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Abstract:

Climate change could undermine grain legumes ability to fix atmospheric nitrogen and their contribution to increase cropping systems sustainability. Pea (*Pisum sativum* L.) and faba bean (*Vicia faba* L.) are the two most widely grown grain legumes in Europe, yet the potential impact of climate change on their performances has not been quantified. We calibrated and evaluated the STICS soil-crop model for spring pea, winter pea and winter faba bean using experimental data from southwestern France and explored the effect of contrasting climate change scenarios. After calibration, STICS accurately simulated grain yield and amount of N_2 fixed for the experimental growing seasons. Assuming no change in crop management, mean and inter-annual variability of grain yield and fixed N_2 were assessed for historical (1995-2015), mid-term (2020-2040) and long-term (2060-2080) periods in one location in southwestern France. We considered projections from three climate models and two Representative [CO_2] Pathways (RCP 4.5 and RCP 8.5). The climate models spanned a wide range of changes in temperature (+0.3 to +4.1 °C) and rainfall (-15% to +8%) depending on time horizon and RCP. Simulated grain yield increased over the long term in most scenarios (+1 to +25%), and spring pea tended to benefit less than winter pea and winter faba bean. Nevertheless, for the climate scenario with a decrease in rainfall and the strongest increase in temperature, simulated spring pea grain yield decreased by 28% while winter legumes yields were less affected (-14% for pea and no decrease for faba bean). Simulated changes in the amount of N_2 fixed followed the grain yield response. Temperature rise caused a shortening in crop cycle duration. Simulated temperature stress significantly increased for spring and winter pea in most climate change scenarios while winter faba bean was rather unaffected due to greater upper temperature thresholds. N_2 fixation of spring pea was reduced by above-optimal temperature during its vegetative growth in spring while N_2 fixation of winter legumes was enhanced by the increase in temperature during their vegetative growth in winter. Simulated drought stress only increased in the climate scenario predicting a decrease in rainfall. Overall, [CO_2] increase would allow offsetting negative effects of temperature and drought on grain yield and N_2 fixation, except for climate scenarios involving a decrease in rainfall and the strong increase in temperature. The contrasted simulated response of winter and spring grain legumes to climate change in southwestern France points to the opportunity to tap grain legume diversity and cultivar choice as an adaptation strategy.

Key-words: STICS, pea, faba bean, crop modelling

1. Introduction

Legumes are a key source of proteins for food and feed, and provide several ecosystem services (Watson et al., 2017). In particular, biological fixation of N_2 can improve nitrogen use efficiency in cropping systems and contribute to reduce mineral N-fertilizer application and greenhouse gases emissions (Foyer et al., 2016). Pea (*Pisum sativum* L.) and faba bean (*Vicia faba* L.) are the two most widely grown winter and spring grain legumes in Europe, representing 0.47% and 0.36% of European utilized agricultural area, respectively. In 2018, pea and faba bean yield averaged 2.4 t/ha and 2.1 t/ha, respectively. France, Spain, Italy and United Kingdom and Germany are the top producing countries (http://ec.europa.eu/eurostat, last accessed 20/04/2020). Despite their advantages, legumes remain poorly adopted by farmers in Europe and their cultivated area has even been decreasing, notably due to high inter-seasonal yield variability (Cernay et al., 2015, Watson et al., 2017). Climate change is likely to affect grain legumes yield and N_2 fixing capacity thus hampering even more their capacity to be adopted by farmers and to deliver the expected benefits for cropping systems sustainability.

The response of grain legumes to climate change in Europe is expected to vary across seasons and regions, depending on the future changes in [CO_2], temperature, and precipitation. Temperature is expected to increase in North, Central and South Europe, multi-model climate projections indicating a warming of 1 to 5°C in 2081–2100 relatively to 1986–2005 depending on the Representative Concentration Pathway (RCP) considered. Annual rainfall is expected to increase in North and Central Europe (+1 to +12% depending on RCP) and to decrease in South Europe (-7 to -26% depending on RCP) (IPCC, 2013). Rise in temperature cause a shortening in crop cycle duration and thus decreases solar radiation interception by the crop (Craufurd and Wheeler, 2009). Glasshouse experiments have explored the impact of heat and drought stress on pea and faba bean growth. Heat stress, *i.e.* temperature above 30°C imposed during seed set and/or seed development compared with a baseline situation at 20-25°C, was found to (i) compromise flower, pollen grain and seed development (Bishop et al., 2016; Larmure and Munier-Jolain, 2019; Stanfield et al., 1966); (ii) decrease photosynthetic rate (Haldimann and Feller, 2005; McDonald and Paulsen, 1997); and (iii) decrease nitrogenase activity (Dart and Day, 1971). Water stress (*i.e.* plants grown in pots with soil let to dry near wilting point) reduces root nodule activity and nitrogen-fixing potential (Sprent, 1972). Field experiments have confirmed that heat and drougth stress can severely impact grain yield and N_2 fixation. For example, Sadras et al. (2013) calculated a 0.31 $t.ha^{-1}$ loss in pea grain yield per 1 °C increase in maximum temperature around flowering. Carranca et al. (1999) found a 40 and 70% decrease in N_2 fixation of faba bean and pea related to a 45% decrease in seasonal rainfall. Elevated [CO_2] on the other hand has a positive effect on net photosynthesis efficiency of these C_3 legumes thanks to a decrease in carbon loss through photorespiration (Wang et al., 2012).

How these environmental stresses will interact under plausible climate change scenarios, and their potential impact on yield and N_2 fixation, have so far not been extensively quantified for grain legumes such as pea and faba bean in temperate production areas. Quantifying the impact of climate change and the factors driving yield change will be crucial for the design of relevant adaptations and favor a push toward a greater adoption of grain legumes by farmers.

Crop models are relevant tools to quantify the impact of multiple stresses occurring with different timing during crop growth (Asseng et al., 2015). STICS is a generic crop model that is adapted to several grain legumes (Falconnier et al., 2019; Jégo et al., 2010) and accounts for several temperature and water stresses on both grain formation and N_2 fixation. Though not initially developed for climate change studies, it has been adapted to take into account climate change issues, in particular the effect of elevated [CO_2] (Bergez et al., 2014).

The aim of this study was to assess the growth and N_2 fixation response of spring pea, winter pea and winter faba bean to climate change in southwestern France, an area representative of temperate Mediterranean environment. The studied area was characterized by summer droughts and cool, wet winters, and has been identified as a climate change hot-spot (Giorgi, 2006). In particular, the objectives were to: (i) calibrate and assess simulation accuracy of the STICS soil/crop model under current climate; (ii) use the model to assess how these legume species and cultivars would be affected by climate change; and (iii) identify the main abiotic factors

([CO_2], temperature, rainfall) driving change in grain yield and N_2 fixation under future climate in order to discuss relevant adaptation strategies.

2. Methods

We calibrated the STICS model for pea (this study) and faba bean (Falconnier et al., 2019), based on data from crop experiments with detailed monitoring of plant growth, as well as soil water and nitrogen dynamics carried-out from 2002 to 2014 in southwestern France. Responses to climate change of the two crops were then investigated using the parameterized model.

In what follows, we successively describe the study site and experimental data, the crop model and its calibration, the historical and future climates, and the analysis of model simulations.

2.1. Study site and experimental data

The study area in southwestern France falls into the temperate climatic group and belongs to the north Mediterranean environmental zone (Peel et al., 2007). The typical cropping system of the region is wheat–sunflower rotation. Diversified cropping systems include winter and spring legumes (Plaza-Bonilla et al., 2017) usually sown in November-December and February-March respectively and harvested between mid-June and mid-July. The experimental data was collected in two sites: (i) National Research Institute for Agriculture, Food and Environment (INRAE) in Auzeville (43°31'39''N 1°30'4''E, , 168 m above sea level), and (ii) "Centre Régional de Recherche et d'Expérimentation en Agriculture Biologique de Midi-Pyrénées" (CREAB-MP) in Auch (43°38'27''N 0°36'22''E, 134m above sea level). Collected data included: (i) dates of emergence, end of juvenile phase, beginning of grain filling and maturity; (ii) in-season variables (leaf area index, aboveground biomass, accumulated fixed N_2 and total aboveground accumulated plant N, soil moisture content and soil mineral N content to maximum rooting depth); and (iii) end of season variables (grain yield and total amount of N_2 fixed). Weather data was obtained from stations at the two sites. Measured variables included daily maximum and minimum air temperatures (°C), precipitation (mm), global solar radiation (MJ m^{-2}), average wind speed (m s^{-1}) and relative humidity (%). Average rainfall over the growing season (November-July) for the experimental years was 528 mm and 542 mm at Auzeville and Auch, respectively. Average temperature over the growing season for the experimental years was 12.4 and 11.3 °C at Auzeville and Auch, respectively. Experimental plots were on deep clay-loamy soils in Auzeville with averaged maximum rooting depth of 135 cm, and on shallow clay loamy soils in Auch with averaged maximum rooting depth of 70 cm. Site, year, and management factors (cultivar, crop density, incorporation of a cover crop before planting and sowing date) defined 61 Site–Year–Management units (Table S1). The experiments were extensively described by Bedoussac and Justes (2010), Kammoun (2014) and Plaza-Bonilla et al. (2017).

2.2. Crop model

2.2.1. General overview of the STICS model

The soil–crop model STICS (Brisson et al., 2009, 2002, 1998) was chosen for its robustness (Coucheney et al., 2015) and ability to simulate grain legume growth and nitrogen fixation (Falconnier et al., 2019). STICS simulates daily carbon, water and nitrogen dynamics. Crops are defined by species parameters (*e.g.* potential radiation use efficiency), ecophysiological options (*e.g.* effect of photoperiod) and cultivar specific parameters (*e.g.* time to flowering). Required inputs are: (i) daily weather variables (minimum and maximum temperature, solar radiation, rainfall, wind speed and relative humidity, and [CO_2] for climate change simulations); (ii) permanent soil characteristics (*e.g.* field capacity and wilting point); and (iii) crop and soil management (*e.g.* sowing density, tillage). Crop temperature calculated from weather variables and photoperiod drive crop daily development. The model simulates: (i) daily root development to compute water and nitrogen uptake; and (ii) daily canopy establishment that drives transpiration and light interception to produce crop biomass. Dry matter accumulation in grains results from a dynamic harvest index that increases with time during the reproductive phase (Amir and Sinclair, 1991). With regard to soil dynamics, net nitrogen mineralization from soil organic matter and crop residues, nitrate leaching, ammonia and nitrous oxide gaseous emissions are daily simulated as well as vertical water drainage when field capacity is exceeded. STICS also simulates nitrogen acquisition and N_2 fixation of legumes. Nodule formation depends on soil thermal time and sets potential fixation. The process equations of the soil-crop system are based on a unique set of general parameters. An exhaustive description of inputs, equations and default parameter values of the STICS model is given in Brisson et al. (2008) and Bergez et al. (2014). Stress factors are computed daily and vary between 0 (maximum stress) and 1 (no stress).

2.2.2. Water and nitrogen stress

Water and nitrogen stresses can indirectly affect grain yield and N_2 fixation through plant growth. The water stress factor – the ratio of actual to potential evapotranspiration – affects radiation use efficiency and plant transpiration.

Actual N_2 fixation depends on: (i) shoot biomass growth rate (carbon limitation for N_2 fixation); and (ii) water deficit defined as the proportion of soil layers in the nodulation area for which moisture is above wilting point. The nitrate concentration in the nodulation layer also reduces nitrogen fixation when it exceeds a maximal nitrate concentration threshold. Nitrogen stress factor – the ratio of actual crop nitrogen concentration to critical crop nitrogen concentration (Lemaire and Gastal, 1997) – affects Leaf Area Index increase, radiation use efficiency and senescence.

2.2.3. Effect of temperature and [CO_2] in the model

The model accounts for the effect of thermal stress on legume performance through three different processes: (i) reduction of radiation use efficiency and biomass growth; (ii) interruption of grain filling; and (iii) reduction of potential N_2 fixation.

For biomass growth (radiation use efficiency) and N_2 fixation, the model defines four cardinal temperatures: base (T_{min}), lower optimal (T_{opt1}), upper optimal (T_{opt2}) and maximum (T_{max}) temperatures. The model simulates a linearly increasing rate (thermal stress factor goes from 0 to 1) with daily average temperature from T_{min} to T_{opt1}, a stable maximum rate from T_{opt1} to T_{opt2} (stress factor of 1) and a linearly decreasing rate from T_{opt2} to T_{max} (stress factor goes from 1 to 0). For grain filling, the model defines only one daily maximal temperature above which grain filling stops (stress factor of 0 versus 1 otherwise).

An exponential function with a species–specific parameter (lower for C_4 than for C_3 crops) accounts for the effect of elevated atmospheric [CO_2] on radiation use efficiency (Bergez et al., 2014). This function allowed to account for the effect of elevated [CO2] on net photosynthesis of C_3 legumes species (Wang et al., 2012). STICS can account for the impact of elevated [CO_2] on transpiration efficiency with a specific option. However this option was not activated for this study, as increase in transpiration efficiency was not found to be a significant contributor to the response of C_3 legumes to elevated [CO_2] (Wang et al., 2012). A full description of the equations and parameters governing the stresses definition can be found in Brisson et al. (2008).

2.2.4. Parameterization and evaluation of the soil-crop model

35 Site–Year–Management units were already used for the calibration and evaluation of winter faba bean in a previous study: the dataset, measurement methods and calibration procedure are described in details in Falconnier et al. (2019). 26 Site–Year–Management units were added for the calibration and evaluation of winter and spring pea done in this study (Table S1), following

the procedure described in Falconnier et al. (2019) for faba bean. Below we summarize the main steps of this calibration and evaluation procedure.

Soil analysis informed the soil input parameters required by the STICS model (Table S1). Moisture at field capacity and wilting point were first obtained using pedo-transfer functions (Saxton and Rawls, 2006) and also based on laboratory measurements on sieved soil for Auzeville field capacity. Field capacity and wilting point were then adjusted for each trial by using in situ soil water measurements at sowing, harvest and during crop cycle in order to minimize the error between simulated and observed soil water content, as field measurements have proven more reliable than laboratory measurements when simulating dynamic water balance (Gijsman et al., 2002). Average maximum available water to maximum rooting depth, *i.e.* soil water content at field capacity minus soil water content at wilting point, was higher in Auzeville (178 mm) than in Auch (64 mm). Initial soil mineral nitrogen (nitrate and ammonium) and water content were set based on the measurements for each Site–Year–Management unit (Table S1).

The calibration procedure followed the three steps as described in Guillaume et al. (2011): (i) a literature review to determine existing parameters; (ii) the direct measurement of parameters using experimental data; and (iii) a mathematical parameter optimisation. The stepwise optimisation focused successively on parameters related to crop development, leaves development, root growth, shoot growth, N_2 fixation, N uptake for mineral-N and yield formation. This optimisation was carried out with the OptimiSTICS software (Wallach et al., 2011). The goodness-of-fit criterion – the average squared error between observed and simulated value per Site–Year–Management units simulation – was minimised using a simplex algorithm. We calibrated three separate plant files: spring pea, winter pea and winter faba bean. Falconnier et al. (2019) give the details of the calibration for winter faba bean. The calibration was performed on Site–Year–Management units covering a range of growing seasons, management situations and two types of soil (40 Site–Year–Management units, Table S1). The units with growing season and/or management not used in calibration were used for model evaluation (21 Site–Year–Management units, Table S1).

Mean Bias Error (MBE) and its relative value (rMBE), Root Mean Square Error (RMSE) and its relative value (rRMSE), and Efficiency (EF) were calculated to quantify model performance with the optimised parameter set as follows:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad (1)$$

$$rMBE = \frac{MBE}{\bar{O}} \times 100 \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \quad (3)$$

$$rRMSE = \frac{RMSE}{\bar{O}} \times 100 \quad (4)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (5)$$

where O_i and P_i are the observed and simulated values for the i^{th} measurement, n is the number of observations and $\bar{O}$ is the mean of the observed values. The joint calculation of these four indicators allowed a detailed assessment of model accuracy.

2.3. Historical and future climates

The climate change impact study was carried-out for the site of Auzeville at INRAE station. The historical climate (1995-2015) data, belonging to INRAE, was obtained from the weather station at this site. Mean annual air temperature was 18.8 °C with daily temperature ranging from -8.8 to 40.4 °C. Mean annual precipitation was 654 mm ranging from 401 to 1000 mm. Mean annual cumulative global radiation was 5021 MJ m^{-2} ranging from 4373 to 5556 MJ m^{-2}. Average daily global radiation was 6, 17, 22 and 11 MJ m^{-2} in winter, spring, summer and fall, respectively.

For future climate, outputs from three Regional Circulating Models (RCM) available from the European Coordinated Regional climate Downscaling Experiment (Euro-CORDEX, http://www.euro-cordex.net/) (Jacob et al., 2014) and the Drias (http://www.drias-climat.fr/) were selected. RCMs are high-resolution meteorological models that use boundary conditions defined by coarse-resolution Global Circulation Models (GCMs) to produce downscaled climate projections relevant for region-scale impact studies. Three GCM-RCM combinations (further referred as "climate model") were used to span a range of changes in future temperature and rainfall, namely (i) the Institute Pierre-Simon Laplace Climate Model with the weather and research forecasting (ISPL_WRF) model, (ii) the Centre National de Recherches Météorologiques Model and the Alladin model (CNRM_Alladin) and (iii) the Irish Centre for High-end Computing EC-EARTH model and the HIRHAM5 model (EC-EARTH_HIRHAM5).

Two greenhouse gas emission scenarios (Representative Concentration Pathways, RCPs) were considered (Vuuren et al., 2011). In the high-emission RCP 8.5 scenario, [CO_2] reaches 1370 ppm by 2100 while in the intermediate mitigation RCP 4.5 scenario, [CO_2] stabilizes at around 650 ppm in 2100. Temperature, rainfall and daily solar radiation were bias-corrected using quantile mapping (Themeßl et al., 2011). In quantile mapping, historical simulated values (hindcasts) and observed values (historical weather data) are ordered by magnitude to obtain Empirical Cumulative Distribution Functions (ECDF). The bias correction is an empirical transfer function that allows to map hindcast ECDF onto observations ECDF. The correction was performed with the R Package "qmap" (https://cran.r-project.org/web/packages/qmap/qmap.pdf).

Changes in cumulative rainfall and average and maximum temperatures between future and historical climates were calculated for the November-July period that corresponds to grain legumes growing season in Auzeville. Climate models projections were used individually, as we did not want to assess a mean change in temperature and rainfall, but rather explore a range of contrasting but plausible climate change scenarios.

2.4. Analysis of model simulations

Spring pea, winter pea and winter faba bean grain yield and fixed N_2 were simulated with the historical climate (1995-2015) and with future climate corresponding to the projections of the three climate models for RCP 4.5 and RCP 8.5. Two future 21-year periods were simulated, namely mid-term (2020-2040) and long-term (2060-2080). We assumed a similar crop management (sowing date, initial N and water) for simulation with historical and future climates. Winter faba bean was sown on November 20th, winter pea on December 10th and spring pea on February 4th. Sowing density was 30, 72, and 100 plants m^{-2} for winter faba bean, winter pea and spring pea, respectively. No cover crop incorporation prior to legume cultivation was considered.

For each 21-year periods (historical, mid-term and long-term), we computed a yield average that was then scaled by the historical yield simulated with the historical climate (1995-2015). The scaled yield (YS) for a given period *p* was computed as:

$$YS_p = \frac{Y_p}{Y_{historical}} \quad (6)$$

where Y_p is the 21-year simulated average yield for period *p* (mid-term or long-term) and $Y_{historical}$ is the 21-year simulated average yield under the historical climate (1995-2015).

Yield threshold for yield failure (YFT*)* was calculated as the 20th percentile of yield with historical climate (Guan et al., 2017) using the R function *quantile*. Probability of yield failure, – the probability to obtain a yield below YFT – was then calculated with empirical cumulative distribution functions as provided by the R function *ecdf*. For example, a probability of yield failure of 0.6 means that for 60% of the years over a 21-year future climate, simulated annual crop yield was lower than the 20th percentile of the crop yield in the historical climate. Since *ecdf* gave a discrete step function, the probability to obtain YFT with historical climate could diverge marginally from 0.2. Following a similar procedure, scaled average N_2 fixation and probability of N_2 fixation failure were computed.

Simulated heat and drought stress factors (see section 2.3.2 and 2.3.3) during vegetative phase (sowing to beginning of grain filling) and during reproductive phase (beginning of grain filling to maturity) were averaged per period. For each RCP and climate model, the effect of the period on the simulated stress factors was tested using a linear analysis of variance (ANOVA) using a probability of < 0.05. All analyses were performed with R 3.6.1 (R Development Core Team, 2019; http://www.R-project.org, last accessed 19/09/2019).

3. Results

3.1. Crop parameterization and model evaluation

Calibrated model parameters (Table S2) led to a satisfactory prediction of crop development phenology (Figure S1). For beginning of grain filling, rRMSE was 3, 2 and 9% for winter faba bean, winter pea and spring pea, respectively. For maturity, rRMSE was 7, 2 and 4% for winter faba bean, winter pea and spring pea, respectively.

Grain yield, aboveground biomass, aboveground plant nitrogen and amount of fixed N_2 at harvest were satisfactorily predicted, with rMBE ranging from 3 to 7% with calibration dataset and -5 to 1% with evaluation dataset, and rRMSE ranging from 20 to 29% with calibration dataset, and 24 to 26% with evaluation dataset (Figure 1).

The model was able to reproduce variation in total soil water content, both at specific dates during the cropping season and at the end of season (Figures 2a, 2b). Variability in total soil mineral nitrogen content at specific dates during cropping season and at the end of the season was also well reproduced in calibration dataset (rRMSE = 33%) (Figure 2c). Variations in total soil mineral nitrogen content in the evaluation dataset was less well reproduced (rRMSE = 49%) (Figure 2d), but simulations were in the range of the observed low values.

These overall good performances on both plant and soil related variables point to the consistency of the model in representing water and nitrogen supply by the soil and water and nitrogen uptake by the crop.

3.2. Future climates

The climate projections spanned a wide range of change in temperatures and rainfall (Figure 3). The three selected climate models consistently predicted an increase in maximal and average daily temperature during grain legumes growing season (November-July), likely to affect differently winter and spring crops (Table 1 and Figure S2). Under RCP 4.5, increase in maximal temperature (averaged across the growing season) ranged 0.3-1.1°C and 1.0-2.8°C for mid-term and long-term projections respectively, depending on the climate model considered (Table 1). Under RCP 8.5, increase in maximal temperature (averaged across the growing season) ranged 0.5-1.5°C and 2.7-4.4°C for mid-term and long-term projections respectively, depending on the climate model considered (Table 1).

Climate models diverged in their projections with regard to rainfall, CNRM-Alladin and EC-EARTH_HIRHAM5 generally predicted an increase in rainfall, while ISPL_WRF generally predicted a decrease (Table 2 and Figure S3). Under RCP 4.5, change in average growing season rainfall ranged from -5 to +4% and from -8 to +8% for mid-term and long-term projections, respectively, depending on the climate model considered (Table 2). Under RCP 8.5, change in average growing season rainfall ranged from -3 to +4% and from -15 to +3% for mid-term and long-term projections, respectively, depending on the climate model considered (Table 2).

3.3. Impact of climate change on grain yield and amount of N_2 fixed

For long-term projections, grain yield and amount of N_2 fixed increased in scenarios involving EC-EARTH_HIRAM5 and CNRM_Alladin climate models (Figures 4a, 4b). In most cases spring pea benefited less than winter pea and winter faba bean. For scenarios involving the ISPL_WRF climate model – the climate model that predicted the strongest increase in temperature and a decrease in rainfall – changes in yield were contrasted. With this climate model, under RCP 4.5 legume yield decreased and spring pea was more affected (28% yield decline) than winter pea and winter faba bean (-19% and +1% yield change, respectively) (Figure 4a). Under RCP 8.5, spring pea was also the most affected legume, with a 9% decrease in yield, while winter pea and winter faba bean benefited from climate change with a 15% and 39% increase in yield respectively.

Overall, when considering all climate change scenarios (Figures 4a, 4b), amount of N_2 fixed followed a pattern similar to the one observed for grain yield. However, amount of N_2 fixed tended to (i) benefit more from climate change (EC-EARTH_HIRAM5 and CNRM_Alladin climate models); or (ii) be less affected (ISPL_WRF climate model).

3.4. Impact of climate change on yield and N_2 fixation failure

For long-term projection, probability of grain yield failure remained relatively stable in scenarios involving EC-EARTH_HIRAM5 and CNRM_Alladin climate models (Figure 4c). Probability of failure for the amount of N_2 fixed showed contrasted response depending on legume crops (Figure 4d), with an increase for spring pea (except for EC-EARTH-HIRAM5; RCP 8.5) and a decrease for winter pea. For both yield and amount of N_2 fixed, the failure probability of spring pea was always higher than that of winter pea and winter faba bean.

For the scenarios involving the ISPL_WRF climate model, probability of yield failure would increase drastically for spring pea, reaching 64% and 43% for RCP 4.5 and RCP 8.5 scenarios respectively (Figure 4c). Probability of failure for amount of N_2 fixed would reach 57% for spring pea for RCP 4.5, and decrease to 12% for RCP 8.5 (Figure 4d). Probably of failure for yield and amount of N_2 fixed of winter faba bean and winter pea would be less affected (Figures 4c, 4d).

3.5. Effect of temperature on crop growth and N_2 fixation

3.5.1. Effect on crop cycle duration

The increase in temperature with future climate shortened crop cycle duration in all climate change scenarios (Table 3). Depending on the projections and the climate change scenario, crop cycle duration decreased from 0 to 29 days for spring pea, 0 to 28 days for winter pea and 0 to 35 days for winter faba bean. Crop cycle duration was significantly correlated ($P<0.001$) with final grain yield: a decrease of one day in crop cycle duration corresponded to an average decrease in grain yield of 30, 42 and 16 kg ha^{-1} for spring pea, winter pea and winter faba bean respectively (Figure S4).

3.5.2. Effect of thermal stress on radiation use efficiency, grain filling and N_2 fixation

Heat stress for radiation use efficiency during the vegetative phase significantly increased in mid and long-term projections for spring pea as shown by lower stress factor values in almost all climate change scenario (Figure 5a and Table 4). On the contrary, thermal stress for radiation use efficiency tended to decrease during the vegetative phase for winter faba bean.

Heat stress on radiation use efficiency during reproductive phase (Figure 5b) and heat stress on grain filling (Figure 5c) increased for spring pea and winter pea in mid and long-term projections in half of climate change scenarios. No increase in these stresses was observed for winter faba bean (Figures 5b, 5c and Table 4).

For winter pea and winter faba bean, thermal stress for N_2 fixation usually significantly decreased during the vegetative phase that occurred mainly in winter where temperature are usually sub-optimal while it tended to increase for spring pea, as its vegetative phase occurs in spring when temperature are already optimal (Figure 6a and Table 4). During reproductive phase, heat stress for N_2 fixation remained mainly unaffected under the EC-EARTH-HIRAM5 and CNRM_Alladin projections and increased from 0 to 9% in the ISPL_WRF projection (Figure 6b, Table 4).

3.6. Effect of drought on crop growth and N_2 fixation

There was no significant change in drought stress for biomass growth during the vegetative period with EC-EARTH_HIRAM5 and CNRM_Alladin climate models (Figure 7a and Table 4). On the contrary, drought stress for biomass growth during reproductive phase significantly increased in the climate change scenario with ISPL_WRF model for winter pea (Figure 7a and Table 4), but was not different for spring pea and winter faba bean. With this climate change scenario, drought stress on N_2 fixation increased significantly during reproductive phase for all grain legumes (Figure 7b and Table 4).

4. Discussion

4.1 Impact of climate change on grain legume functioning and yield formation

Grain yield and amount of N_2 fixed increased in climate change scenarios involving moderate temperature rise and no change in rainfall over the long term (*i.e.* with CNRM Alladin and EC-EARTH_HIRAM5 climate models): grain yield increased by 1% to 25%, and amount of N_2 fixed by 8% to 34% depending on RCP and climate models. Our simulations show that the effect of the increase in [CO_2] offsets the negative effects of heat stress on crop growth and N_2 fixation (see section 3.5 and 3.6). Pea and faba bean are C_3 species for which elevated [CO_2] increases net photosynthesis (Ainsworth and Rogers, 2007). Such increase has been quantified in Free Air CO_2 Enrichment (FACE) experiments in Australia where pea yield increased by 26% with [CO_2] at 550 ppm compared with current [CO_2] at 390 ppm (Bourgault et al., 2016). In a similar FACE experiment in Australia, faba bean grain yield increased by 59% and amount of N_2 fixed by 60% with elevated [CO_2] under well-watered conditions (Parvin et al., 2019). N_2 fixation benefits from elevated [CO_2], as the greater carbon supply often translates into increased nodule biomass and stimulates N_2 fixation (Rogers et al., 2009).

Projection of ISPL_WRF climate model under RCP 4.5 was the most constraining climate change scenario with strong temperature increase and rainfall reduction. In this scenario, [CO_2] increase could not offset temperature and drought stress on grain yield and N_2 fixation: grain yield decreased by 1% to 27% and amount of N_2 fixed by 0% to 13%. The FACE experiments in Australia supports such simulation outcome, where [CO_2] increase (550 ppm) could not offset the detrimental impact on yield of a 3-days heat wave on lentil (Bourgault et al., 2018). Yield penalties with rising temperature are also supported by glasshouse experiments: (i) pea yield decreased by 54% with an increase in day-night temperature from 20-15 to 30-25 °C (McDonald and Paulsen, 1997); and (ii) faba bean yield declined by 24% after an increase in day-night temperature for five days during anthesis (18-10 to 34-26 °C) (Bishop et al., 2016). Such yield penalties were attributed to flower abortion, reduced grain filling duration and also reduced seed weight (Bishop et al., 2016; McDonald and Paulsen, 1997). Reduced grain filling duration and reduced seed weight due to heat stress on grain filling can be accounted for by STICS: our diagnosis (see section 3.5) showed that reduced crop cycle duration (-6 days per 1°C temperature increase on average across RCPs, climate models and crops) and increased heat stress occurred in the different climate change scenarios. Flower abortion is not explicitly taken into account in the STICS model. However, if biomass growth is reduced during a short period before the start of grain filling – by heat stress for example – it can affect the simulated number of grains (Falconnier et al., 2019). We diagnosed a significant increase in simulated heat stress on radiation use efficiency that causes a reduction in net photosynthesis. This result is in line with experimental findings on the impact of heat on photosynthesis of other grain legumes like lentil (Bourgault et al., 2018) and kidney bean (*Phaseolus vulgaris* L.) (Prasad et al., 2002).

Drought also can strongly affect yield and N_2 fixation, thus offsetting the beneficial effect of [CO_2] increase. Under current Mediterranean climate with mean annual rainfall of 320 mm, faba bean grain yield was 56% smaller in rainfed treatments with moderate water stress compared with full irrigation treatments (Karrou and Oweis, 2012). In southern Portugal with average seasonal rainfall of 520 mm, amount of N_2 fixed by faba bean and pea decreased by 40 and 70%, respectively, when seasonal rainfall decreased by 45% (Carranca et al., 1999).

Overall, the amount of N_2 fixed was less affected or benefited more from climate change than grain yield. This could be because temperature thresholds for N_2 fixation were higher than temperature thresholds for radiation use efficiency and grain filling, leading to lower heat stress on N_2 fixation than on radiation use efficiency. Maximum temperatures were set according to literature (Table S2), *i.e.* 40 and 35 °C for N_2 fixation of faba bean and pea, respectively, and 34°C and 30°C for radiation use efficiency of faba bean and pea, respectively. Consequently, the simulated contribution of synthetically fixed N_2 to total plant nitrogen increased by three percent (across crops, RCP and climate models) in future scenarios compared with historical climate.

The relatively large number of published experimental studies on the impact of elevated [CO_2], heat and drought on grain legumes contrasts with the paucity of crop modelling studies dealing with climate impact on grain legumes. Modelling studies on the impact of climate on crops in Europe focused mainly on cereals like maize and wheat (Webber et al., 2018). To our knowledge, there is only one published modelling study exploring the impact of climate change on cool-season grain legumes in temperate environments (Ravasi et al., 2020). In line with one of the climate change scenario of our study, the simulations of Ravasi et al. (2020) indicated that the increase in [CO_2] could not offset the negative impact of temperature and drought stress on spring pea in Northern Italy. Impact of climate change on grain legumes was also investigated with crop models in tropical environment, on peanut (Faye et al., 2018) and on chickpea (Mohammed et al., 2017). In line with our study, these simulations pointed to slight increases in yield of grain legumes with climate change thanks to the effect of [CO_2] increase on plant growth. However, these studies did not investigate the impact of climate change on N_2 fixation.

4.2 Contrasted responses to climate change between cultivars and species

In our simulations, spring pea tended: (i) to benefit less from climate change when the effect of [CO_2] increase offsets heat and drought stress; or (ii) to be more affected when [CO_2] could not offset heat and drought stress compared with winter pea and winter faba bean. Spring pea vegetative phase occurred in spring when temperatures are already high (Figure S2). Therefore, STICS simulated an increase in heat stress for radiation use efficiency in long-term projections in almost all climate change scenarios. On the contrary, winter pea vegetative phase occurred in winter when temperatures are low (Figure S2) and an increase in heat stress for radiation use efficiency only occurred in the scenarios with the strongest increase in temperature. Even in these latter case of high increase in temperature, no increase in heat stress was simulated for winter faba bean, due to greater threshold temperatures for photosynthesis (24-34 °C for faba bean versus 20-30 °C for winter and spring pea) (Table S2). Similarly, thermal stress on N_2 fixation increased for spring pea because its vegetative growth occurred in spring when temperatures were already optimal with historical climate. Conversely, it decreased for winter pea and winter faba bean since their vegetative growth occurred in winter where temperatures were sub-optimal with historical climate. Secondly, grain filling started later for spring pea than for winter pea and winter faba bean (*i.e.* three days after winter pea and thirteen days after winter faba bean on average across climate change scenarios). As a result, when heat stress on grain filling occurred, it was greater for spring pea than for the winter legumes (see section 3.3). In the scenarios with a decrease in rainfall, drought stress on spring pea did not change significantly, but yield decreased drastically, indicating that heat stress still prevailed in this case. Possibly, the heat stress constrained plant growth, thus reducing transpiration and the impact of the reduction in water availability (*e.g.* Affholder, 1997).

Earlier development, heat stress avoidance and thus greater yield potential of winter pea and winter faba bean over spring pea and spring faba bean were reported under current climate in central Europe (Neugschwandtner et al., 2019). For cereal crops, the better adaptation of winter barley over spring barley was also reported with simulations of the impact of climate change using a statistical model (Gammans et al., 2017).

4.3 Uncertainties in crop simulation

Crop models are increasingly used for climate change impact studies. Uncertainty in crop model simulation can arise from improper calibration (Wallach et al., 2019), model structure or climate predictions uncertainty (Tao et al., 2018).

If not calibrated against multiple in-season variables such as soil water content, plant nitrogen content or Leaf Area Index, soil-crop models run the risk of accurately simulating grain yield without accurately simulating growth dynamics. This can undermine their relevance for climate change studies (Challinor et al., 2014; Martre et al., 2015). Our calibration procedure involved the assessment of simulation accuracy for multiple in-season variables (soil water, soil nitrogen, biomass growth, nitrogen uptake and amount of N_2 fixed) in order to minimize error compensations in the simulation of the processes leading to grain yield and fixed N_2. Such procedure led to accurate simulation of grain yield and N_2 fixed under current climate (see section 3.1) and gives us confidence that water and nitrogen dynamics of the soil-crop system were well simulated. However, rRMSE for simulated soil mineral nitrogen content was high due to: (i) the high absolute RMSE (12 and 16 kg N ha^{-1} for calibration and evaluation dataset, respectively); and (ii) the low average level of observed soil mineral nitrogen in our experiments (38 and 32 kg N ha^{-1} for calibration and evaluation dataset, respectively). High RMSE of 20-35 kg N ha^{-1} are typical of current soil-crop models like STICS or The Agricultural Production Systems sIMulator (APSIM) model (Coucheney et al., 2015; Probert et al., 1995), owing to the complexity of the processes to be simulated (soil organic matter and crop residue mineralization, losses through leaching and gaseous emissions and their interaction with plant uptake). As a result, our calibrated model was not able to reproduce the small variations in the amount of soil mineral nitrogen in the evaluation dataset. However, simulations were on average in the range of the low observed values and deemed relevant for our climate impact assessment.

Uncertainty can also be attributable to model structure (*i.e.* the mathematical equations implemented in the model to account for various soil and crop processes). Impact of model structure on simulation uncertainty is often evaluated with inter-comparison of models (Tao et al., 2018). Ensemble modelling to quantify simulation uncertainty related to model structure have developed over the past decade (Asseng et al., 2013; Falconnier et al., 2020; Fleisher et al., 2017). However, these inter-comparisons focused mainly on cereals or tubers and did not include legumes so far. The recent inter-comparison initiative for soybean (https://agmip.org/soybean-pilot/) will allow a first evaluation of simulated response of legumes to changes in [CO_2], temperature and rainfall and will hopefully help initiating further studies on others grain legumes. Comparison of the STICS-simulated grain legume response to heat with the response simulated by models dealing explicitly with heat stress on flower abortion like CROPGRO (Boote et al., 2002) would be of particular interest.

We explored the impact of climate change using the projections of three climate models from the wider CMIP5 ensemble (Taylor et al., 2011). Some climate models not considered here may predict greater changes in temperature and/or rainfall at our study location. Some climate models of the ensemble indeed predicted an increase in temperature reaching more than 4°C for South Europe/Mediterranean region, and decrease of annual rainfall around 40% for the long-term period (IPCC, 2013).

4.4 Adaptations to climate change and avenues to extend the work

Uncertainty in the magnitude and the direction of the changes in legume grain yield does not preclude the design of robust adaptation options*, i.e.* that provide a yield advantage regardless of the climate change scenario (Vermeulen et al., 2013). In our simulations at our study site, winter legume tended to benefit more from climate change or to be less affected than the spring pea cultivar. In the most constraining climate change scenarios, the risk of yield failure for the latter would rise considerably (see section 3.4). Yield variability, a prominent constraint to widespread adoption of grain legumes by farmers, would therefore be magnified for this crop. Favoring winter over spring grain legumes therefore appears as a promising strategy to adapt to future climate in southwestern France.

The diversity in current temperature and seasonal rainfall climate conditions is often very useful in explaining crop response to climate change. Global studies show that yield losses due to rise in temperature are greater at warmer locations, while impact of water stress is predicted to be stronger at drier locations (Waha et al., 2013; Zhao et al., 2017). Plant-available water content is also a critical soil parameter that drives the risk of water stress on crops (Whitbread et al., 2017). Our study site located at the northern fringe of the Mediterranean region is characterized by a cooler and wetter area compared with others regions in lower latitudes such as Spain and Greece. Soils are also deep (135cm) in Auzeville. Further modelling work should focus on model calibration against field data and exploration of the impact of climate change in additional sentinel sites in southern locations and/or with contrasting soil types. This would allow for a more comprehensive assessment of the impact of climate change on grain legumes in Southern Europe. Possibly, the advantage of winter-legumes over spring legumes will be magnified in sites that are warmer and drier and/or with shallower soils. Our study would provide a useful basis for comparison.

Rise in temperature causes a decrease in crop cycle duration and therefore yield potential (see section 3.5.1). Adoption of late-maturing cultivars could help to regain this reduction in the length of vegetative and/or reproductive period (see Bregaglio et al., 2017 for a useful example on rice). However, the trade-offs between extended crop cycle duration and possible additional heat and drought stress have to be quantified. Our model calibration for pea and winter faba bean could offer the opportunity to explore these trade-offs and to define best suited ideotypes with optimal vegetative and reproductive growth duration that minimize abiotic stresses (see Senapati et al., 2019 for a useful example on wheat and Ravasi et al., 2020 on pea). In our study, sowing dates were identical in historical and future climate to isolate the effect of climate change. However, explorations of ideotypes should also consider the interactions between cultivar characteristics and sowing date (see Dobor et al., 2016 for an example on maize and winter wheat), and notably the opportunity to sow earlier spring legume cultivars as temperatures rise and winters become milder. The identification of these ideotypes can help set priorities for breeders aiming at developing new cultivars adapted to climate change. Analysis of current cultivar diversity (*e.g.* Bodner et al., 2018 for faba bean) will also help identify specific traits that confer adaptation to heat stress. For example, Delahunty et al., (2018) showed that some lentil genotypes were able to maintain grain set under high temperature. Soil compaction associated with the increase in machinery weight (Keller et al., 2019) can decrease root growth, soil water storage capacity and legumes N_2 fixation. Mitigation of compaction effects with *e.g.* lighter machinery may help to improve soil water storage capacity and adapt to plausible increases in drought stress. STICS has a specific option to account for the impact of soil compaction on roots growth (Brisson et al., 2009), so that future modelling studies on adaptation could incorporate options to mitigate soil compaction, provided that the STICS module has been sufficiently evaluated. Irrigation could also help reduce water stress, but the design of ideotypes with shifts in growth cycle to take better advantage of spring precipitations could also help lower crop water requirements (Ravasi et al., 2020). Our study did not consider the potential impacts of biotic factors (weeds, pests and diseases). STICS does not simulate interactions between crops and parasitic /pathogenic organisms and no simulation tool for biotic interactions coupled to STICS is operational yet. Yet, pea and faba bean can host above- and belowground pests and pathogenic species (e.g. aphids, sitones, seed beetles, *Aschochyta*, rust, *Aphanomyces*) that can significantly reduce crop yield (Rubiales et al., 2015). In the future, climate change may alter these biotic threats through shifts in phenology, multi-trophic relationships, distribution and severity of known biotic stressors and emergence of new ones (Juroszek et al., 2020). Assessing whether these changes may have positive or negative outcomes on such crops is an important complementary step, especially in the prospect of sustainable agriculture, where pesticide use is reduced and pest and disease control might be more uncertain (Thurman et al., 2017).

Eventually, if diversification with grain legume is to contribute substantially to climate change adaptation, it is important that the risk associated with their integration in cropping systems is transferred equitably along the value chain. The development of risk sharing instruments like indemnity or index-based insurances, along with changes in diet to increase market demand are examples of the needed transformative changes (Smith et al., 2019).

5. Conclusion

Our study shows that the STICS crop model reproduced accurately the growth, grain yield and N_2 fixation of currently under-studied cool-season grain legumes like faba bean and pea under current climate. Model simulations showed that these cool-season grain legumes would benefit from climate change, the effect of [CO_2] increase generally offsetting the negative impact of heat and drought stress on grain yield and N_2 fixation. For one constraining climate scenario with strong increase in temperature and decrease in rainfall, [CO_2] increase would however not be sufficient to offset the negative impacts of climate change and spring pea would be then more affected than winter pea and winter faba bean. Such results have to be confirmed by simulations with extended crop model ensembles to quantify the uncertainty in how models simulate the impact of [CO_2] increase, heat and drought stress on yield and N_2 fixation of these grain legumes. Our study already documents the need to adapt cultivar choice to climate change, and the opportunity to tap into the differences between spring and winter legumes for such adaptation.

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Figures

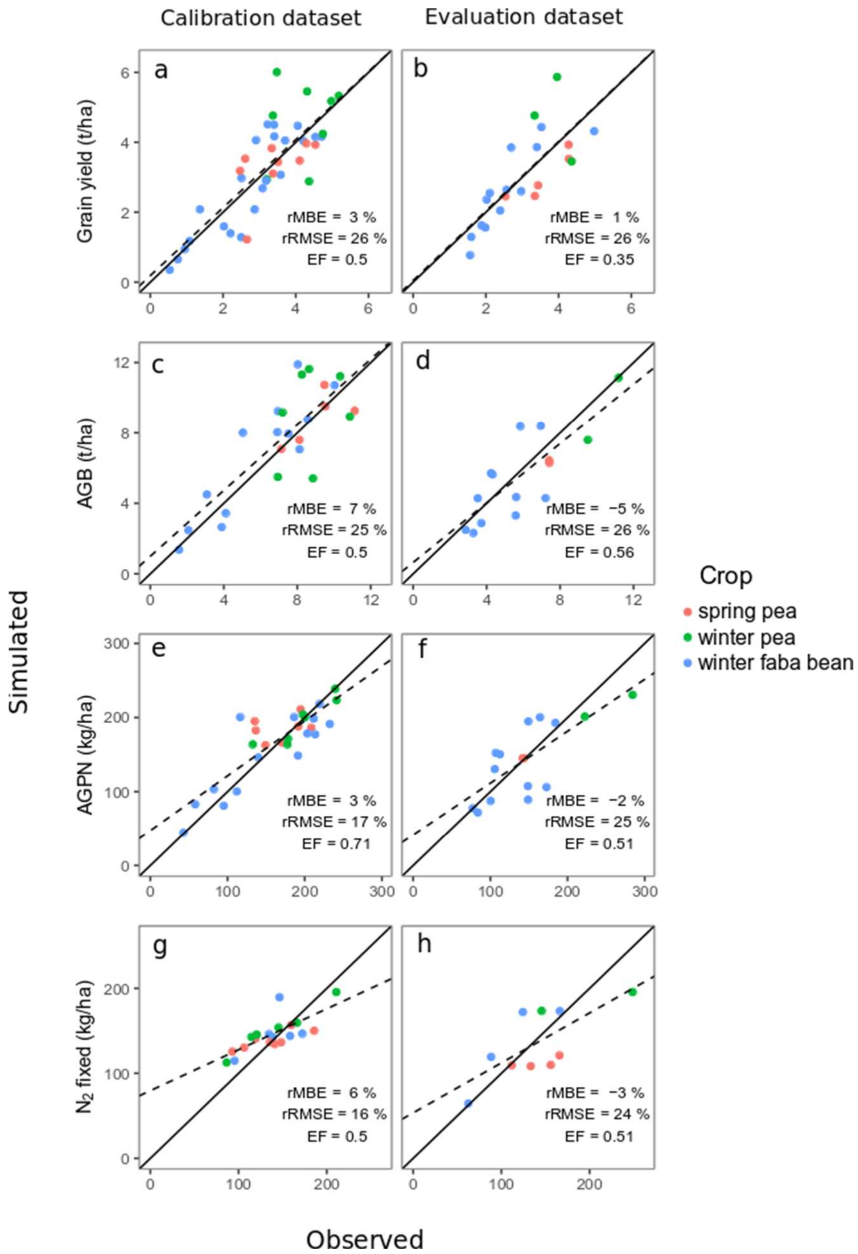

Figure 1: Comparison of observed and simulated crop variables for grain yield (a,b), above ground biomass (AGB) (c,d), above ground plant N (AGPN) (e,f) and amount of N_2 fixed at harvest (g,h), for calibration (a,c,e,g) and evaluation datasets (b,d,f,h) for spring pea (red), winter pea (green) and winter faba bean (blue). rMBE = relative mean bias error, rRMSE = relative Root Mean Square Error, EF = Efficiency. The black line is the 1:1 line. The dotted line represents the regression of simulated against observed values. The reader is referred to the web version of this article for interpretation of references to colors.

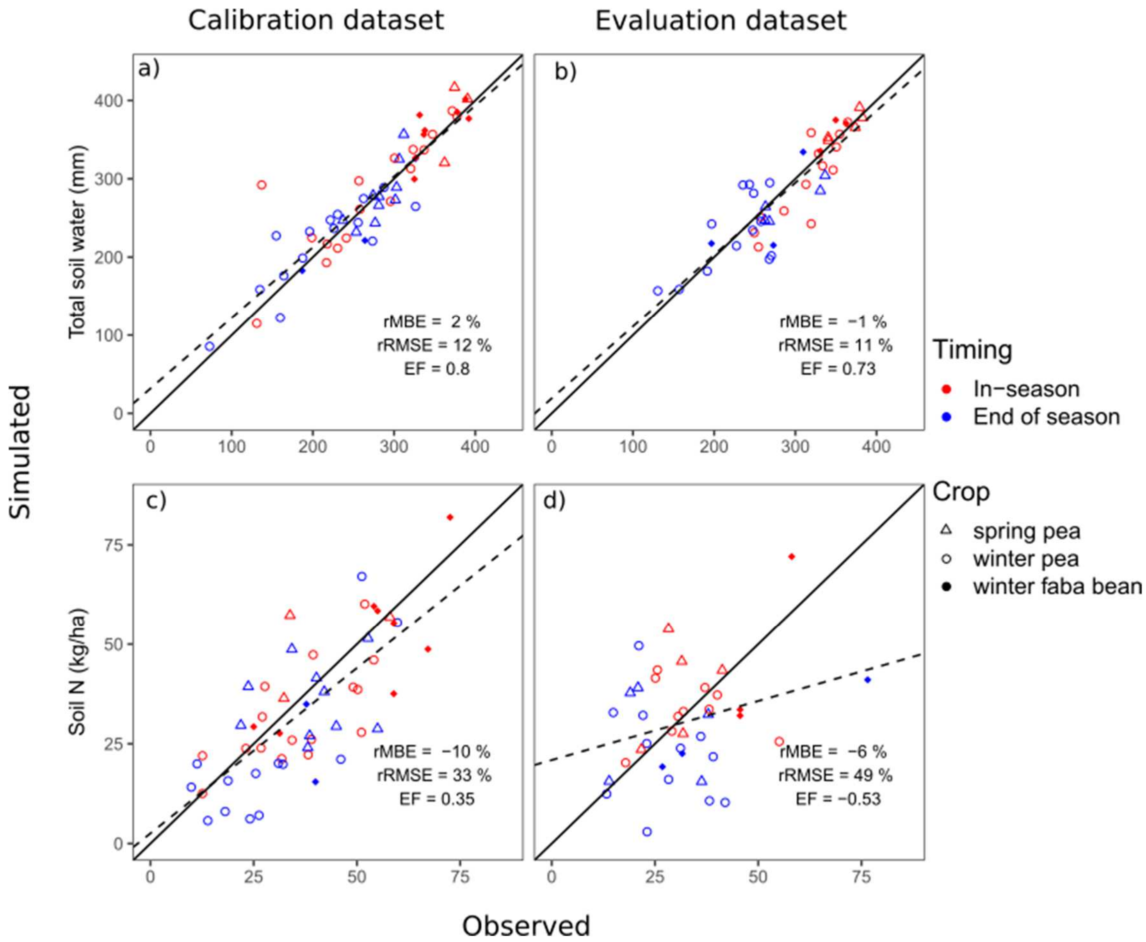

Figure 2: Comparison of observed and simulated soil variables: total soil water content (a,b) and total soil nitrogen content (c,d) for calibration (a,c) and evaluation datasets (b,d) for spring pea (triangles), winter pea (open circles) and winter faba bean (close circles), for in-season (red) and end of season measurements (blue). rMBE = relative mean bias error, rRMSE = relative Root Mean Square Error, EF=Efficiency. The black line is the 1:1 line. The dotted line represents the regression of simulated against observed values. The reader is referred to the web version of this article for interpretation of references to colors

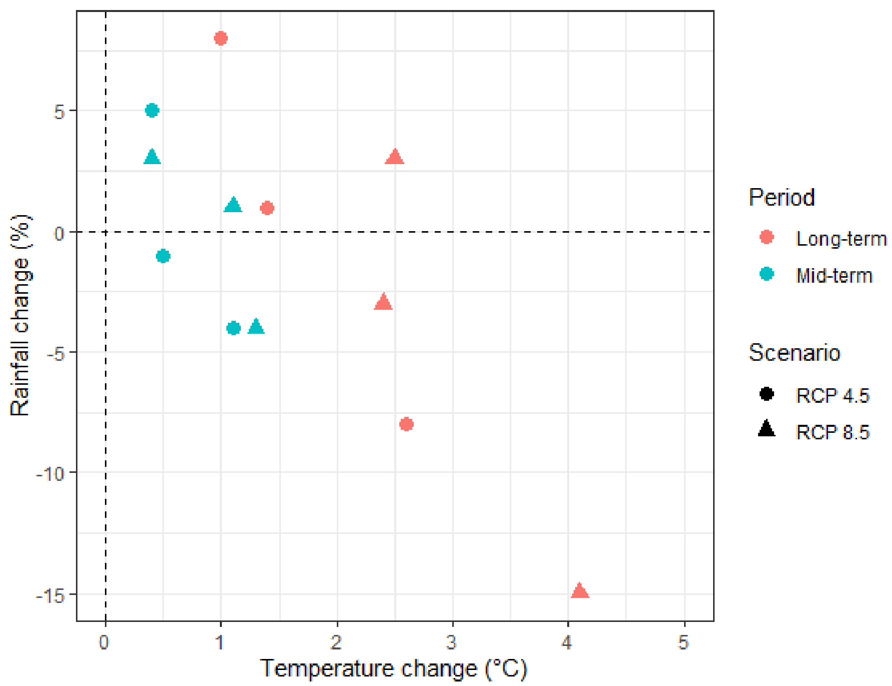

Figure 3: Change in cumulative rainfall and temperature (averaged across grain legume growing season corresponding to November-June period) as projected by three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 with circles and RCP 8.5 with triangles) and two projections mid-term (2020-2040 in blue) and long-term (2060-2080 in red).The reader is referred to the web version of this article for interpretation of references to colors

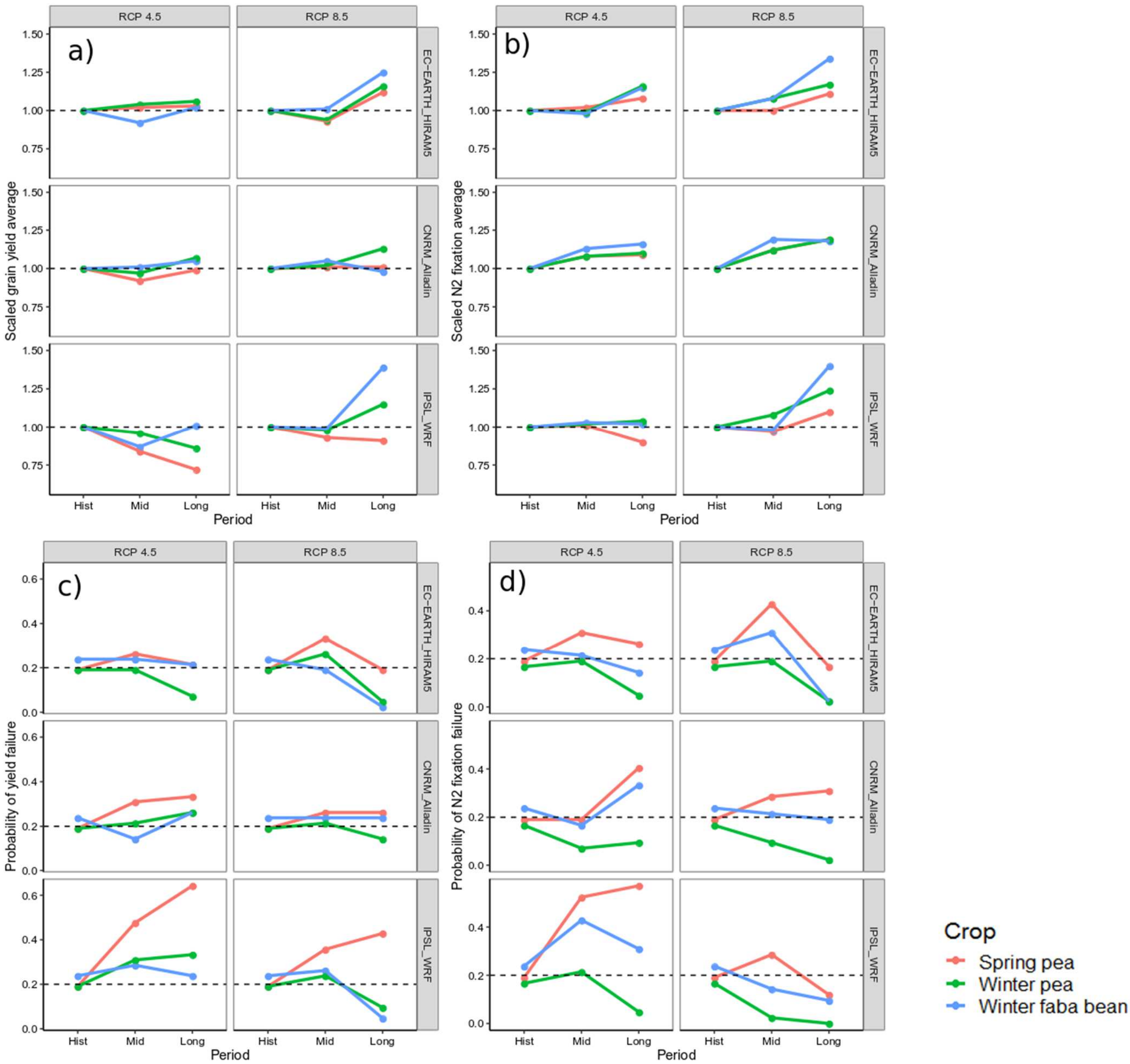

Figure 4: Scaled simulations of grain yield (a), N_2 fixation (b) and their respective risks of failure (c, d) under historical climate (Hist) (1995-2005), mid-term (Mid) (2020-2040) and long-term (Long) projections (2060-2080) for three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5) at one location in the southwestern France for three grain legumes (spring pea in red, winter pea in green and winter faba bean in blue). The dotted horizontal line is the probability of yield failure with historical climate. The reader is referred to the web version of this article for interpretation of references to colors.

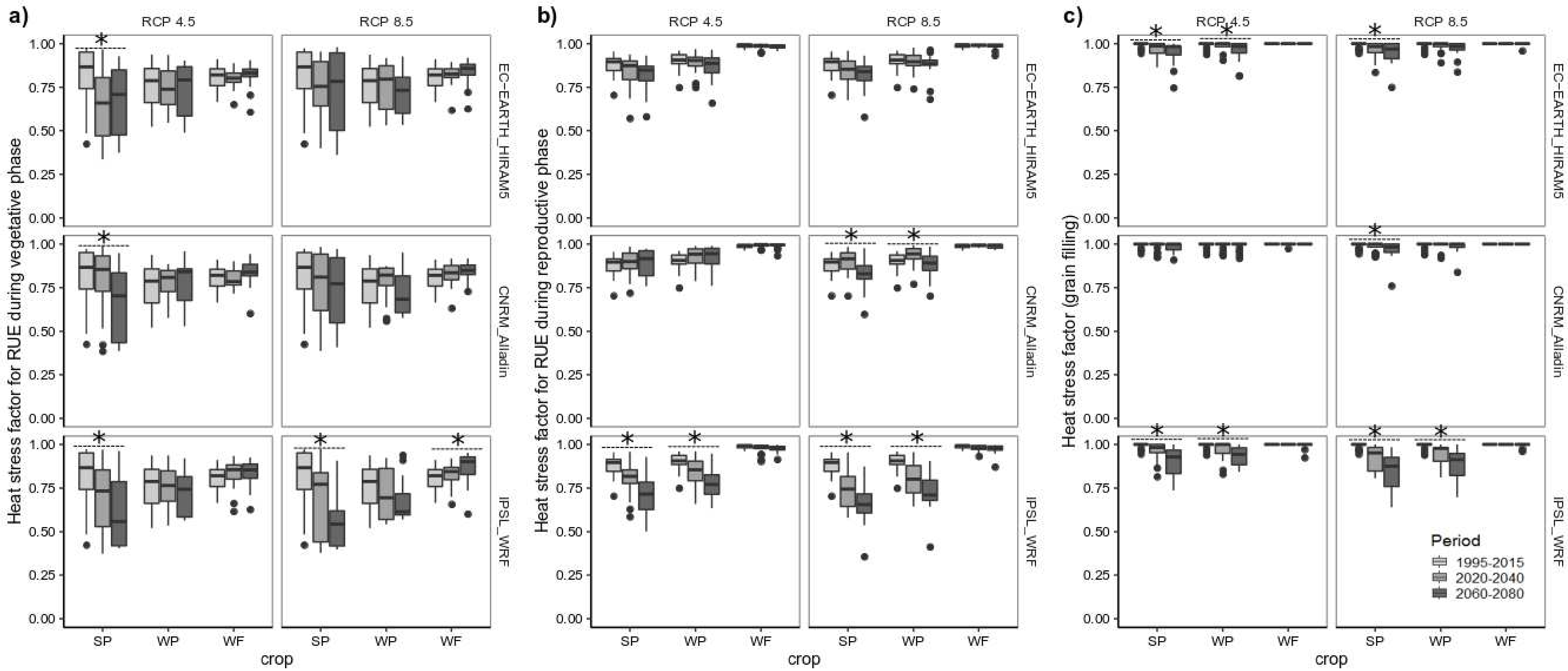

Figure 5: Simulated thermal stress factor for radiation use efficiency (RUE) during vegetative (a) and reproductive (b) phase and heat stress on grain filling (c) for historical climate, mid-term and long-term projections according to three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5) for spring pea (SP), winter pea (WP) and winter faba bean (WF) in one location in southwestern France. Significant (P<0.05) effect of the period (historical, mid-term and long-term) on the simulated stress factor (for a given RCP and climate model) are indicated with a star on top of boxplots. For stress factors, a value of 1 indicates no stress while a value of 0 indicated maximum stress.

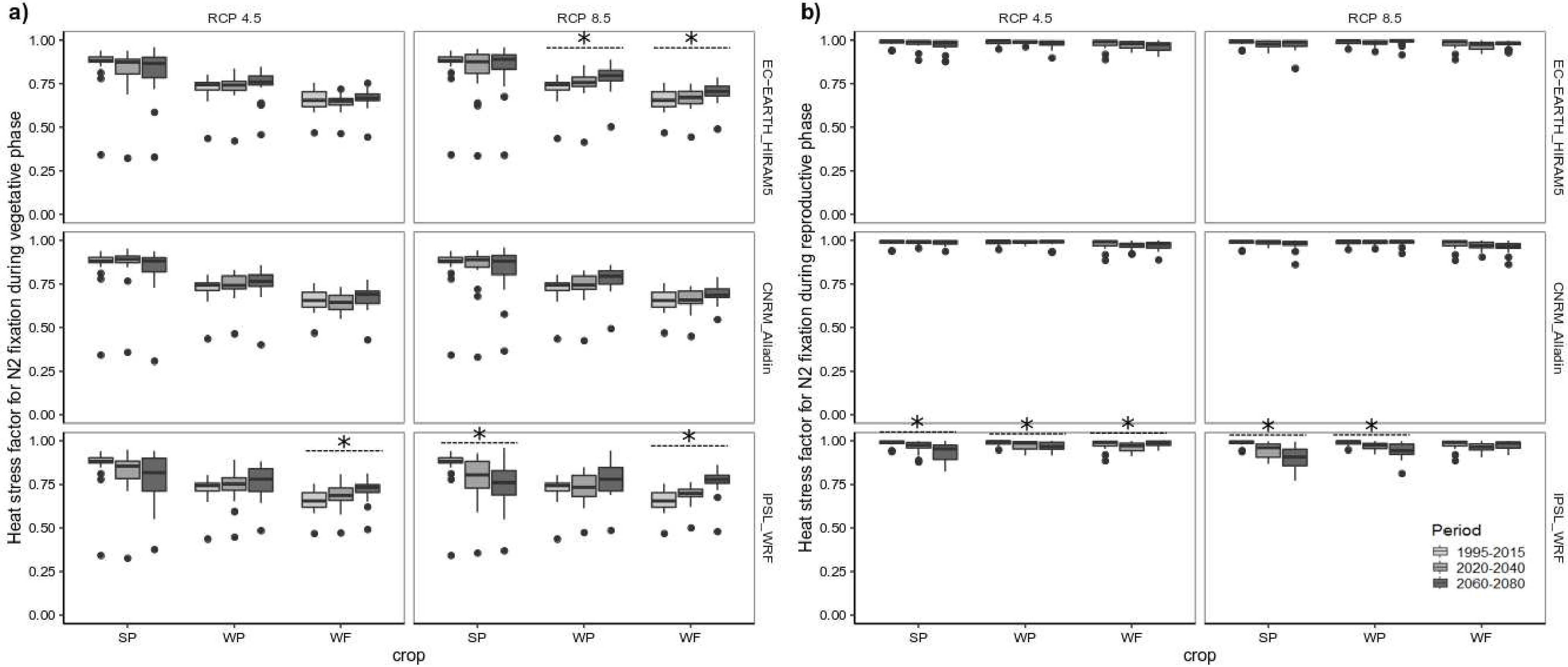

Figure 6: Simulated thermal stress factor for N_2 fixation during vegetative (a) and reproductive (b) phase for historical climate, mid-term and long-term projections according to three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5) for spring pea (SP), winter pea (WP) and winter faba bean (WF) in one location in southwestern France. Significant (P<0.05) effect of the period (historical, mid-term and long-term) on the simulated stress factor (for a given RCP and climate model) are indicated with a star on top of boxplots. For stress factors, a value of 1 indicates no stress while a value of 0 indicated high stress.

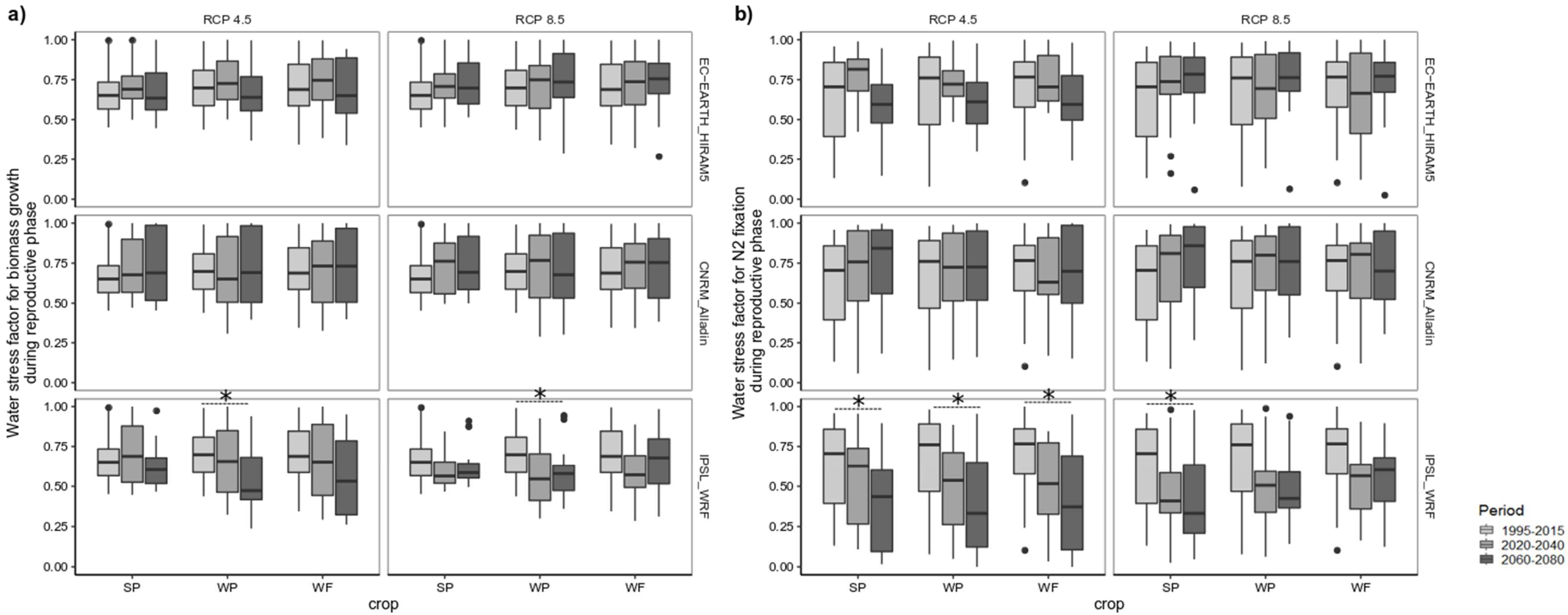

Figure 7: Simulated water stress factor for biomass growth (ratio of actual to potential transpiration) (a) and water stress on N_2 fixation (b), during reproductive phase, for historical climate, mid-term and long-term projections according to three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5) for spring pea (SP), winter pea (WP) and winter faba bean (WF) at one location in southwestern France. Significant (P<0.05) effect of the period (historical, mid-term and long-term) on the simulated stress factor (for a given RCP and climate model) are indicated with a star on top of boxplots. For stress factors, a value of 1 indicates no stress while a value of 0 indicated high stress.

Tables

Table 1: Change in maximum and average temperatures (averaged across grain legume growing season, *i.e.* November to June) as projected by three climate models for two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5).

Variable	Scenario	Climate model	Change in temperature between 2020-2040 and historical climate (1995-2015) (°C)	Change in temperature between 2060-2080 and historical climate (1995-2015) (°C)
Maximum temperature (°C)	RCP 4.5	CNRM_Alladin	0.3	1.0
		EC-EARTH_HIRAM5	0.6	1.5
		IPSL_WRF	1.1	2.8
	RCP 8.5	CNRM_Alladin	0.5	2.7
		EC-EARTH_HIRAM5	1.5	2.9
		IPSL_WRF	1.5	4.4
Average temperature (°C)	RCP 4.5	CNRM_Alladin	0.4	1.0
		EC-EARTH_HIRAM5	0.5	1.4
		IPSL_WRF	1.1	2.6
	RCP 8.5	CNRM_Alladin	0.4	2.4
		EC-EARTH_HIRAM5	1.1	2.5
		IPSL_WRF	1.3	4.1

Table 2: Change in cumulative rainfall (averaged across grain legume growing season, *i.e.* November to June) as projected by three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5)

Variable	Scenario	Climate model	Relative change in rainfall between 2020-2040 and historical climate (1995-2015)	Relative change in rainfall between 2060-2080 and historical climate (1995-2015)
Rainfall (mm)	RCP 4.5	CNRM_Alladin	5%	8%
		EC-EARTH_HIRAM5	-1%	1%
		IPSL_WRF	-4%	-8%
	RCP 8.5	CNRM_Alladin	3%	-3%
		EC-EARTH_HIRAM5	1%	3%
		IPSL_WRF	-4%	-15%

Table 3: Change in average simulated crop cycle duration for future climates, as projected by three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5).

Rcp	Gcm	Crop	Change in average crop cycle duration between 2020-2040 and historical climate (1995-2015) (days)	Change in average crop cycle duration between 2060-2080 and historical climate (1995-2015) (days)
RCP 4.5	CNRM_Alladin	Spring pea	-2	-3
		Winter faba bean	-3	-5
		Winter pea	-1	-2
	EC-EARTH-HIRAM5	Spring pea	1	-6
		Winter faba bean	-3	-10
		Winter pea	-1	-7
	IPSL_WRF	Spring pea	-7	-20
		Winter faba bean	-10	-26
		Winter pea	-8	-20
RCP 8.5	CNRM_Alladin	Spring pea	0	-12
		Winter faba bean	-2	-17
		Winter pea	0	-10
	EC-EARTH-HIRAM5	Spring pea	-4	-12
		Winter faba bean	-7	-17
		Winter pea	-3	-11
	IPSL_WRF	Spring pea	-11	-29
		Winter faba bean	-14	-35
		Winter pea	-12	-28

Table 4: Relative change in simulated thermal and water stress factors between long term projections (2060 – 2080) and historical climate of three climate models under two greenhouse gas emission scenarios (Representative Concentration Pathways; RCP 4.5 and RCP 8.5) for spring pea, winter pea and winter faba bean at one location in southwestern France. Relative changes corresponding to a significant (P<0.05) effect of the period on the simulated stress factor are indicated in bold. A decrease in the simulated stress factor value indicates an increase in the stress.

			Heat stress factor					Water stress factor			
rcp	gcm	crop	RUE-vegetative phase	RUE-reproductive phase	Grain filling	N_2 fixation - Vegetative phase	N_2 fixation - Reproductive phase	Growth - vegetative phase	Growth - reproductive phase	N_2 fixation - vegetative phase	N_2 fixation - Reproductive phase
RCP 4.5	CNRM_Alladin	Spring pea	**-18%**	1%	-1%	-2%	0%	0%	9%	13%	14%
		Winter faba bean	2%	0%	0%	3%	-1%	1%	3%	3%	6%
		Winter pea	3%	2%	0%	4%	0%	1%	4%	5%	6%
	EC-EARTH_HIRAM6	Spring pea	**-20%**	-7%	**-4%**	-5%	-2%	0%	0%	4%	-6%
		Winter faba bean	1%	-1%	0%	2%	-2%	2%	-1%	0%	-7%
		Winter pea	-3%	-3%	**-3%**	4%	-1%	1%	-3%	1%	-2%
	IPSL_WRF	Spring pea	**-24%**	**-20%**	**-10%**	-9%	**-6%**	-2%	-9%	-13%	**-39%**
		Winter faba bean	2%	-1%	0%	**11%**	**0%**	-1%	-20%	-6%	**-36%**
		Winter pea	-5%	**-14%**	**-6%**	7%	**-2%**	-1%	**-23%**	-9%	**-38%**
RCP 8.5	CNRM_Alladin	Spring pea	-13%	**-6%**	**-2%**	-2%	-1%	-1%	10%	13%	17%
		Winter faba bean	5%	0%	0%	6%	-2%	0%	1%	5%	1%
		Winter pea	-5%	**-2%**	-1%	8%	0%	0%	3%	7%	14%
	EC-EARTH_HIRAM6	Spring pea	-12%	-7%	**-4%**	-2%	-1%	1%	9%	11%	17%
		Winter faba bean	2%	-1%	0%	**8%**	0%	2%	6%	3%	10%
		Winter pea	-5%	-2%	-2%	**10%**	0%	2%	4%	7%	17%
	IPSL_WRF	Spring pea	**-32%**	**-26%**	**-14%**	**-14%**	**-9%**	1%	-9%	-22%	**-36%**
		Winter faba bean	**7%**	-2%	0%	**17%**	-1%	2%	-6%	-6%	-15%
		Winter pea	-11%	**-19%**	**-10%**	8%	**-4%**	2%	**-14%**	-12%	-26%