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1 Grain legume response to future climate and adaptation strategies in 2 Europe: a review of simulation studies

3 Marie Marteau-Bazouni^{1*}, Marie-Hélène Jeuffroy¹, Nicolas Guilpart¹

4 ¹ Université Paris-Saclay, AgroParisTech, INRAE, UMR Agronomie, 22 Place de l'agronomie,
5 Bâtiment F, CS 20040, 91123 Palaiseau cedex, France

6 * Corresponding author: marie.marteau-bazouni@inrae.fr

7 Abstract

8 In Europe, increasing the area of legume crops has been identified as a key measure to
9 achieve the objectives set by the European Green Deal and transition toward more sustainable
10 food systems. Although the role of grain legumes in climate change mitigation has been closely
11 examined, little research has focused on how climate change will challenge the development
12 of these crops. This article systematically reviews recent simulation studies to assess the
13 impact of climate change on grain legume performances in Europe and the effect of adaptation
14 strategies. Forty papers using process-based, ecological niche, or statistical models were
15 selected to simulate the response of eight grain legume species to future climate (2020-2100)
16 in Europe. The lack of data on adaptation strategies in Europe was compensated for by
17 enlarging the study area to climatically similar regions. The review highlights a notable
18 imbalance between research about soybeans versus other grain legumes, with soybeans
19 representing approximately 80% of selected studies. Studies focused on soybeans found good
20 agreement, with yield or suitability gains simulated in Northern Europe and a higher probability
21 of yield losses in Southern and South-Eastern Europe. While a similar spatial pattern may be
22 expected for other grain legumes, the scarcity of data makes this result more uncertain. The
23 review also shows that several adaptation strategies have the potential to mitigate the negative

24 impact of climate change on grain legume performances or enhance its positive impact. The
25 most promising strategies tested include irrigation, change in sowing date, and cultivar choice.
26 In addition, we identify several knowledge gaps that, if addressed, would support legume
27 development in Europe. In particular, key species such as field peas, faba beans, lentils, and
28 chickpeas remain blind spots, despite their prominent role in European environmental,
29 agricultural, and nutritional policies. Other knowledge gaps include a lack of accounting for
30 crop response to elevated CO₂, ozone, and future biotic pressure, and a limited range of
31 adaptation strategies tested and indicators assessed. Implementing multi-criteria analyses that
32 involve stakeholders would help identify relevant input and output for future simulations.

33 **Keywords**

34 Climate change; protein crop; soybean; *Leguminosae*; crop model

35 1. Introduction

36 In Europe, increasing the area of legume crops has been identified as a key measure to
37 transition toward more sustainable food systems (Schneider and Huyghe, 2015). Thanks to
38 their ability to fix atmospheric nitrogen (N), legumes contribute to climate change mitigation by
39 reducing greenhouse gas emissions from synthetic fertilizer production and application
40 (Peoples et al., 2019). Legumes are known to provide numerous agronomic services including
41 increased soil N availability benefitting the subsequent crop, improved soil structure, enhanced
42 soil microbial activity, and “break-crop” effect (Jensen et al., 2010; Jensen and Hauggaard-
43 Nielsen, 2003; Köpke and Nemecek, 2010). Legumes grown in rotation can enhance main
44 crop yields, especially in low-input systems (Cernay et al., 2018; Preissel et al., 2015; Zhao et
45 al., 2022). Intercropped with cereals, they allow to increase the total yield in comparison to
46 mean sole crops (Bedoussac et al., 2015). Among all legumes, grain legumes such as
47 soybeans and peas are particularly interesting, as they represent a healthy source of proteins
48 for both animal feed and human food. Substituting grain legumes for animal-based proteins
49 has been proposed as a way to transition toward healthier and more sustainable diets (Davis
50 et al., 2010; Prudhomme et al., 2020; Rööös et al., 2020). In this way, increasing the production
51 and consumption of grain legumes is considered a key measure to achieve the objectives set
52 by the European Green Deal and the Farm to Fork Strategy in terms of reducing the
53 environmental footprint of European food systems and ensuring protein self-sufficiency
54 (European Commission, 2020).

55 In spite of their agronomical, environmental, and nutritional benefits, the production area of
56 grain legumes remains low in Europe. In 2020, they represented less than 4% of European
57 cropland, in contrast to 15.2% worldwide (FAOSTAT, 2023) (Table S1). Numerous interacting
58 factors (e.g. public policies, market dynamics, agronomic R&D activities, and breeding efforts),
59 resulting in a so-called technological lock-in, have hampered their development (Magrini et al.,
60 2016). Yield instability is one component of this lock-in (Watson et al., 2017). Indeed, grain

61 legume yields are often considered to be more variable than cereal yields (Cernay et al., 2015),
62 especially as they are frequently sown in spring, which makes them more exposed to heat
63 stress and water deficit during key stages of their growing cycle (Falconnier et al., 2020;
64 Reckling et al., 2018). Drought (Farooq et al., 2017), cold and heat stresses (Bhat et al., 2022;
65 Gogoi et al., 2018), or waterlogging (Pasley et al., 2020) can strongly affect biological nitrogen
66 fixation (Salon et al., 2011), grain legume growth, reproduction, and yield.

67 Climate change is likely to increase the occurrence of such stresses, and thus impact grain
68 legume performances (Ahmed et al., 2022; Vadez et al., 2012). Although the role of grain
69 legumes in climate change mitigation has been closely examined (Jensen et al., 2012;
70 Prudhomme et al., 2020), little research has focused on how climate change will challenge
71 their development in Europe. In particular, although a large body of literature has evaluated
72 the effect of a single climatic factor - mainly elevated CO₂, temperature and water stress - on
73 grain legume physiology and performances (Ahmed et al., 2022; Bhattacharya, 2010; Dutta et
74 al., 2022), little is known on how these crops will respond to the simultaneous, climate change-
75 driven variations of all these factors (Hatfield et al., 2011; Rötter et al., 2018; Vadez et al.,
76 2012).

77 Crop models have been shown to be useful tools for assessing crop responses to climate
78 change, as they can use projections for future climate under different emission scenarios and
79 account for the simultaneous variations in several climate parameters. As several sources of
80 uncertainty are associated with crop models (Wallach and Thorburn, 2017), results may differ
81 among studies. Reviews are therefore needed to synthesize the outcomes of several
82 simulations and assess consensus on the direction of change. To our knowledge, reviews of
83 simulation studies have mainly focused on major crops such as cereals (e.g. Carr et al. 2022;
84 Challinor et al. 2014; Knox et al. 2016). Although some of them include major grain legumes
85 such as soybeans, results often focus on main production areas, for example Brazil, the United
86 States, and Asia in Hasegawa et al. (2022) and Zhao et al. (2017), excluding Europe. However,
87 the impact of climate change on crops is known to vary depending on regions and crop species

88 (Moore and Lobell, 2015). Therefore, the impact of climate change on grain legumes in Europe
89 needs to be assessed in a crop-specific spatially explicit manner. Recently, several studies
90 have simulated grain legume response to climate change in Europe using different types of
91 models, including process-based crop models (Nendel et al., 2023), machine learning
92 techniques (Guilpart et al., 2022), and ecological niche models (Manners et al., 2020).
93 However, their results may be diverging as in Guilpart et al. (2022) and Manners et al. (2020)
94 for soybeans, which motivates the need for a review.

95 Adjusting crop management can significantly modify the impact of climate change on crop
96 performances (Abramoff et al., 2023). Here again, crop response to adaptation has been
97 investigated for major crops but less frequently for grain legumes, especially in Europe. We
98 also lack data on the relative potential of different adaptation strategies, as the approach used
99 in existing reviews does not always allow for a comparison of different strategies (e.g. Abramoff
100 et al., 2023; Makowski et al., 2020). As adaptation can take many forms that differ in their
101 intent, spatial scale, timing, actors involved, and effort-to-benefit ratio (Iglesias et al., 2012;
102 Smit and Skinner, 2002), comparing several strategies may help plan an effective adaptation
103 to increase food systems resilience (Rosenzweig and Tubiello, 2007).

104 Altogether, these points highlight the need to synthesize recent simulation studies to answer
105 the following questions: (i) How will climate change impact grain legume performances in
106 Europe and how will this impact vary across regions and species? (ii) Which adaptation
107 strategies have been assessed and what is their potential to sustain grain legume
108 performances in the context of climate change? To that end, we systematically searched and
109 reviewed the literature on grain legume response to climate change in Europe, with and without
110 considering adaptation.

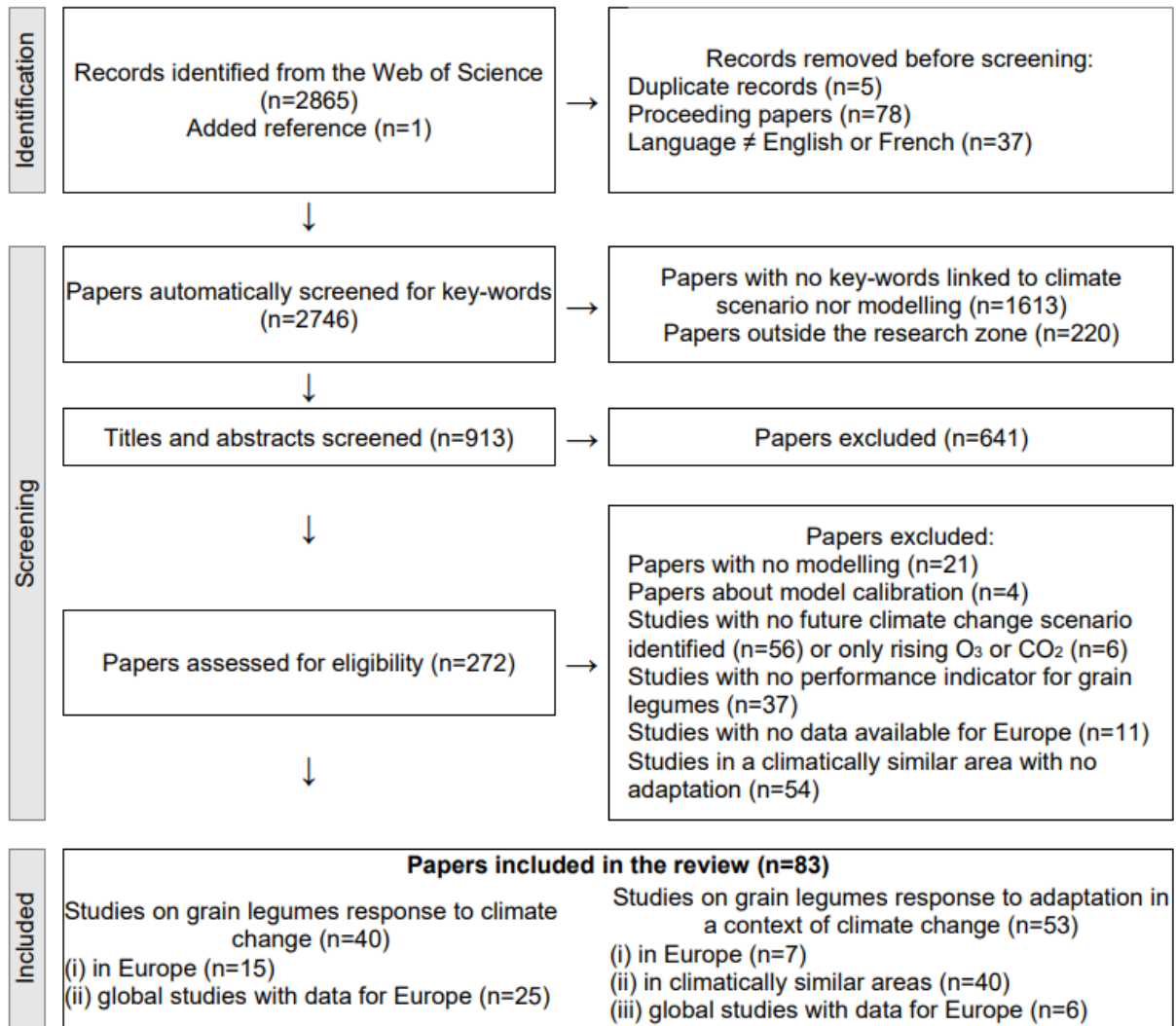
111 2. Materials and methods

112 2.1. Literature search

113 We conducted a systematic review using the PRISMA guidelines (Page et al., 2021) to select
114 two collections of papers answering each of our research questions (see Figure 1 for the
115 PRISMA flow diagram). We considered articles from peer-reviewed journals, reviews, books,
116 and book chapters published between 01/01/2007 and 01/05/2023. We identified 2865 records
117 from the Web of Science using the following research equation (updated on May 16th, 2023):

```
118 TS= (("climat*" AND ("chang*" OR "variabilit*" OR "risk*" OR "smart*" OR "futur*" OR  
119 "extrem*" OR "scenario*") OR "global warming*")  
120 AND ("*pea" OR "*peas" OR "Pisum" OR "Cicer" OR "*bean" OR "*beans" OR "Phaseolus"  
121 OR "Vigna" OR "faba*" OR "soy*" OR "Glycine max" OR "lentil*" OR "Lens culinaris" OR  
122 "lupin*" OR "legum*" OR "proteaginous*" OR "protein crop*")  
123 AND ("model*" OR "simulat*" OR "project*" OR "predict*")  
124 NOT ("Caribbean" OR "fish*" OR "vineyard" OR "grapevine" OR "coffee" OR "cocoa"))
```

125 We used generic terms such as “legumes” and “protein crop” but also scientific and common
126 names for the major grain legume species grown in Europe (soybean, pea, bean, faba bean,
127 lentil, chickpea, and lupin). The keywords “Caribbean”, “coffee” and “cacao”, on one hand, and
128 “fish”, “vineyard” and “grapevine”, on the other hand, were excluded because they provided
129 many out-of-scope items containing the terms “bean” and “pea”, respectively. To provide up-
130 to-date information, we excluded articles published before 2007, the year of the IPCC AR4
131 assessment report.



132
133 **Figure 1:** PRISMA diagram depicting paper collection and selection. *n* is the number of papers.

134 2.2. Study selection

135 Two collections of papers were brought together. The “impact” corpus consisted of simulation
136 studies that investigated the impact of climate change on grain legumes in Europe. The
137 “adaptation” corpus was composed of studies assessing how grain legumes respond to
138 adaptation strategies under future climate conditions.

139 For the “impact” corpus, the study area was limited to Europe, from ca. 35°N to 72°N and 15°W
140 to 40°E, excluding the Russian Federation. For the “adaptation” corpus, results in Europe were
141 too scarce to allow a comparison between several adaptation strategies. Therefore, the study
142 area was enlarged to all regions climatically similar to Europe at the global scale. Climatically

143 similar regions were identified using the Köppen-Geiger climate classification updated by
144 Kottek et al. (2006) and Rubel et al. (2017). The enlarged study area includes regions in
145 Northern America, Southern Brazil, Australia, Iran, Russia, and China (see Section 3.2.1).

146 To be selected in the “impact” corpus, a publication had to meet the following criteria: (i) study
147 one or several grain legume species; (ii) simulate the impact of future climate change on crop
148 performances using a climate scenario (Free-Air Concentration Enrichment experiments were
149 not considered in this review); (iii) provide data for Europe. Studies conducted at a global scale
150 were selected if it was possible to extract exploitable data for Europe. To facilitate comparison,
151 we considered only climate scenarios from IPCC assessment reports (AR4 to AR6) or the Half
152 a degree Additional warming, Prognosis and Projected Impacts initiative (HAPPI) project.
153 Studies assessing the sole impact of rising O₃ or CO₂ on crop performances were not included.

154 The indicators used to assess crop performances varied across studies. To facilitate
155 comparison and synthesis, we focused on the main indicators used in selected studies, namely
156 grain yield, crop production, and suitability index. Therefore, in this paper, the term “crop
157 performances” is used to refer to these indicators. Other features of interest such as harvested
158 biomass, water use efficiency, and biological nitrogen fixation (see Section 3.1.1 for the
159 complete list) are referred to as “other indicators”; their response to climate change or
160 adaptation is discussed but not included in figures.

161 To be selected in the “adaptation” corpus, a publication had to meet the following criteria: (i)
162 study one or several grain legume species; (ii) compare the impact of future climate change
163 on crop performances with and without adaptation; (iii) provide data for Europe or a climatically
164 similar area. Based on Lobell (2014), we defined adaptation as any action undertaken to
165 mitigate negative impacts or enhance positive impacts of climate change on crop
166 performances. We discarded papers in which the nature of the adaptation strategy simulated
167 could not be identified.

168 After removing duplicates and proceeding papers, a first automated screening was performed
169 with Excel to exclude out-of-scope publications. A list of keywords related to modelling and
170 future climate scenarios was established (Supplementary text 1). When none of these
171 keywords could be found in the title, authors' keywords, or abstract of a record, this record was
172 discarded. Titles and abstracts were also screened for countries and continent names to
173 exclude papers outside the study zone. Then, the titles and abstracts of the 908 remaining
174 papers were assessed manually and 271 articles were selected for full reading. An additional
175 reference (Rosenzweig et al., 2014) was identified from the bibliography of selected papers
176 and added to the "impact" corpus. Finally, 40 papers met all the criteria to be selected in the
177 "impact" corpus, and 53 in the "adaptation" corpus (83 papers in total, with 10 papers belonging
178 to both corpora).

179 2.3. Data collection

180 The following data were extracted from the selected papers:

- 181 i) crop species under study;
- 182 ii) spatial scale of the analysis, defined as site-based studies in which models were
183 run using climate, soil type, and management of one or several particular sites
184 (e.g. Ravasi et al., 2020), studies conducted at regional or country scale using
185 several points or gridded data (e.g. Coleman et al., 2021; Wagner et al., 2016),
186 European or global scale studies (e.g. Nendel et al., 2023; Soares et al., 2021);
- 187 iii) temporal scale, i.e. time slices used as "baseline" and "future". When the median
188 point of the future time slice was higher than 2050 it was considered as "far
189 future", otherwise it was considered as "near future";
- 190 iv) climate scenario(s) used;
- 191 v) model(s) name(s) and type(s), the latter being described using three main
192 categories adapted from Fodor et al. (2017): statistical models that describe the
193 relationship between crop yields and input variables (most often climate

194 variables) in a form of regression or machine learning algorithm, niche models
195 that describe the conditions required for a crop species survival by matching
196 environmental variables with the presence or absence of the crop, and process-
197 based models that use mathematical representations of main biophysical
198 processes driving plant growth, in interaction with environmental and
199 management factors;

200 vi) abiotic and biotic factors included in the model (e.g. temperature, rainfall, CO₂,
201 pests and diseases);

202 vii) crop performance indicators assessed.

203 When available, we collected data for crop performance indicators with and without adaptation
204 in the baseline and the future. The impact of climate change (I_{CC}) and the effect of adaptation
205 (I_a) on crop performances were defined as follows:

$$206 \quad I_{CC} = \frac{Y_{CC} - Y_0}{Y_0} \times 100 \quad (\text{Equation 1})$$

$$207 \quad I_a = \frac{Y_{CC_a} - Y_{CC}}{Y_{CC}} \times 100 \quad (\text{Equation 2})$$

208 where Y_0 is the yield (or any other performance indicator) simulated in the baseline period, Y_{CC}
209 is the yield under future climate conditions without adaptation, and Y_{CC_a} is the yield under
210 future climate conditions with adaptation. In the irrigation strategy, the rainfed yield represented
211 the yield “without adaptation”, while the irrigated yield represented the yield “with adaptation”.
212 The effect of switching cultivars was assessed by comparing the highest-yielding cultivar to
213 the other cultivars simulated. When several sowing dates were tested, we selected those that
214 resulted in the highest yield (one or two options) and compared them to sowing dates
215 considered as “standard” in the baseline. For tillage, fertilization or sowing density, the “new”
216 option was compared to the “standard” one. The impact of climate change and the effect of

217 adaptation were evaluated as positive if over +5%, neutral if between -5% and +5%, and
218 negative otherwise.

219 When results were provided for different locations, time periods, or climate scenarios, the
220 maximum level of detail was kept. When papers did not provide raw data, yields or suitability
221 indexes were extracted from figures using the free software ImageJ (<https://ij.imjoy.io/>). In the
222 “impact” corpus, when only maps were provided and no aggregated data available, the impact
223 of climate change was appraised using ImageJ and classified into positive, negative, or neutral
224 at a regional or national scale. When models were run at a global scale, only data concerning
225 Europe were extracted. All data were compiled into a .csv file available in the Supplementary
226 materials.

227 2.4. Data analysis

228 A spatial representation was chosen to illustrate the impact of climate change on crop
229 performances, highlight regional discrepancies, and identify areas where results diverge
230 between studies. To do so, we counted the number of papers that simulated a positive, neutral,
231 or negative impact of climate change per geographical area, without accounting for the
232 magnitude of change. Some papers provided more details than others (e.g. several
233 combinations of time periods, climate scenarios, and climate models), with results sometimes
234 diverging between the combinations tested. To account for these divergences without giving
235 too much weight to articles testing numerous combinations, an equal weight was given to each
236 article, as in White et al. (2011). For example, if three climate models were considered in a
237 paper, each climate model was given a weight of one third. A regional (NUTS1) scale was
238 found a good compromise between local variability and data availability. When the spatial
239 resolution of simulations was too low, a national scale was used instead. A NUTS3 scale was
240 used to represent site-based studies.

241 To compare different adaptation strategies, as the level of detail provided in the papers was
242 very heterogeneous, the effect of adaptation was averaged for each paper over all time
243 periods, climate scenarios, climate models, and locations. Several other methods for averaging
244 and aggregating results were tested and conclusions were not found to be sensitive to the
245 method used (Figure S1). It must be noticed that, due to methodological differences and data
246 availability, not all papers mentioned in the corpus description sections could be included in
247 the figures (see Tables S2-3).

248 Data were analysed and figures elaborated using the free software R version 4.2.2
249 (<https://www.r-project.org/>). The R packages mapview (Appelhans et al., 2023), giscoR
250 (Hernangómez, 2023), and magick (Ooms, 2023) were used to create maps, ggplot2
251 (Wickham, 2016) for figures and kableExtra (Zhu, 2021) for tables.

252

253 3. Results

254 3.1. Impact of climate change on grain legume performances 255 without adaptation

256 3.1.1. Description of selected studies

257 Forty studies simulated the impact of climate change without adaptation on one or several
258 grain legumes in Europe. A large majority of them (80%) focused on soybeans, followed by
259 peas and beans (13% each) (Table 1). Only 45% of selected papers differentiated between
260 rainfed and irrigated conditions, while 35% considered a combination of both, and 20% failed
261 to specify the irrigation status.

262 Global scale studies were largely predominant (63% of papers) (Table 2a). The others were
263 almost equally distributed between European scale (10%), national or regional scale (15%),
264 and site-based studies (13%). Process-based models were more common (55%) than niche
265 models (25%) and statistical models (20%) (Table 2b). Future time horizons differed between
266 species (Figure 2a): for soybeans, a majority of studies focused on the far future, with two
267 peaks around 2050 and 2100, whereas for other pulses, the impact of climate change was
268 mainly assessed for the near future (before 2050). 55% of selected papers compared two or
269 more climate scenarios. RCP4.5 (moderate warming) and RCP8.5 (intense warming) were the
270 most studied scenarios, with 55% of selected papers using at least one of them (Table 2c).

271 Only a small number of papers considered crop response to elevated CO₂ (45% of the corpus)
272 or ozone (8%). Only five papers (13%) were found on the combined impact of climate change
273 and weeds or pests. Although the three soybean pests (the soybean stem fly *M. sojae*, the
274 southern armyworm *S. eridania*, and the red-banded stink bug *P. guildinii*) and two bean pests
275 studied (the Asian soybean rust *P. pachyrhizi* and the beet armyworm *S. exigua*) were not

276 currently of major concern in Europe, they could become an issue if they were to expand
 277 beyond their native range.

278 The impact of climate change was measured on grain yield in 63% of select studies (36% of
 279 them providing absolute grain yield data and 64% relative changes) and on suitability index in
 280 25% of cases (Table 2e). Only 4 papers (10%) analysed yield variability and risks of crop
 281 failure. About 10% and 15% of studies investigated the impact of climate change on crops'
 282 water use efficiency and water demand, respectively, while only one paper focused on
 283 biological nitrogen fixation (Table 2f). Economic indicators were seldom used to study the
 284 future profitability of grain legumes (1 paper).

285 **Table 1:** Number of papers in the “impact” and “adaptation” corpus, per crop species and irrigation use

	Soybean	Bean	Pea	Faba bean	Chick-pea	Cow pea	Lentil	Lupin	Total*
“Impact” corpus	32	5	5	2	1	1	1	1	40
of which:									
<i>rainfed crops</i>	11	4	2	1	1	1	1	1	16
<i>irrigated crops</i>	4	1	1	0	0	0	0	0	6
<i>composite (mix of rainfed and irrigated crops)</i>	14	0	0	0	0	0	0	0	14
<i>unclear</i>	7	0	2	1	0	0	0	0	8
“Adaptation” corpus	41	2	5	1	4	0	0	1	53

* A paper can appear in several categories.

286 **Table 2:** Description of selected studies simulating grain legume response to climate change (“impact”
 287 corpus) and adaptation (“adaptation” corpus). We present here the number of papers per spatial scale
 288 of the analysis (a), type of model used (b), climate change scenario (c), biotic and abiotic parameters
 289 considered (d), and indicators assessed (e-f).

	Impact			Adaptation		
	Soybean	Other grain leg.	Total*	Soybean	Other grain leg.	Total
a) Spatial scale of the analysis						
Global scale with data for Europe	23	2	25	6	0	6
European scale	4	1	4	1	0	1
Country scale	3	1	4	2	0	2
Regional scale	0	2	2	20	6	26
Site-based studies	2	3	5	12	6	18

b) Type of model*

Process-based model	18	4	22	37	11	48
Niche model	8	3	10	0	0	0
Statistical model	7	1	8	4	1	5
Others ^a	1	1	2	0	0	0

c) Climate change scenario used*

SRES scenarios (IPCC AR4)						
A1B	7	4	11	14	3	17
A2	5	3	8	8	2	10
B1	1	1	2	4	0	4
RCP scenarios (IPCC AR5) & SSP scenarios (IPCC AR6)						
RCP2.6 / SSP1-2.6	4	0	4	5	0	5
RCP4.5 / SSP2-4.5	13	4	16	20	7	27
RCP6.0	3	0	3	2	0	2
SSP3-7.0	0	0	0	2	0	2
RCP8.5 / SSP5-8.5	18	3	21	21	7	28
HAPPI scenarios						
+1.5°C World	2	0	2	0	0	0
+2°C World	1	0	1	0	0	0

d) Climate parameter and biotic stresses considered*

Temperature	32	9	40	41	12	53
Rainfall	30	8	37	41	12	53
CO ₂	15	3	18	24	9	33
Biotic stress (pest, weed, pathogen)	4	1	5	0	1	1
Ozone	3	0	3	0	0	0

e) Crop performance indicators assessed*

Grain yield (relative changes in %)	14	2	16	13	5	18
Grain yield (absolute values in t/ha)	6	3	9	24	6	30
Suitability index	8	3	10	2	0	2
Yield variability or risk of crop failure	3	1	4	1	1	2
Crop production	2	0	2	3	0	3

f) Other indicators assessed*

Irrigation demand	3	3	6	4	3	7
Risk of pest occurrence	4	1	5	0	1	1
Water use efficiency	3	1	4	5	5	10
Biomass or biological N fixation	0	1	1	4	1	5
Economic indicators	1	0	1	1	1	2
Future water availability	0	1	1	1	1	2
Soil organic carbon, nutrient balance or erosion	0	0	0	8	1	9
Greenhouse gas emissions	0	0	0	3	1	4
Yield loss due to pest	0	0	0	0	1	1
Others ^b	2	1	3	1	0	1

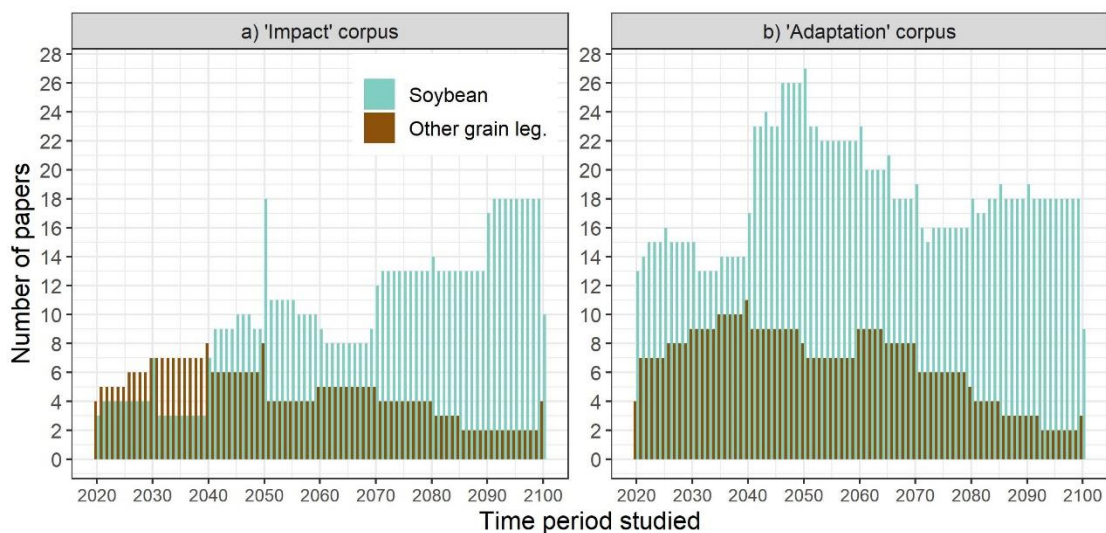
g) Total

32	9	40	41	12	53
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* A paper can appear in several categories.

^a Includes: agroclimatic indicators (1), probabilistic model (1)

^b Includes: agroclimatic indicators (1), probability of maturing (1), risk for non-existing adapted varieties (1), time of emergence (1)



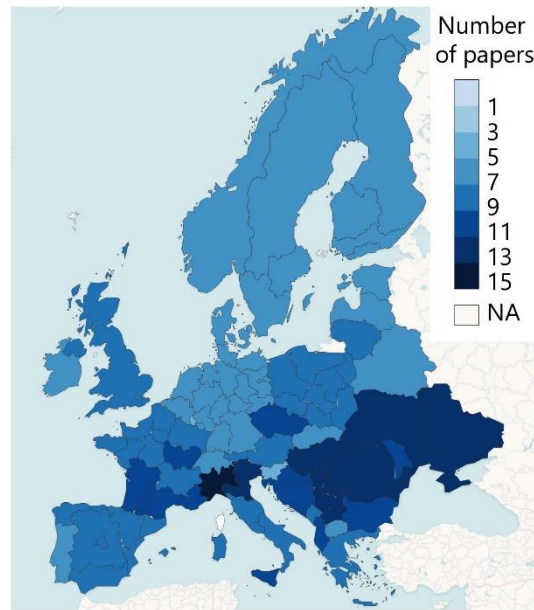
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291 **Figure 2:** Number of papers in the “impact” (a) and the “adaptation” corpus (b) per future time period
 292 studied

293

294 3.1.2. Impact of climate change on soybean performances without
 295 adaptation

296 For soybeans, although papers selected in the “impact” corpus covered the whole European
 297 continent (Figure 3), more data were available for current production hotspots (11 to 14 papers
 298 in Southern France, Northern Italy, and South-Eastern Europe) than Northern Europe (7 to 8
 299 papers in the Baltic states and Scandinavia). Two reasons may explain this discrepancy: site-
 300 based studies were more numerous in countries where soybeans are currently grown (Figure
 301 S2), and global-scale simulations did not always consider high latitudes.



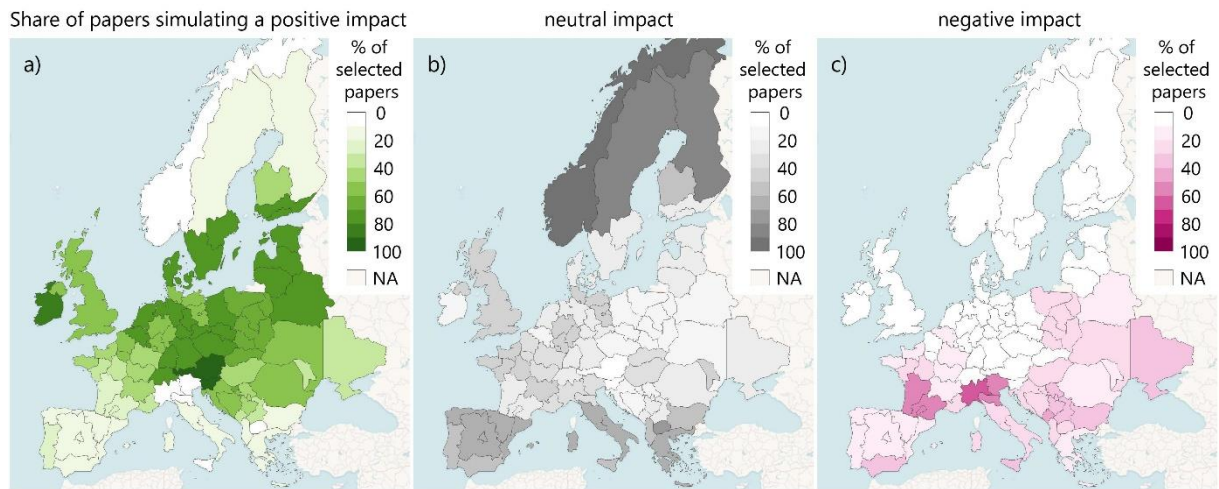
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303 **Figure 3:** Number of papers simulating the impact of climate change on soybean performances without
 304 adaptation per geographical area. Due to methodological differences and data availability, only 21
 305 papers of the “impact” corpus were included here (see Table S2).

306 The impact of climate change was found to vary spatially, with yield gains simulated in the
 307 North and a higher probability of yield losses in the South (Figure 4). All studies simulated a
 308 neutral or positive impact of climate change on soybean performances in the British Isles,
 309 Germany, Austria, Czech Republic, Western Poland, Belarus, and the Baltic states (Coleman
 310 et al., 2021; Feng et al., 2021; Guilpart et al., 2022; Manners et al., 2020; Rosenzweig et al.,
 311 2014; Soares et al., 2021; Tatsumi et al., 2011). Yield gains were simulated in the South of
 312 Finland and Sweden, but not in Norway.

313 Conversely, a negative impact of climate change was simulated in Northern Italy and South-
 314 Western France (Deryng et al., 2014; Guilpart et al., 2022; Jägermeyr et al., 2021; Lesk et al.,
 315 2021; Osborne et al., 2013; Tatsumi et al., 2011), with up to 60% of agreement among studies
 316 on the sign of change. In Eastern Europe, results were more diverging. Irrigated soybeans
 317 were found to benefit from rising temperatures in Serbia (Jancic et al., 2015; Mihailović et al.,
 318 2015; Tovjanin et al., 2019) and Croatia (Marković et al., 2020). Deryng et al. (2014) also found
 319 an overall positive impact in Eastern Europe under RCP8.5. Conversely, yield losses were
 320 simulated in several studies (Deryng et al., 2011; Guilpart et al., 2022; Jägermeyr et al., 2021;

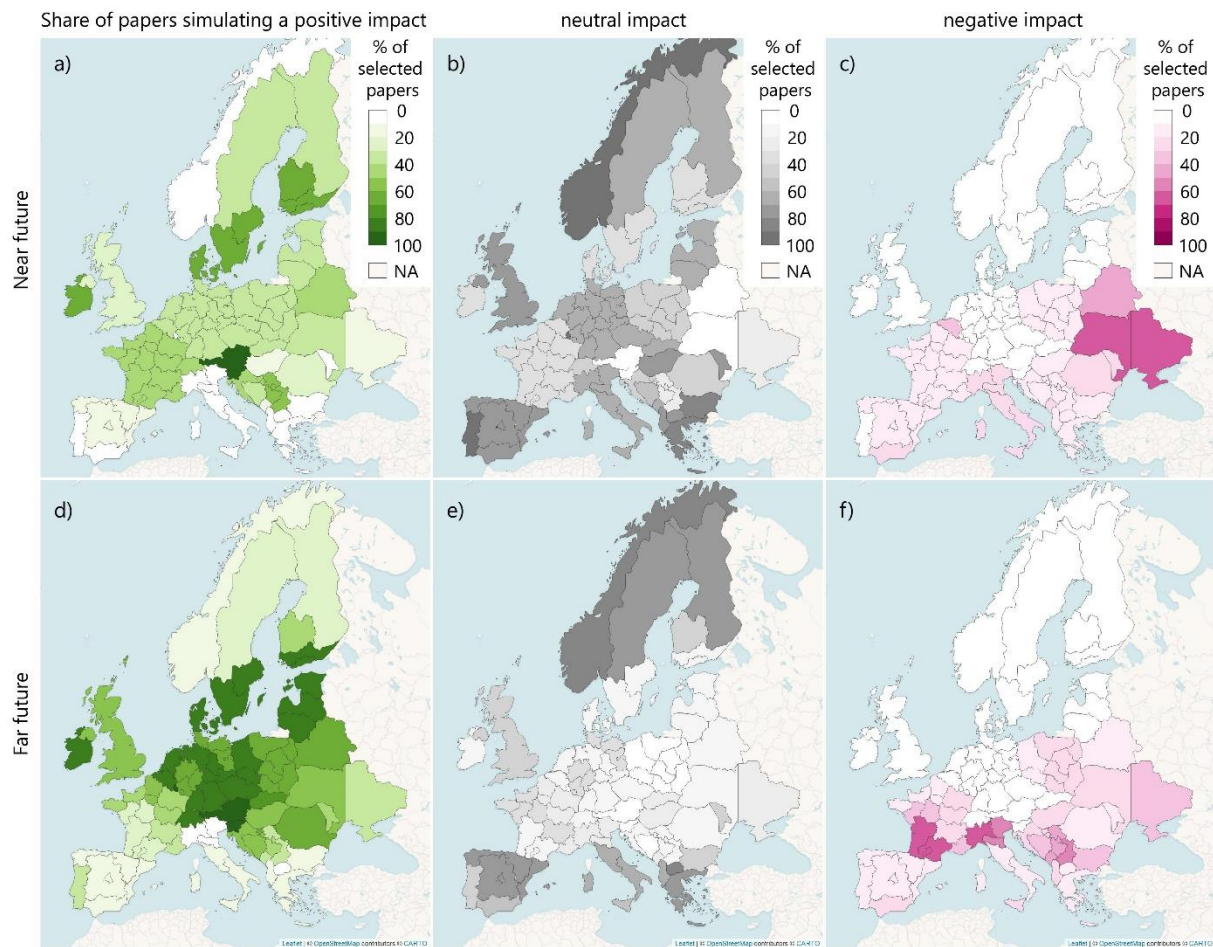
321 Lesk et al., 2021; Ruane et al., 2018; Tatsumi et al., 2011). Consensus among studies was
322 low in this area, with less than 40% agreement on the sign of change (Figure 4).



323

324 **Figure 4:** Share of papers simulating a positive (a), neutral (b), and negative (c) impact of climate
325 change on soybean performances. The share is calculated by dividing the number of articles simulating
326 a positive (resp. neutral and positive) impact by the total amount of articles for each geographical area.
327 Articles are weighted as explained in the Materials and methods section (one article testing two climate
328 models with positive results for one and negative results for the other will be counted as 0.5 positive and
329 0.5 negative).

330 Except for Ukraine, the impact of climate change was more contrasted in the far future (Figure
331 5d-f) than near future (Figure 5a-c), with a decrease in the proportion of “neutral” results and
332 an increase in the proportion of “negative” and “positive” results. Unsurprisingly, results were
333 slightly more contrasted for warmer scenarios (RCP6.0 and RCP8.5) than others (Figures S4-
334 5). Niche models seemed slightly more conservative than process-based models, with a higher
335 proportion of “neutral” results, while statistical models were more contrasted (Figures S6-7).
336 This discrepancy may arise from differences in model structure or from the methodology used
337 in data collection. Simulations considering CO₂ were usually more optimistic than those without
338 CO₂ (Figures S8-9). However, even when the effect of CO₂ was accounted for, the impact of
339 climate change remained negative in some simulations for Serbia, Bosnia, Hungary
340 (Jägermeyr et al., 2021), Italy (Osborne et al., 2013) and Southern France (Deryng et al.,
341 2014).



342

343 **Figure 5:** Share of papers simulating a positive (a, d), neutral (b, e), and negative (c, f) impact of climate
 344 change on soybean performances in the near (≤ 2050) (a-c) and far future (>2050) (d-f). Figure S3 shows
 345 the number of articles for each geographical area.

346 Additional damages from ozone exposure were simulated by Tai et al. (2014) and Tai and Val
 347 Martin (2017), whereas soybeans were almost unaffected by this factor in Lombardozzi et al.
 348 (2018). In addition to these abiotic factors, an increased pressure from some weeds and insect
 349 pests was simulated. The risk of parasitism increased for three of the five *Cuscuta* species
 350 studied by Cai et al. (2022). Future climate conditions in Europe were also found favourable
 351 for the expansion of *P. guildinii* and *M. sojae* (Chen et al., 2023; Marchioro and Krechemer,
 352 2023), whereas *S. eridania* was not identified as a serious threat for soybeans (Weinberg et
 353 al., 2022).

354 3.1.3. Impact of climate change on other grain legume performances
355 without adaptation

356 Very few studies were found on other grain legumes (9 papers, Table 1), so robust spatial
357 patterns of climate change impact could not be identified for these crops. Despite this, the few
358 studies available still offer some useful insights, which are outlined below. The most complete
359 was the work of Manners et al. (2020), who studied the impact of climate change in 27
360 European countries on 13 legumes and pseudo-cereal protein crops (only 8 grain legume
361 species were retained in our analysis). The simulated spatial pattern was similar to that found
362 for soybeans (see Section 0.), with a positive impact of climate change for almost all crops in
363 the British Isles and Northern Europe in 2050, and suitability losses in Southern Europe,
364 especially in France, Portugal, and Hungary. Andean lupin was found to benefit the most from
365 future climate conditions, whereas blue lupin benefitted the less.

366 In agreement with Manners et al., Ramirez-Cabral et al. (2016) found an increased suitability
367 for beans in Northern Europe under climate change. In Eastern Europe, France, and the
368 Mediterranean area, results were more uncertain, as suitability strongly decreased with one
369 climate model and increased with the other. In Greece, climatic conditions became less
370 favourable for bean growth (van der Schriek et al., 2020), while only a negligible impact was
371 found in Germany in the near future (Wagner et al., 2016). In Western and Northern Europe,
372 the risk of damage from *P. pachyrhizi* and *S. exigua* was expected to rise from low to medium
373 levels for this crop (Ramirez-Cabral et al., 2019).

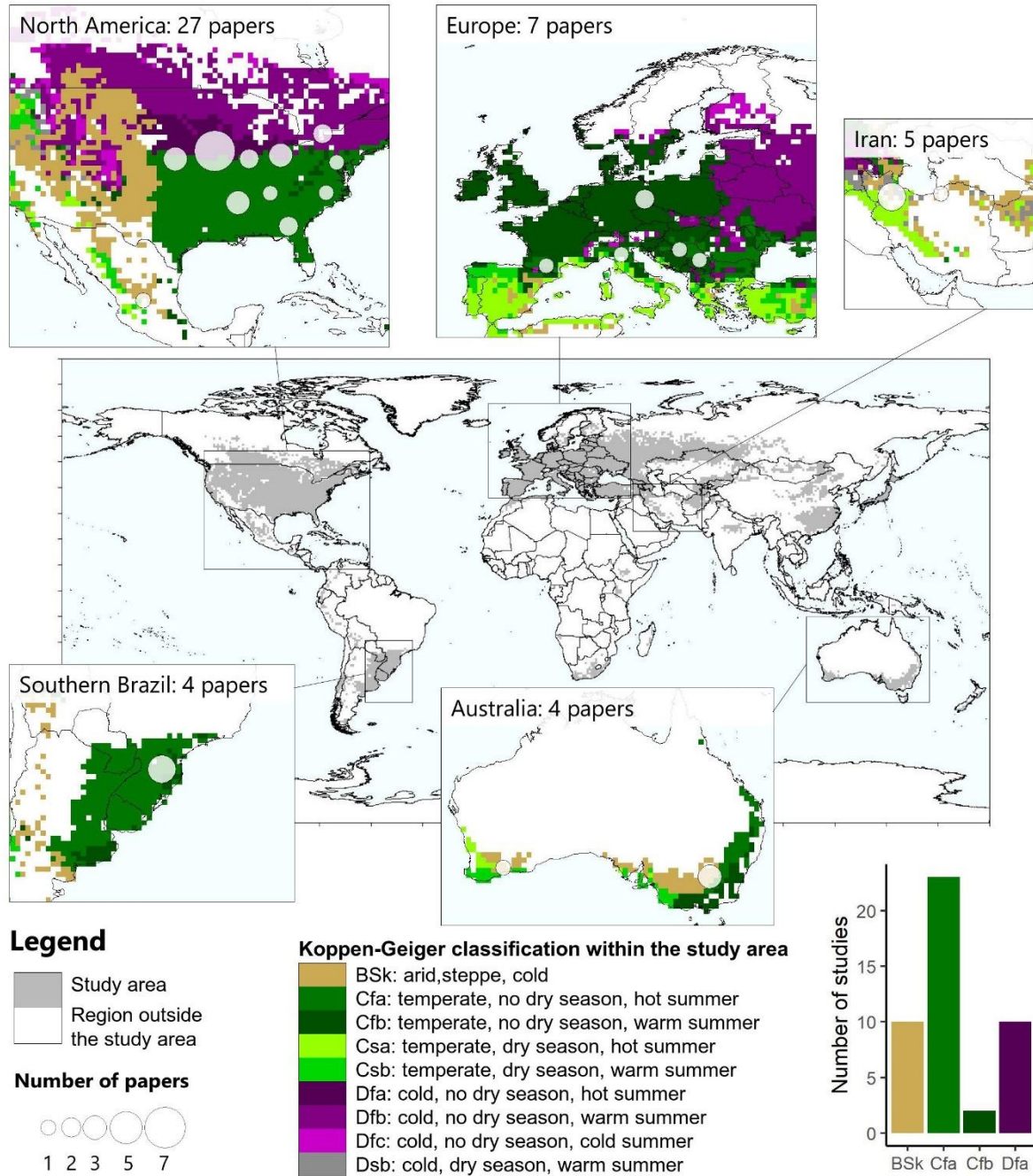
374 Spring pea yields responded positively to rising temperatures in Finland (Peltonen-Sainio et
375 al., 2009). Conversely, a productivity loss due to increased drought and heat stress was
376 simulated in France and Italy (Falconnier et al., 2020; Ravasi et al., 2020).

377

3.2. Effect of adaptation strategies on grain legume performances

378

3.2.1. Description of selected studies



379

380 **Figure 6:** Study area and geographical distribution of the papers selected in the “adaptation” corpus.
 381 The study area is composed of Europe and climatically similar regions. We used the Köppen-Geiger
 382 climate classification updated by Kottek et al., (2006) and the script provided by Rubel et al., (2017) to
 383 build the maps.

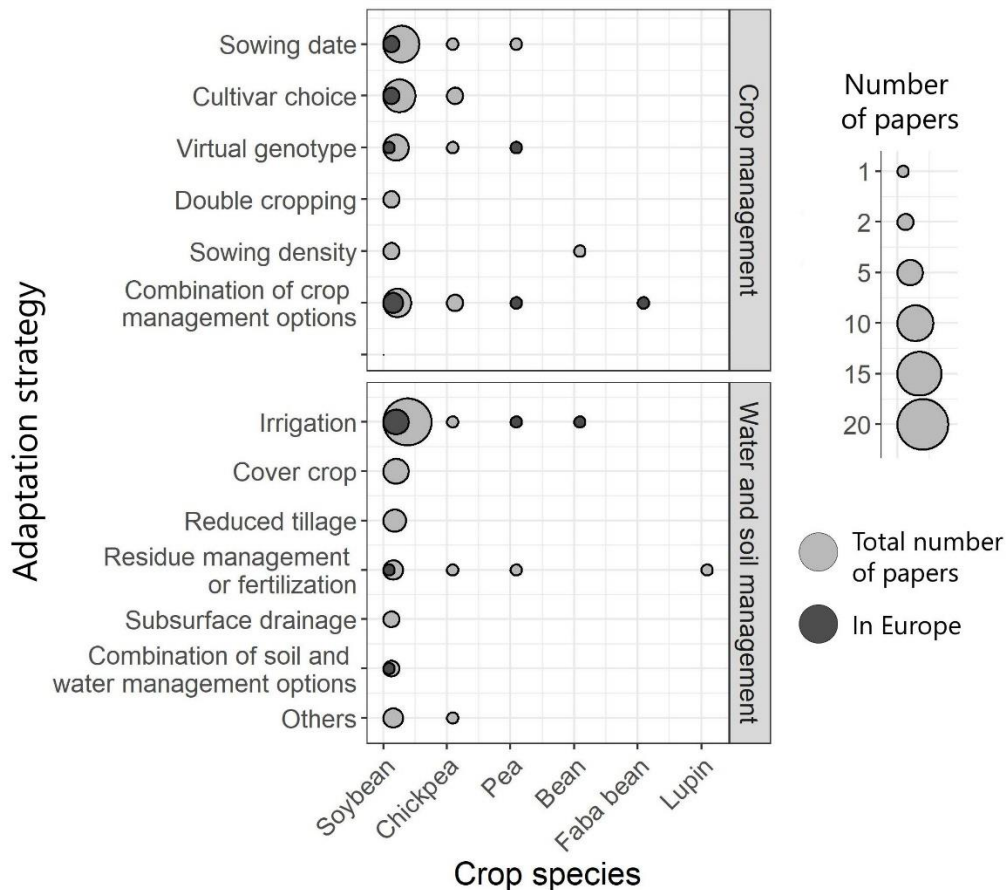
384 Fifty-three papers assessed the effect of adaptation on grain legume performances. Among
385 them, only 13% were located in Europe, and 11% were global studies providing data for Europe
386 (Table 2a). The remaining 76% were located in climatically similar regions and were divided
387 between Northern America (51%), Southern Brazil (8%), Iran (9%), and Australia (8%) (Figure
388 6). Soybeans were studied in 77% of papers, followed by peas (9%) and chickpeas (8%) (Table
389 1). Only process-based and statistical models were used for these simulations (Table 2b).

390 Unlike the “impact” corpus, the first part of the century was more studied than the far future,
391 both for soybeans and other grain legumes (Figure 2b). RCP4.5 and RCP8.5 remained the
392 most studied climate scenarios, used in 60% of papers (Table 2c). All studies accounted for
393 changes in temperature and rainfall, and 62% of them considered the effect of CO₂ (Table 2d).
394 Only one paper accounted for biotic stresses, and none of the selected studies considered the
395 effect of ozone.

396 The effect of adaptation was measured on grain yield in 91% of papers, with 62% of them
397 providing absolute grain yield data and 38% relative changes (Table 2e). Similar to the “impact”
398 corpus, studies assessing the effect of adaptation on yield variability were scarce (2 papers).
399 Numerous studies investigated the effect of irrigation, which explains the higher number of
400 results on crop water use efficiency (19%), future water demand (13%), and water availability
401 (4%) (Table 2f). Some variables assessed in the “adaptation” corpus were not considered in
402 the “impact” corpus, for example greenhouse gas emissions (8%), soil organic matter content,
403 or soil erosion (17%). This suggests that adaptation strategies are also often assessed for their
404 contribution to climate change mitigation. Economic indicators remained scarce (2 papers).

405 Crop management options were studied in 53% of papers, and soil and water management in
406 62% (Figure 7). Irrigation was the most studied technical option (40%), followed by modified
407 sowing dates (23%), cultivar choice (19%), and virtual genotype (13%). Combinations of
408 several adaptation strategies were seldom assessed (26% of selected studies), and little
409 variety was found in the choice of the strategies combined (changes in sowing date and cultivar

410 choice represented 64% of the combinations tested). Results on the effect of adaptation mostly
 411 apply to soybeans, as few data were available for other grain legumes. Faba beans and lupins
 412 represent extreme cases, with only one paper found for each species.



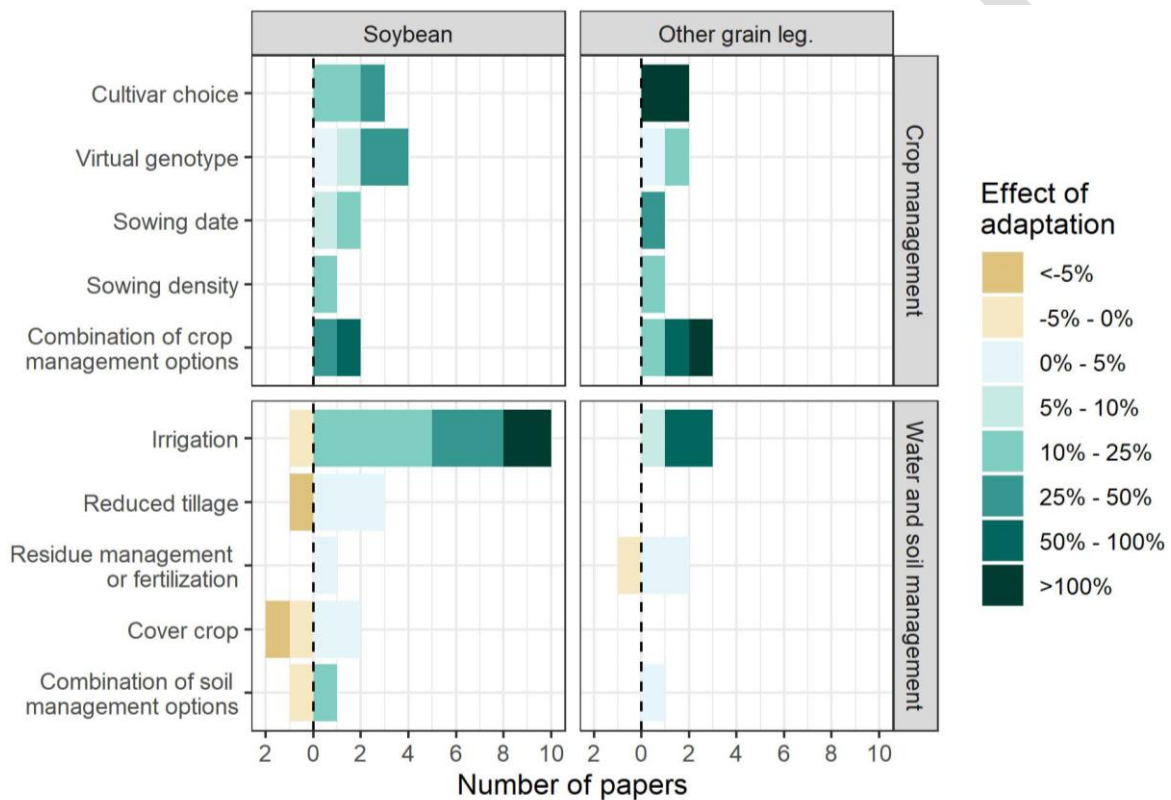
413

414 **Figure 7:** Number of papers per crop species and adaptation strategy. The size of the circle is
 415 proportional to the number of papers. Light grey circles represent the total number of papers and dark
 416 grey circles the number of studies focusing on Europe. A same paper can appear in several categories.

417 3.2.2. Crop management

418 The effect of shifting cultivar and sowing date was assessed on soybean performances in a
 419 majority of cases (76% of papers), but data were also available for peas (12%) and chickpeas
 420 (12%) (Figure 7). The simulated effect was neutral or positive in all studies, but its magnitude
 421 varied significantly among locations and species (from 4% to more than 100% yield increase)
 422 (Figure 8). Combining cultivar choice and changes in sowing date appeared as the most
 423 efficient strategy, with yield gains higher than 20%. Benefits were simulated not only on mean

424 yield but also on yield stability (Falconnier et al., 2020) and pest management (Salam et al.,
 425 2011). In most studies, the choice of the optimal maturity group, cultivar, and sowing date was
 426 site-specific (Bao et al., 2015a; Nendel et al., 2023; van Versendaal et al., 2023). For example,
 427 in Canada (Jing et al., 2017) and in South-eastern Europe (Minoli et al., 2022), early-sown
 428 soybeans benefitted from a longer growing season and higher yields, while in the USA, late
 429 sowing was identified as an adaptation strategy to avoid heat and water stress occurring earlier
 430 in the growing season (Bao et al., 2015b, 2015a).



431

432 **Figure 8:** Effect of different adaptation strategies on crop yields for soybeans (left) and other grain
 433 legumes (right). For each paper, the effect of adaptation is calculated as the ratio of the yield with
 434 adaptation to the yield without adaptation (expressed in %) and averaged over all time periods, climate
 435 scenarios, climate models and locations considered in that same paper (see Methods for details). Due
 436 to methodological differences and data availability, only 34 papers of the “adaptation” corpus were
 437 included here (see Table S3).

438 When designing virtual genotypes, the crop cycle length was often studied as a key parameter
439 to maintain or increase yields under climate change (Fu et al., 2016; Jing et al., 2017; Minoli
440 et al., 2022; Osborne et al., 2013; Ravasi et al., 2020; Soltani and Sinclair, 2012). In several
441 studies, extending the length of the growing period, and especially the grain filling period (Fu
442 et al., 2016), was found to offset the negative impact of elevated temperature on crop cycle
443 duration and soybean yields (Jing et al., 2017; Minoli et al., 2022). Conversely, in some areas
444 where water and thermal stresses were frequent (e.g. Southern France), an early maturity was
445 found preferable for this crop (Minoli et al., 2022). A reduced vegetative phase allowing an
446 early flowering also gave positive results for peas in Italy (Ravasi et al., 2020) and chickpeas
447 in Iran (Soltani and Sinclair, 2012). Other crop parameters were also explored, such as
448 maintaining the harvest index to current levels for soybeans (Jing et al., 2017) and widening
449 the optimal temperature range for peas (Ravasi et al., 2020). Increased drought resistance
450 was obtained for soybeans by manipulating water-related traits (rooting depth, transpiration
451 function) (Battisti et al., 2017) or irradiating seeds with gamma rays (Beiranvand and
452 Ghamghami, 2022).

453 Other crop management options tested included double-cropping and changes in sowing
454 density. In the USA, climate change alleviated phenological constraints and allowed for
455 expanding winter wheat-soybean double-cropping (Seifert and Lobell, 2015), especially in
456 areas where the suitability of a corn-soybean rotation was predicted to decline (Lant et al.,
457 2016). Sowing density influences within-crop competition for light, nutrients, and water, and
458 was tested as an adaptation strategy for beans in Mexico (Baez-Gonzalez et al., 2020) and for
459 soybeans in Brazil (Battisti et al., 2018). Increasing crop density led to higher yields due to
460 faster leaf area development (resulting in better radiation interception) and reduced soil
461 evaporation (Battisti et al., 2018). For beans, however, increasing sowing density also led to a
462 higher occurrence of water stress (Baez-Gonzalez et al., 2020).

463

3.2.3. Irrigation

464 A positive effect of irrigation was found in a majority of cases (92%), with yield increases
465 ranging from 8% to more than 100% (Figure 8). In Germany, both bean (Wagner et al., 2016)
466 and pea yields (Nendel et al., 2014) have been shown to increase with irrigation. Yield gains
467 were also simulated for soybeans in Eastern Europe (Elliott et al., 2014; Marković et al., 2020;
468 Mihailović et al., 2015), in Iran (Araji et al., 2018), in the USA (Bao et al., 2015b; Ma et al.,
469 2021; Timilsina et al., 2023; Zhu et al., 2019) and in Southern Brazil (Battisti et al., 2018).
470 Conversely, in the USA, Lychuk et al. (2017) and Paul et al. (2020) found a non-significant or
471 negative impact of irrigation on soybean yields in the long term, possibly due to higher nutrient
472 leaching under irrigated conditions. Irrigation was found to reduce yield instability for American
473 soybeans by Zhu et al. (2019).

474 Although irrigation seemed effective to adapt to climate change, strong hypotheses were often
475 made in simulations that did not always reflect the reality experienced by farmers. In particular,
476 irrigation water availability was often considered infinite, whereas huge challenges already
477 exist today in water availability. Future water availability was assessed in only two papers, with
478 diverging results. In Germany, Wagner et al. (2016) estimated that only 33% to 43% of the
479 studied area could provide all the water required for pea irrigation under future climate
480 conditions. On the opposite, Elliott et al. (2014) estimated that renewable water available for
481 irrigation would still exceed demand in most European countries. Optimizing irrigation systems
482 may be required to make the most of the available water resources. For example, Amiri et al.
483 (2021) pointed out the importance of irrigation timing and found that chickpeas benefitted more
484 from supplemental irrigation at the pod-filling stage than at the flowering stage. Another
485 optimization simulated by Baule et al. (2017) was the use of sub-irrigation, i.e. water capture
486 and recycling for summer irrigation.

487

3.2.4. Soil management

488 Soil management options were presented as interesting strategies for both adaptation and
489 mitigation, in order to design “climate-smart” systems. Climate change is indeed expected to
490 affect N processes (enhanced mineralization, reduced biological nitrogen fixation), and thus
491 indirectly impact crop performances (Elli et al., 2022; Malone et al., 2020). Management
492 options such as reduced tillage, crop residue incorporation, and cover crops, which play a role
493 in N processes, were assessed both for the environmental services they could provide and for
494 their potential to sustain crop performances in the context of climate change.

495 Switching to conservation tillage or implementing a cover crop during the previous winter was
496 only tested for soybeans (Figure 7). These two management options were found to have a
497 positive impact on water storage (Li et al., 2021), soil erosion, and nutrient leaching
498 (Panagopoulos et al., 2014). The effect of reduced tillage on crop performances was found
499 neutral (He et al., 2018; Panagopoulos et al., 2014, 2015; Parajuli et al., 2016), except in He
500 et al. (2018) where no tillage reduced yields under severe climate change. Likewise,
501 implementing a rye or a wheat cover crop in winter had no significant effect in Li et al. (2021),
502 Malone et al. (2020), and Panagopoulos et al. (2015). A slight yield reduction was observed in
503 Basche et al. (2016) and Panagopoulos et al. (2014), especially for dry years, and was
504 attributed to the competition between soybeans and cover crops for nutrients and soil water.
505 As they provided environmental services without significantly harming crop yields, these
506 options were advocated as mitigation and adaptation strategies (Malone et al., 2020).

507 Crop residue incorporation was assessed in several papers in Australia to reduce soil erosion
508 and improve water and organic matter content. Neither chickpeas (Liu et al., 2017) nor lupins
509 (Wang et al., 2019) nor peas (He et al., 2022) did respond to residue management. Adapting
510 fertilization to increase crop yields under climate change was not found efficient either (Lychuk
511 et al., 2017; Wang et al., 2019).

512 4. Discussion

513 4.1. The impact of climate change on future grain legume 514 production remains uncertain in Europe

515 Conclusions on the impact of climate change mostly apply to soybeans, as very few data were
516 available for the other crops. For soybeans, we found a good agreement between studies, with
517 yield gains simulated in Northern Europe and a higher probability of yield losses in Southern
518 and South-Eastern Europe. This spatial pattern of climate change impact is consistent with
519 expectations from climate projections and crop physiology knowledge. Indeed, while climate
520 change is expected to lengthen crop growing seasons in the North, it may lead to faster crop
521 development in the South and increase the occurrence of stresses, eventually causing yield
522 losses (Osborne et al., 2013). A similar spatial pattern was found for wheat, another C3 crop,
523 by Hristov et al. (2020).

524 These conclusions were relatively robust across climate scenarios, time periods, and types of
525 models. In some regions, the divergences between studies may be explained by differences
526 in model inputs (e.g. climate models and scenarios), structure, or parameters (Wallach and
527 Thorburn, 2017). Additional work is needed to quantify these sources of uncertainty, as it has
528 been made for major crops (Li et al., 2015; Rosenzweig et al., 2014). In particular, a major
529 source of uncertainty arises from models often neglecting the impact of CO₂ (considered in
530 only 36% of selected papers), ozone (4%), and abiotic stresses such as cold snap and
531 waterlogging (not assessed in this review).

532 Our analysis did not make it possible to assess whether yield gains in the North will
533 compensate for yield losses in current soybean production hotspots, mainly located in
534 Southern and Eastern Europe (Figure S2). Indeed, the few results available were diverging.
535 While Guilpart et al. (2022) simulated a reduction of high-yielding production areas under
536 climate change, resulting in a decrease in the average soybean yield in Europe, Nendel et al.

537 (2023) found an overall productivity gain. To assess how climate change will impact the
538 average grain legume yield and production at the European scale and identify future production
539 hotspots, we suggest that future simulations should provide absolute yield values instead of
540 relative values. Indeed, relative changes can easily reach very high values when the baseline
541 yield is low. Therefore, even with a strong positive impact of climate change in Northern
542 Europe, future soybean yields in these areas may not be attractive to farmers.

543 4.2. Adaptation strategies can mitigate the impact of climate 544 change on grain legumes

545 This review showed that adaptation strategies have the potential to mitigate the negative
546 impacts of climate change or enhance its positive impacts. Yet, the strategies investigated
547 differed in their effects on yields. Overall, irrigation and crop management options resulted in
548 significant yield gains. A neutral or slightly negative effect on yields was frequently simulated
549 for alternative soil management and fertilization, which was not surprising given grain legume
550 reliance on biological nitrogen fixation (Liu et al., 2017). However, these options provided
551 secondary benefits, for example soil erosion prevention, which could motivate their adoption.

552 Our analysis revealed an imbalance between relatively well-studied strategies (e.g. irrigation
553 or change in sowing dates) and strategies whose potential remains to be examined (e.g.
554 intercropping). Combining different adaptation strategies also appears as a promising yet
555 underexplored strategy. In particular, we suggest water-saving soil management options
556 should be tested in combination with optimized irrigation systems, in order to sustain yields in
557 spite of a growing pressure on water resources. Engaging stakeholders in the co-design of
558 adaptation strategies would help identify relevant combinations and increase the scope of
559 strategies tested (Farrell et al., 2023; Tui et al., 2021).

560 Our assessment of the adaptation effect involves some limitations both from the method used
561 in the review and in selected papers. First, our work does not consider the dynamic evolution

562 of adaptation efficiency. In particular, Lobell (2014) distinguishes between an “impact-neutral”
563 adaptation strategy (e.g. a strategy enhancing yields by 10% both in baseline and future), and
564 an “impact-reducing” strategy (e.g. a strategy enhancing yields by 10% in baseline climate and
565 20% in the future, and thus mitigating the impact of climate change on yields). Impact-reducing
566 strategies are likely to be the key to resilient and sustainable systems and should therefore
567 receive more attention than strategies whose efficiency decreases with time. However, in this
568 review, the effect of adaptation was quantified as the ratio between yield with and without
569 adaptation in the future, which did not allow us to identify impact-reducing strategies. Our
570 choice was mainly dictated by data availability, as only 36% of selected papers provided a
571 complete dataset including yields with and without adaptation for baseline climate. The few
572 results available sometimes diverged (Figure S12). In particular, irrigated soybeans benefitted
573 less from climate change than rainfed soybeans in several studies (Bao et al., 2015b; Ma et
574 al., 2021; Nendel et al., 2023), while contradictory results were found in others (Marković et
575 al., 2020; Timilsina et al., 2023). This issue needs further investigation in order to avoid
576 overestimating adaptation benefits from some strategies.

577 Second, the effect of adaptation was generally assessed independently of the technical and
578 economic feasibility of the strategy considered. In particular, 90% of studies assessing the
579 effect of irrigation did not estimate future water availability. It is also uncertain whether virtual
580 genotypes obtained by varying crop traits could realistically be developed in breeding
581 programs. Besides, studies generally overlooked the cost of adaptation. For strategies such
582 as irrigation and increased sowing density, this cost may outweigh the increase in crop
583 productivity (Elliott et al., 2014). Therefore, the evaluation of adaptation strategies would be
584 improved by the development of multi-criteria assessment methodologies including
585 stakeholders’ constraints and objectives (Naulleau et al., 2021, 2022).

586 4.3. Knowledge gaps and future research avenues

587 4.3.1. Grain legumes other than soybeans as blind spots

588 Our review highlighted a need for further European-scale modelling, especially for other grain
589 legumes than soybeans. In agreement with Magrini et al. (2019), we found a great imbalance
590 between soybeans and other grain legumes in the literature, with soybeans representing
591 approximately 80% of selected studies. The paucity of data for these crops contrasts with their
592 prominent positions in European environmental, agricultural, and nutritional policies. We
593 recommend prioritizing research on key species including peas, faba beans, lentils, and
594 chickpeas. To fully comprehend the impact of climate change on these crops, it seems
595 important to differentiate between spring and winter-sown cultivars, as well as rainfed and
596 irrigated crops. However, this differentiation was not consistently made in the papers selected
597 for this review.

598 Likewise, simulations at the European scale were scarce. Most data on climate change impact
599 originated from global-scale simulations whose coarse resolution masks a wide local
600 heterogeneity (Zhao et al., 2015). Enlarging the study area to climatically similar regions
601 allowed us to compensate for the lack of data in Europe. However, results transferability may
602 be limited by differences in non-climatic parameters such as soil and farm characteristics.
603 Additional work at the European scale seems necessary to support the development of grain
604 legumes, as targeted by European policies.

605 4.3.2. Choice of the right time and spatial scales

606 The number of studies assessing the impact of climate change on soybeans in the far future
607 (second part of the XXIst century) contrasted with the paucity of results for the near future.
608 Identifying the timing of risks and key adaptations is necessary to ensure that simulated time
609 periods are not disconnected from stakeholders' needs (Challinor et al., 2018). Therefore, we
610 suggest that farmers and other stakeholders should be included in the process of modelling in

611 order to identify relevant inputs and outputs for future simulations (Naulleau et al., 2022).
612 Stakeholders may also guide an adequate choice of baseline period to avoid misestimating
613 the impact of climate change.

614 A reflection should also be undertaken on the choice of the spatial scale used in simulations.
615 The effect of some adaptation strategies (e.g. sowing date and cultivar choice) was found site-
616 specific, which points to the need for a local design of adaptation strategies. For other
617 strategies (e.g. shifting to species originating from other agricultural regions, switching grain
618 legume species), effect assessment may be more relevant at the European scale.

619 The right time and spatial scale will probably depend on the stakeholders. Therefore, multi-
620 scale modelling may be required, as advocated by Peng et al. (2020), who designed a
621 framework from gene to global scale. In the case of grain legumes, we suggest that such a
622 framework should also include crop sequence modelling, as benefits from legumes are
623 strongly dependent on their break-crop effects. Future analyses should also account for the
624 response of cropping mix to climate change. Indeed, the impact of climate change and the
625 effect of adaptation are crop-specific and may lead to changes in crop relative performances
626 and economic profitability. To our knowledge, no study has compared grain legume and cereal
627 response to climate change and adaptation. Further research should explore this issue to
628 investigate whether climate change could enhance or reduce grain legume attractiveness to
629 farmers compared to major crops or innovative minor candidate crops.

630 4.3.3. A need to broaden the scope of estimated climate change impact

631 In our analysis, the impact of climate change and the effect of adaptation were mainly
632 quantified in terms of change in yield. However, yield is only one component of the lock-in
633 hindering the development of grain legumes in Europe (Magrini et al., 2016). Other indicators
634 of interest for the stakeholders were found poorly investigated, in particular the impact of
635 climate change on biotic stresses, yield stability, and services provided by grain legumes.

636 Biotic stresses (weeds, pests, and pathogens) can lead to significant yield losses (Savary et
637 al., 2019) and are likely to be impacted by climate change. Indeed, with the global rise of
638 temperatures, some insects could establish in areas where their proliferation is currently limited
639 by cold temperatures (Bebber et al., 2013; Chaloner et al., 2021). Rising temperatures could
640 also lead to a shortening of reproductive cycles and an increased number of pest generations
641 during crop growing season, thus increasing the influence of pests on yield losses. Elevated
642 CO₂ could increase the relative competitiveness of C3 weeds and make crops less nutritious
643 for insect pests, leading to increased damage (Olesen and Bindi, 2002). In our review, few
644 papers were found on the expected biotic pressure under climate change in Europe, although
645 it is likely that its importance should increase in the future. Most studies used suitability indexes
646 to assess the future overlap between areas suitable to crops and pests, but yield losses were
647 not estimated. Models simulating plant growth and insect life cycles have already been used
648 in other regions of the world to predict future insect damage (Taylor et al., 2018) and could
649 provide valuable information on potential biotic risks and adaptation strategies in Europe.

650 Farming systems are particularly sensitive to yield shocks (Hristov et al., 2020), and even
651 systems well-adapted to long-term trends will not necessarily be the most resilient against
652 extreme climate events (Rosenzweig and Tubiello, 2007). Therefore, we recommend that
653 projections of future yield variability or risks of crop failure should complement existing data on
654 future average yields. Assessing the impact of climate variability on yields will require
655 improving model calibration and representation of climate extremes and CO₂ effect, especially
656 for minor crops such as grain legumes (Kersebaum, 2022; Rötter et al., 2018). Designing
657 successful strategies to cope with climate variability may also require new approaches. For
658 example, instead of relying on future climate estimates, adaptation strategies could be
659 designed with the aim of being effective under a wide range of climate conditions (Corbeels et
660 al., 2018).

661 Finally, as grain legumes are often grown for the N-related ecosystem services they provide,
662 we suggest that future simulations should investigate the impact of climate change on N

663 fixation and provision. Non-yield benefits of adaptation strategies should also be assessed, as
664 well as potential interactions between adaptation and climate change mitigation. Given
665 Europe's growing interest in grain legumes as high-quality protein crops, changes in grain
666 quality and protein content should be simulated to complement already existing experimental
667 data (Scheelbeek et al., 2018).

Preprint

668 5. Conclusion

669 This systematic review provides an original synthesis of model-based studies simulating the
670 impact of climate change and the effect of adaptation on grain legume performances in Europe.
671 Overall, the positive impact of climate change on soybean yields in Northern Europe was
672 relatively consensual among studies, while yield losses may be expected in Southern and
673 Eastern Europe. Although the spatial pattern appeared similar to soybean, lack of data
674 prevented drawing a robust conclusion for other grain legumes at the European scale.
675 Irrigation, changes in sowing date, and cultivar choice were among the most promising
676 adaptation strategies, although authors seldom assessed their environmental desirability and
677 economic feasibility. Alternative soil management generally had a neutral or negative impact
678 on yields but provided secondary benefits, which could motivate its adoption.

679 The main knowledge gaps identified were a lack of data for other grain legumes than soybeans
680 and a need for more Europe-focused studies, especially for adaptation effect assessment.
681 Modelling the impact of climate change and adaptation remains an open research avenue for
682 key crops such as field peas and faba beans. Only a few studies considered crop response to
683 elevated CO₂, ozone, and biotic pressure. Therefore, incorporating these factors would
684 enhance climate change impact assessment. We also suggest that future simulations should
685 broaden the range of adaptation tested (e.g. intercropping, choice of the grain legume species,
686 combinations of several adaptation strategies) and indicators assessed (e.g. economic
687 indicators, yield variability), in the frame of a multi-criteria analysis.

688 Altogether, these points highlight a research focus on just a few aspects of climate change and
689 adaptation, leaving in the dark important issues and challenges for stakeholders. Involving
690 stakeholders would help orient future modelling, in order to provide relevant output to inform
691 adaptation, within the scope of a use-oriented approach.

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1217 Author contributions

1218 M.M-B: Conceptualization, Investigation, Formal analysis, Writing- Original draft preparation.

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1221 Competing interests

1222 The authors declare no competing interests.