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Abstract

In Europe, increasing the area of legume crops has been identified as a key measure to achieve the objectives set by the European Green Deal and transition toward more sustainable food systems. Although the role of grain legumes in climate change mitigation has been closely examined, little research has focused on how climate change will challenge the development of these crops. This article systematically reviews recent simulation studies to assess the impact of climate change on grain legume performances in Europe and the effect of adaptation strategies. Forty papers using process-based, ecological niche, or statistical models were selected to simulate the response of eight grain legume species to future climate (2020-2100) in Europe. The lack of data on adaptation strategies in Europe was compensated for by enlarging the study area to climatically similar regions. The review highlights a notable imbalance between research about soybeans versus other grain legumes, with soybeans representing approximately 80% of selected studies. Studies focused on soybeans found good agreement, with yield or suitability gains simulated in Northern Europe and a higher probability of yield losses in Southern and South-Eastern Europe. While a similar spatial pattern may be expected for other grain legumes, the scarcity of data makes this result more uncertain. The review also shows that several adaptation strategies have the potential to mitigate the negative impact of climate change on grain legume performances or enhance its positive impact. The most promising strategies tested include irrigation, change in sowing date, and cultivar choice. In addition, we identify several knowledge gaps that, if addressed, would support legume development in Europe. In particular, key species such as field peas, faba beans, lentils, and chickpeas remain blind spots, despite their prominent role in European environmental, agricultural, and nutritional policies. Other knowledge gaps include a lack of accounting for crop response to elevated CO_2, ozone, and future biotic pressure, and a limited range of adaptation strategies tested and indicators assessed. Implementing multi-criteria analyses that involve stakeholders would help identify relevant input and output for future simulations.

Keywords

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

1. Introduction

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

In spite of their agronomical, environmental, and nutritional benefits, the production area of grain legumes remains low in Europe. In 2020, they represented less than 4% of European cropland, in contrast to 15.2% worldwide (FAOSTAT, 2023) (Table S1). Numerous interacting factors (e.g. public policies, market dynamics, agronomic R&D activities, and breeding efforts), resulting in a so-called technological lock-in, have hampered their development (Magrini et al., 2016). Yield instability is one component of this lock-in (Watson et al., 2017). Indeed, grain legume yields are often considered to be more variable than cereal yields (Cernay et al., 2015), especially as they are frequently sown in spring, which makes them more exposed to heat stress and water deficit during key stages of their growing cycle (Falconnier et al., 2020; Reckling et al., 2018). Drought (Farooq et al., 2017), cold and heat stresses (Bhat et al., 2022; Gogoi et al., 2018), or waterlogging (Pasley et al., 2020) can strongly affect biological nitrogen fixation (Salon et al., 2011), grain legume growth, reproduction, and yield.

Climate change is likely to increase the occurrence of such stresses, and thus impact grain legume performances (Ahmed et al., 2022; Vadez et al., 2012). Although the role of grain legumes in climate change mitigation has been closely examined (Jensen et al., 2012; Prudhomme et al., 2020), little research has focused on how climate change will challenge their development in Europe. In particular, although a large body of literature has evaluated the effect of a single climatic factor - mainly elevated CO_2, temperature and water stress - on grain legume physiology and performances (Ahmed et al., 2022; Bhattacharya, 2010; Dutta et al., 2022), little is known on how these crops will respond to the simultaneous, climate change-driven variations of all these factors (Hatfield et al., 2011; Rötter et al., 2018; Vadez et al., 2012).

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

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

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

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

2. Materials and methods

2.1. Literature search

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

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

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

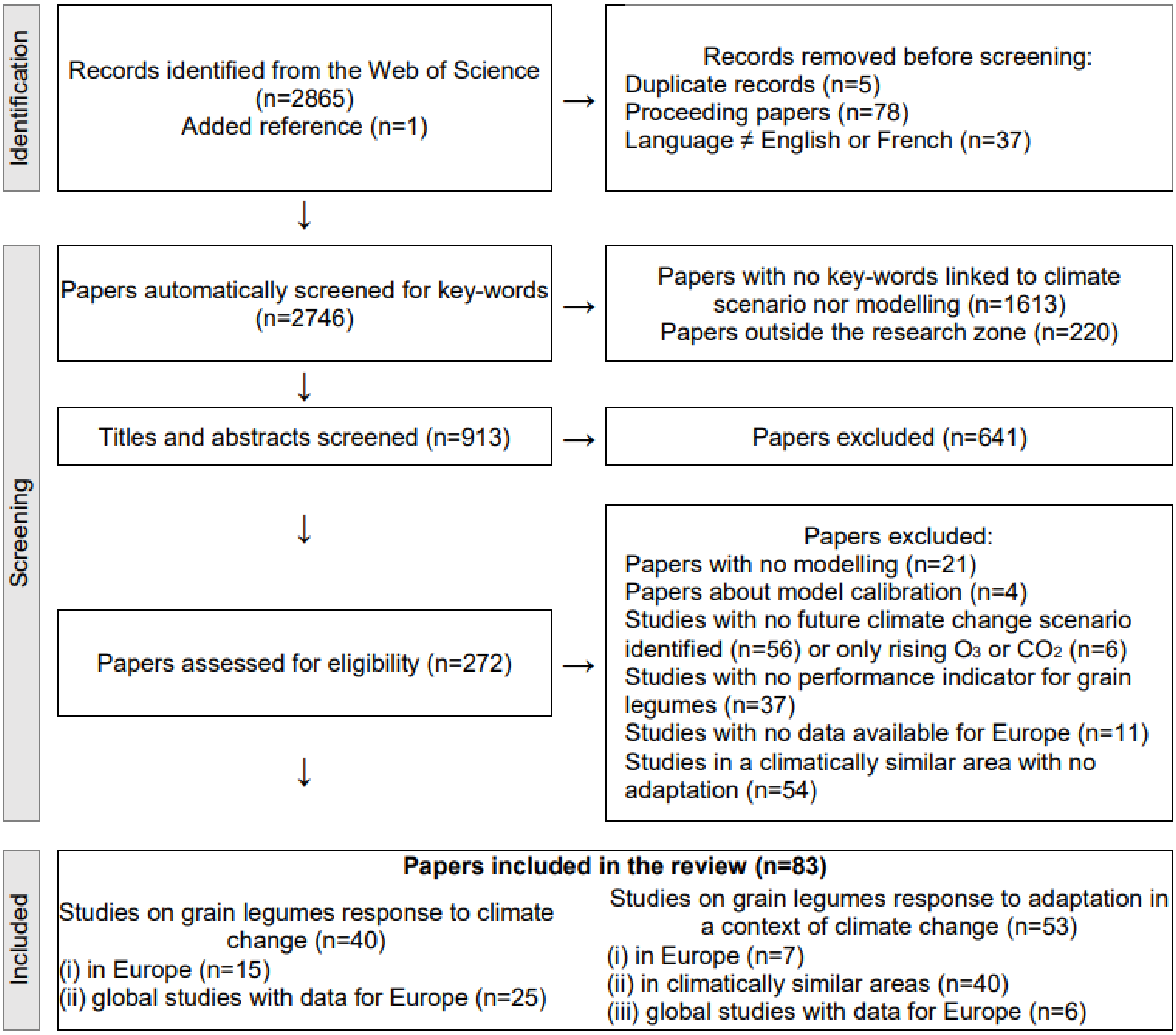

***Figure 1**: PRISMA diagram depicting paper collection and selection. n is the number of papers.*

2.2. Study selection

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

For the “impact” corpus, the study area was limited to Europe, from ca. 35°N to 72°N and 15°W to 40°E, excluding the Russian Federation. For the “adaptation” corpus, results in Europe were too scarce to allow a comparison between several adaptation strategies. Therefore, the study area was enlarged to all regions climatically similar to Europe at the global scale. Climatically similar regions were identified using the Köppen-Geiger climate classification updated by Kottek et al. (2006) and Rubel et al. (2017). The enlarged study area includes regions in Northern America, Southern Brazil, Australia, Iran, Russia, and China (see Section 3.2.1).

To be selected in the “impact” corpus, a publication had to meet the following criteria: (i) study one or several grain legume species; (ii) simulate the impact of future climate change on crop performances using a climate scenario (Free-Air Concentration Enrichment experiments were not considered in this review); (iii) provide data for Europe. Studies conducted at a global scale were selected if it was possible to extract exploitable data for Europe. To facilitate comparison, we considered only climate scenarios from IPCC assessment reports (AR4 to AR6) or the Half a degree Additional warming, Prognosis and Projected Impacts initiative (HAPPI) project. Studies assessing the sole impact of rising O_3 or CO_2 on crop performances were not included.

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

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

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

2.3. Data collection

The following data were extracted from the selected papers:

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

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

vi) abiotic and biotic factors included in the model (e.g. temperature, rainfall, CO_2, pests and diseases);

vii) crop performance indicators assessed.

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

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

$$I_a = \frac{Y_{CC\_a} - Y_{CC}}{Y_{CC}} \times 100 \qquad \text{(Equation 2)}$$

where Y_0 is the yield (or any other performance indicator) simulated in the baseline period, Y_{CC} is the yield under future climate conditions without adaptation, and Y_{CC_a} is the yield under future climate conditions with adaptation. In the irrigation strategy, the rainfed yield represented the yield "without adaptation", while the irrigated yield represented the yield "with adaptation". The effect of switching cultivars was assessed by comparing the highest-yielding cultivar to the other cultivars simulated. When several sowing dates were tested, we selected those that resulted in the highest yield (one or two options) and compared them to sowing dates considered as "standard" in the baseline. For tillage, fertilization or sowing density, the "new" option was compared to the "standard" one. The impact of climate change and the effect of adaptation were evaluated as positive if over +5%, neutral if between -5% and +5%, and negative otherwise.

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

2.4. Data analysis

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

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

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

3. Results

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

3.1.1. Description of selected studies

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

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

Only a small number of papers considered crop response to elevated CO_2 (45% of the corpus) or ozone (8%). Only five papers (13%) were found on the combined impact of climate change and weeds or pests. Although the three soybean pests (the soybean stem fly *M. sojae*, the southern armyworm *S. eridania,* and the red-banded stink bug *P. guildinii*) and two bean pests studied (the Asian soybean rust *P. pachyrhizi* and the beet armyworm *S. exigua)* were not currently of major concern in Europe, they could become an issue if they were to expand beyond their native range.

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

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:									
rainfed crops	*11*	*4*	*2*	*1*	*1*	*1*	*1*	*1*	*16*
irrigated crops	*4*	*1*	*1*	*0*	*0*	*0*	*0*	*0*	*6*
composite (mix of rainfed and irrigated crops)	*14*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*14*
unclear	*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.

Table 2: *Description of selected studies simulating grain legume response to climate change ("impact" corpus) and adaptation ("adaptation" corpus). We present here the number of papers per spatial scale of the analysis (a), type of model used (b), climate change scenario (c), biotic and abiotic parameters 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**

* 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)

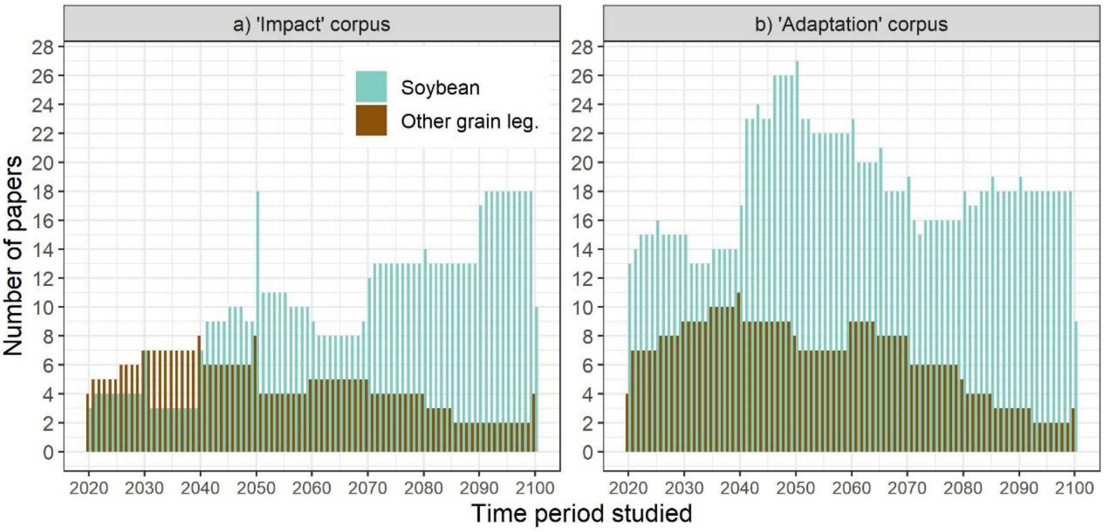

Figure 2: *Number of papers in the "impact" (a) and the "adaptation" corpus (b) per future time period studied*

3.1.2. Impact of climate change on soybean performances without adaptation

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

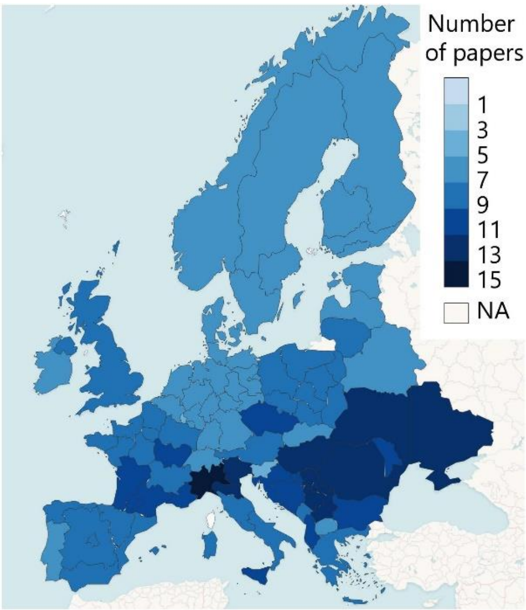

Figure 3: *Number of papers simulating the impact of climate change on soybean performances without adaptation per geographical area. Due to methodological differences and data availability, only 21 papers of the "impact" corpus were included here (see Table S2).*

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

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

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

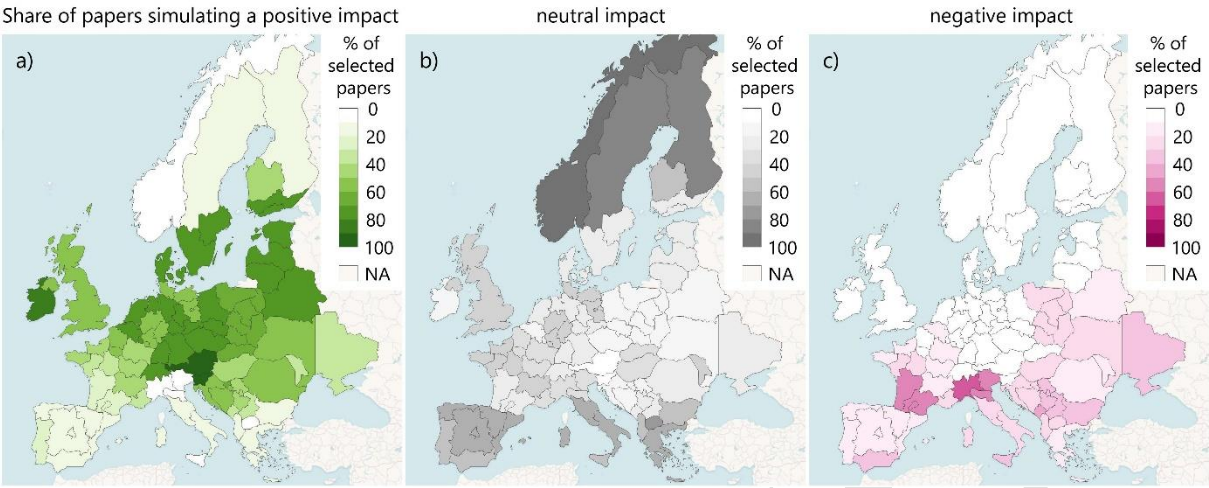

Figure 4: *Share of papers simulating a positive (a), neutral (b), and negative (c) impact of climate change on soybean performances. The share is calculated by dividing the number of articles simulating a positive (resp. neutral and positive) impact by the total amount of articles for each geographical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

Except for Ukraine, the impact of climate change was more contrasted in the far future (Figure 5d-f) than near future (Figure 5a-c), with a decrease in the proportion of “neutral” results and an increase in the proportion of “negative” and “positive” results. Unsurprisingly, results were slightly more contrasted for warmer scenarios (RCP6.0 and RCP8.5) than others (Figures S4-5). Niche models seemed slightly more conservative than process-based models, with a higher proportion of “neutral” results, while statistical models were more contrasted (Figures S6-7). This discrepancy may arise from differences in model structure or from the methodology used in data collection. Simulations considering CO_2 were usually more optimistic than those without CO_2 (Figures S8-9). However, even when the effect of CO_2 was accounted for, the impact of climate change remained negative in some simulations for Serbia, Bosnia, Hungary (Jägermeyr et al., 2021), Italy (Osborne et al., 2013) and Southern France (Deryng et al., 2014).

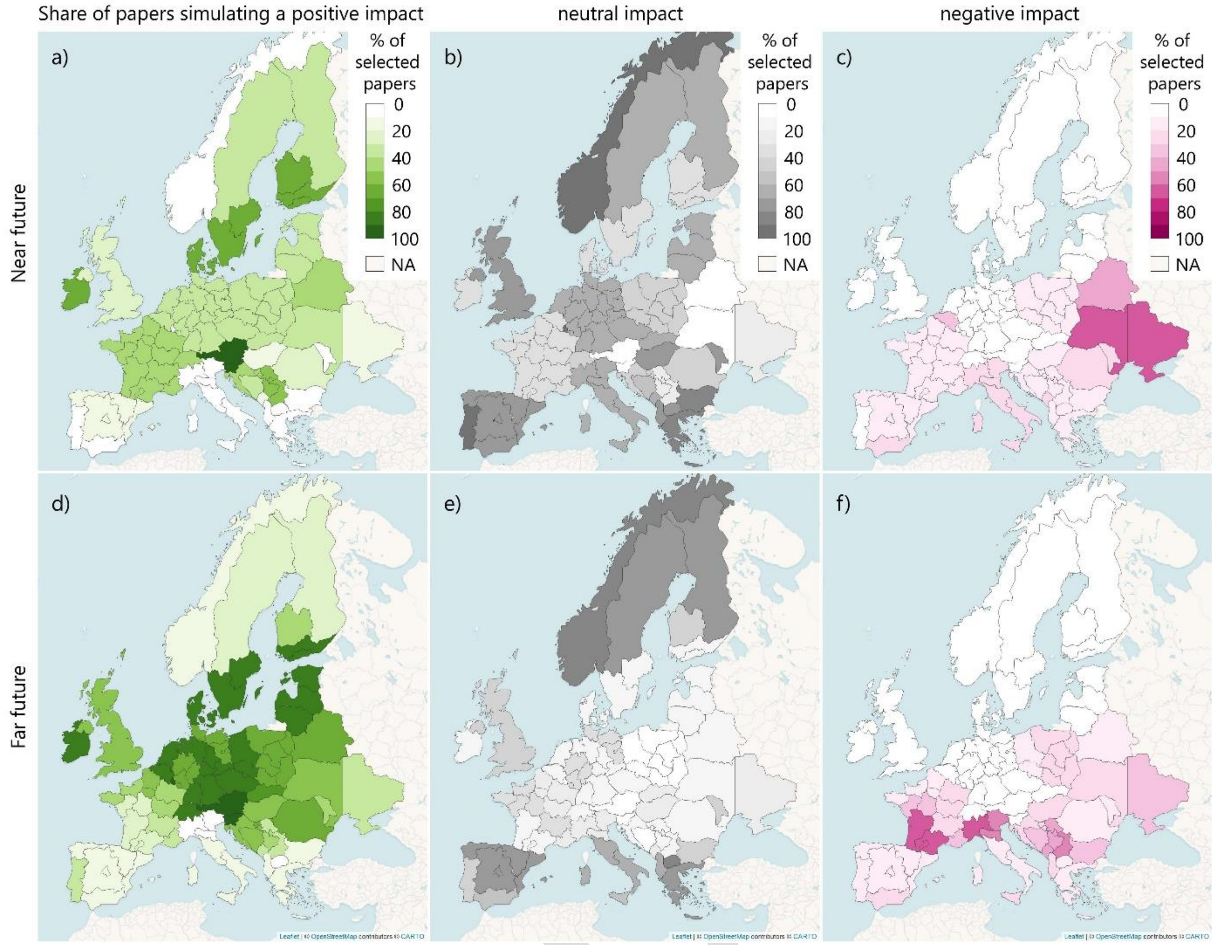

Figure 5: *Share of papers simulating a positive (a, d), neutral (b, e), and negative (c, f) impact of climate change on soybean performances in the near (≤2050) (a-c) and far future (>2050) (d-f). Figure S3 shows the number of articles for each geographical area.*

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

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

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

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

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

3.2. Effect of adaptation strategies on grain legume performances

3.2.1. Description of selected studies

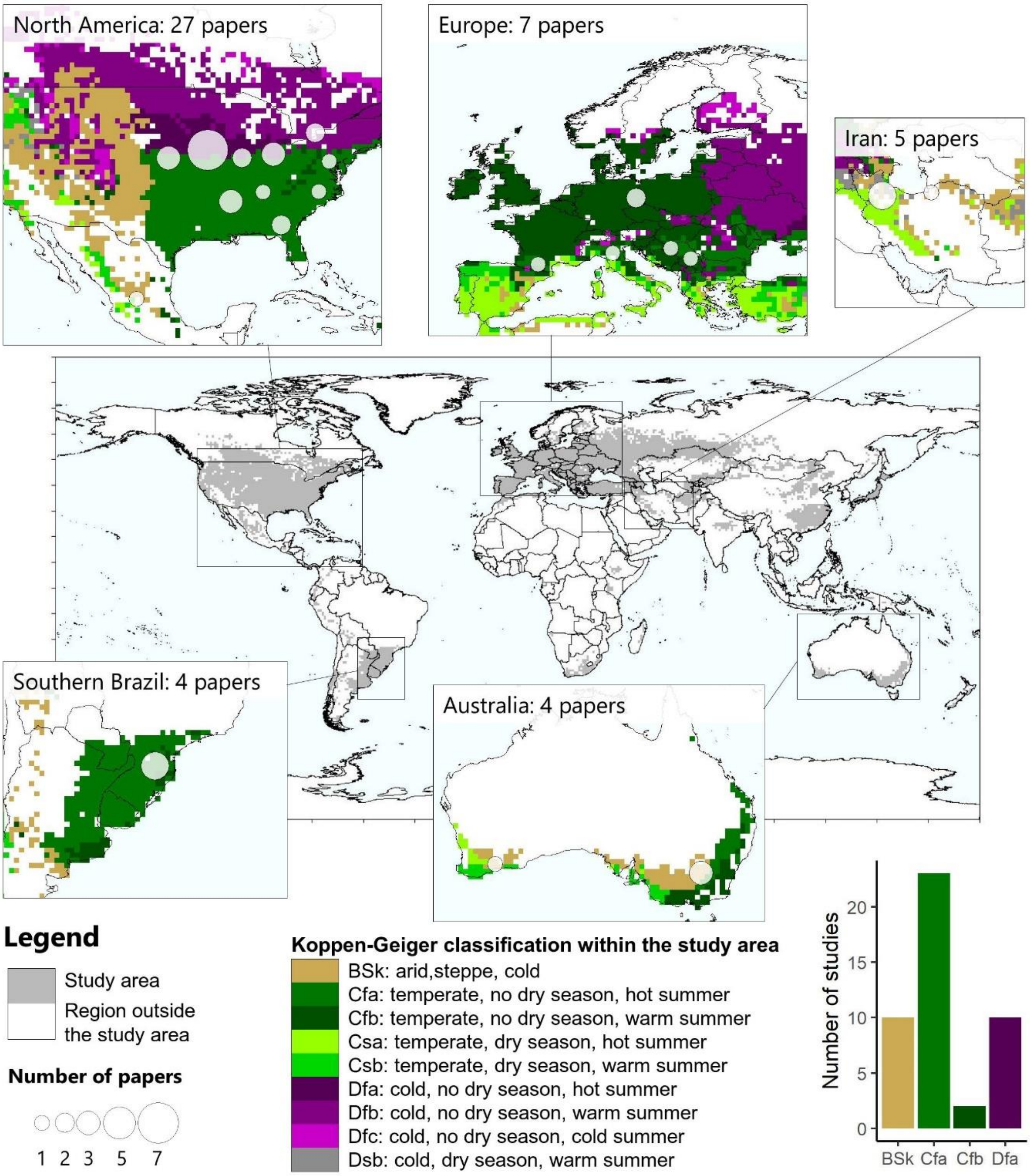

Figure 6: *Study area and geographical distribution of the papers selected in the "adaptation" corpus. The study area is composed of Europe and climatically similar regions. We used the Köppen-Geiger climate classification updated by Kottek et al., (2006) and the script provided by Rubel et al., (2017)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

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

Unlike the “impact” corpus, the first part of the century was more studied than the far future, both for soybeans and other grain legumes (Figure 2b). RCP4.5 and RCP8.5 remained the most studied climate scenarios, used in 60% of papers (Table 2c). All studies accounted for changes in temperature and rainfall, and 62% of them considered the effect of CO_2 (Table 2d). Only one paper accounted for biotic stresses, and none of the selected studies considered the effect of ozone.

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

Crop management options were studied in 53% of papers, and soil and water management in 62% (Figure 7). Irrigation was the most studied technical option (40%), followed by modified sowing dates (23%), cultivar choice (19%), and virtual genotype (13%). Combinations of several adaptation strategies were seldom assessed (26% of selected studies), and little variety was found in the choice of the strategies combined (changes in sowing date and cultivar choice represented 64% of the combinations tested). Results on the effect of adaptation mostly apply to soybeans, as few data were available for other grain legumes. Faba beans and lupins represent extreme cases, with only one paper found for each species.

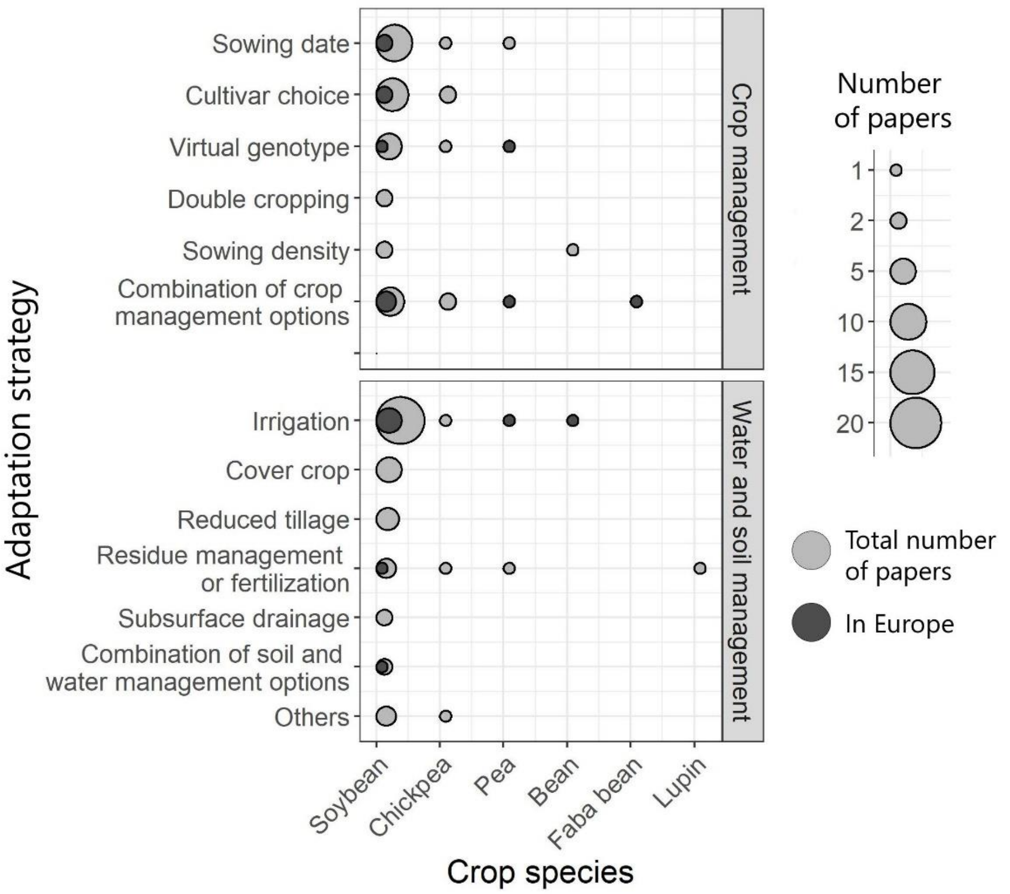

Figure 7: *Number of papers per crop species and adaptation strategy. The size of the circle is proportional to the number of papers. Light grey circles represent the total number of papers and dark grey circles the number of studies focusing on Europe. A same paper can appear in several categories.*

3.2.2. Crop management

The effect of shifting cultivar and sowing date was assessed on soybean performances in a majority of cases (76% of papers), but data were also available for peas (12%) and chickpeas (12%) (Figure 7). The simulated effect was neutral or positive in all studies, but its magnitude varied significantly among locations and species (from 4% to more than 100% yield increase) (Figure 8). Combining cultivar choice and changes in sowing date appeared as the most efficient strategy, with yield gains higher than 20%. Benefits were simulated not only on mean yield but also on yield stability (Falconnier et al., 2020) and pest management (Salam et al., 2011). In most studies, the choice of the optimal maturity group, cultivar, and sowing date was site-specific (Bao et al., 2015a; Nendel et al., 2023; van Versendaal et al., 2023). For example, in Canada (Jing et al., 2017) and in South-eastern Europe (Minoli et al., 2022), early-sown soybeans benefitted from a longer growing season and higher yields, while in the USA, late sowing was identified as an adaptation strategy to avoid heat and water stress occurring earlier in the growing season (Bao et al., 2015b, 2015a).

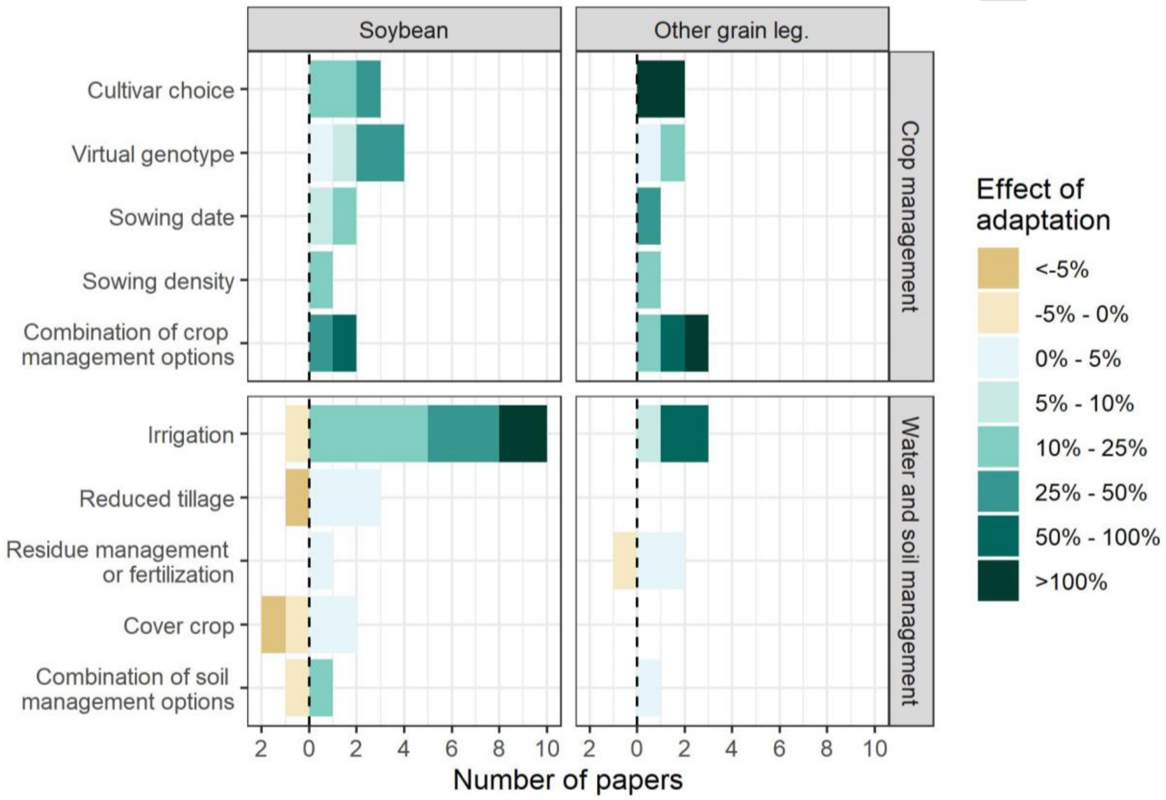

Figure 8: *Effect of different adaptation strategies on crop yields for soybeans (left) and other grain legumes (right). For each paper, the effect of adaptation is calculated as the ratio of the yield with adaptation to the yield without adaptation (expressed in %) and averaged over all time periods,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

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

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

3.2.3. Irrigation

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

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

3.2.4. Soil management

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

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

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

4. Discussion

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

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

These conclusions were relatively robust across climate scenarios, time periods, and types of models. In some regions, the divergences between studies may be explained by differences in model inputs (e.g. climate models and scenarios), structure, or parameters (Wallach and Thorburn, 2017). Additional work is needed to quantify these sources of uncertainty, as it has been made for major crops (Li et al., 2015; Rosenzweig et al., 2014). In particular, a major source of uncertainty arises from models often neglecting the impact of CO_2 (considered in only 36% of selected papers), ozone (4%), and abiotic stresses such as cold snap and waterlogging (not assessed in this review).

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

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

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

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

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

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

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

4.3. Knowledge gaps and future research avenues

4.3.1. Grain legumes other than soybeans as blind spots

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

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

4.3.2. Choice of the right time and spatial scales

The number of studies assessing the impact of climate change on soybeans in the far future (second part of the XXIst century) contrasted with the paucity of results for the near future. Identifying the timing of risks and key adaptations is necessary to ensure that simulated time periods are not disconnected from stakeholders' needs (Challinor et al., 2018). Therefore, we suggest that farmers and other stakeholders should be included in the process of modelling in order to identify relevant inputs and outputs for future simulations (Naulleau et al., 2022). Stakeholders may also guide an adequate choice of baseline period to avoid misestimating the impact of climate change.

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

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

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

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

Biotic stresses (weeds, pests, and pathogens) can lead to significant yield losses (Savary et al., 2019) and are likely to be impacted by climate change. Indeed, with the global rise of temperatures, some insects could establish in areas where their proliferation is currently limited by cold temperatures (Bebber et al., 2013; Chaloner et al., 2021). Rising temperatures could also lead to a shortening of reproductive cycles and an increased number of pest generations during crop growing season, thus increasing the influence of pests on yield losses. Elevated CO_2 could increase the relative competitiveness of C3 weeds and make crops less nutritious for insect pests, leading to increased damage (Olesen and Bindi, 2002). In our review, few papers were found on the expected biotic pressure under climate change in Europe, although it is likely that its importance should increase in the future. Most studies used suitability indexes to assess the future overlap between areas suitable to crops and pests, but yield losses were not estimated. Models simulating plant growth and insect life cycles have already been used in other regions of the world to predict future insect damage (Taylor et al., 2018) and could provide valuable information on potential biotic risks and adaptation strategies in Europe.

Farming systems are particularly sensitive to yield shocks (Hristov et al., 2020), and even systems well-adapted to long-term trends will not necessarily be the most resilient against extreme climate events (Rosenzweig and Tubiello, 2007). Therefore, we recommend that projections of future yield variability or risks of crop failure should complement existing data on future average yields. Assessing the impact of climate variability on yields will require improving model calibration and representation of climate extremes and CO_2 effect, especially for minor crops such as grain legumes (Kersebaum, 2022; Rötter et al., 2018). Designing successful strategies to cope with climate variability may also require new approaches. For example, instead of relying on future climate estimates, adaptation strategies could be designed with the aim of being effective under a wide range of climate conditions (Corbeels et al., 2018).

Finally, as grain legumes are often grown for the N-related ecosystem services they provide, we suggest that future simulations should investigate the impact of climate change on N fixation and provision. Non-yield benefits of adaptation strategies should also be assessed, as well as potential interactions between adaptation and climate change mitigation. Given Europe's growing interest in grain legumes as high-quality protein crops, changes in grain quality and protein content should be simulated to complement already existing experimental data (Scheelbeek et al., 2018).

5. Conclusion

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

The main knowledge gaps identified were a lack of data for other grain legumes than soybeans and a need for more Europe-focused studies, especially for adaptation effect assessment. Modelling the impact of climate change and adaptation remains an open research avenue for key crops such as field peas and faba beans. Only a few studies considered crop response to elevated CO_2, ozone, and biotic pressure. Therefore, incorporating these factors would enhance climate change impact assessment. We also suggest that future simulations should broaden the range of adaptation tested (e.g. intercropping, choice of the grain legume species, combinations of several adaptation strategies) and indicators assessed (e.g. economic indicators, yield variability), in the frame of a multi-criteria analysis.

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

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M.M-B: Conceptualization, Investigation, Formal analysis, Writing- Original draft preparation. M-H.J: Conceptualization, Writing- Reviewing and Editing. N.G: Conceptualization, Writing- Reviewing and Editing.

Competing interests

The authors declare no competing interests.