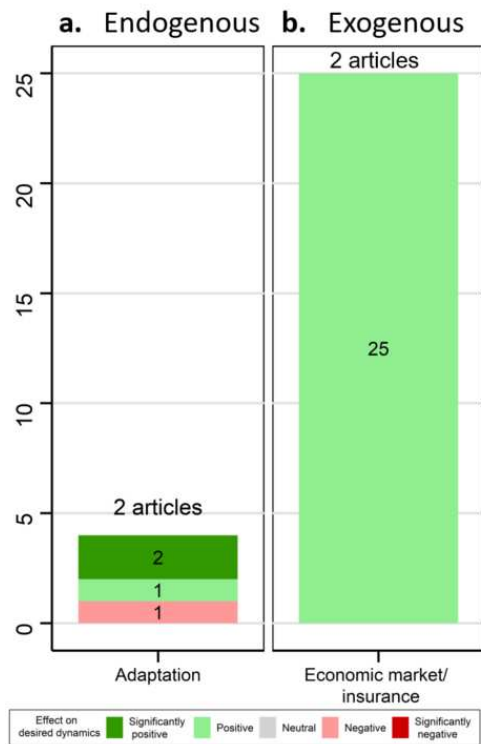


Figure 7. Number of results (and associated number of studies) indicating a direction and degree of effect on the effect of climate variability and change on desired (resilient) dynamics of economic net return, by type of *explanatory factor* (endogenous or exogenous) for all systems. The desired direction 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

420 farming strategy (e.g. "changing to mixed or specialised systems"; Fletcher and Hilbert, 2007; Martin and
421 Magne, 2015; Seo, 2010) and technological progress over the duration of the study (Bardaji and Iraizoz,
422 2015; Reidsma et al., 2009b). Negative effects of adaptation concern mainly the limited ability of
423 technological progress to mitigate the effects of disturbances that can result in a decreasing trend for
424 yield. These effects depend on the European region (some exceptions are mentioned by Reidsma et al.
425 2008b) for arable crops, but not for wine production (Bardaji and Iraizoz, 2015). Although based on the
426 results of only two studies, adaptation also has a mostly positive effect on the dynamics of economic net
427 return (Fletcher and Hilbert, 2007; Seo, 2010).

428 5. Discussion and conclusion

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

442 5.1. Diversity effects

443 The studies reviewed indicate that biodiversity has a positive influence on the (mean) level of yield of
444 grasslands and crop systems. For grasslands, this influence is observed regardless of production level.
445 These results do not converge fully with those of Wang et al. (2019) that confirm the stress-gradient
446 hypothesis: “facilitative interactions amongst plant species dominate under harsh environments,
447 whereas competitive interactions dominate under more favourable conditions”. In their study on the
448 effect of diversity on natural grassland yields over space, these authors highlight the strong effect of the
449 stress gradient in biodiversity-productivity (i.e. production) relationships, with a shift from a strongly
450 positive effect in low-productivity communities to a strongly negative effect in high-productivity
451 communities. We do not observe this difference in effect as a function of productivity level in our results.
452 To explain their results relative to plot-level experiments, Wang et al. (2019) claim that they explore a
453 large gradient of productivity (30-1382 g/m² at peak biomass). However, the studies we reviewed
454 explored an even larger gradient, as Zavalloni et al. (2008) show a positive effect of high functional
455 diversity on a more productive grassland (500-2500 g/m² at peak biomass) with a mixture of species
456 from three functional groups (grasses, N-fixing dicots and non-N-fixing dicots). Differences between
457 results of our study and those of Wang et al. (2019) may be explained by the fact that diversity can be
458 characterised using different indicators/approaches (e.g. functional or taxonomic) and that a functional
459 approach may be necessary to disentangle diversity-productivity relationships (see below).
460 Like for grasslands, but in only two studies, diversity in crop rotations is positively related to yield level
461 (Gaudin et al. 2015; Urruty et al., 2017). To our knowledge, the positive effect of diversified rotations,
462 which provide nutrients and biological regulation services, is debated less, as recent studies confirm that
463 they are strong positive effects of rotation diversity on crop yield level (Bowles et al., 2020; Duru et al.,
464 2015; Kleijn et al., 2019; Kremen and Miles, 2012; Lin, 2011; Palomo-Campesino et al., 2018).

465

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

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

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

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

494 5.2. Effects of agricultural system intensification

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

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

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

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

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

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

531 5.3. Concluding remarks

532 In addition to increasing functional diversity, ensuring that the level of intensification is appropriate for
533 the production situation seems the best way to ensure the resilience/robustness of yields to climate
534 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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