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David Makowski[1,2], Elodie Marajo-Petitzon[3], Jean-Louis Durand[4] and Tamara Ben-Ari[1,2]

[1] INRAE, AgroParisTech, Université Paris-Saclay, UMR 211, France

[2] Centre international de recherche sur l'environnement et le développement (CIRED), UMR 8568 Nogent-sur-Marne, France

[3] INRAE, SAE2, Rennes, France

[4] INRAE, UR P3F, route de sainte 86600 Lusignan, France

E-mail : david.makowski@inrae.fr

Abstract

Climate change is known to impact crop yields, mainly through increased temperatures, changing rainfall patterns and increasing CO_2 concentration in the atmosphere. Although the potential effects of each of these factors have been discussed in a number of separate studies, no recent synthesis has been published to provide quantitative estimates of climate change impacts on crop yields, with or without adaptation strategies. In this paper, we synthetize a broad range of experimental or modeling studies to estimate, at the global scale, crop yield changes resulting from the marginal and combined effects of temperature, CO_2 concentration and precipitation, with and without adaptation strategies. Crop yield sensitivities are estimated by distinguishing between C3 and C4 crops. For C3 crops, our results show that the positive effects of adaptation (+7.25%) and CO_2 (+9% for +100ppm) are high enough to offset the negative effects of temperature increase (-2.4% for +1°C), even at +4°C. On the other hand, for maize (i.e., the only C4 plant species in our database) the somewhat low positive effect from increased CO_2 concentration and the absence of a significant effect of adaptation lead to higher yield losses, in the order of -10% for +4°C. The minimum level of CO_2 concentration increase requested to achieve a yield gain under increased temperature conditions is much higher for maize than for C3 crops, in particular for wheat. The estimated effects of adaptation are uncertain, especially for soybean and rice, but also for maize, where the absence of a significant adaptation effect is probably at least partly due to limited data availability. Our results demonstrate that CO_2 effects on crop yields should not be overlooked in foresight studies on the impacts of climate change. Our analysis also highlights the importance of improving the reliability of estimating the effects of adaptation strategies on crop yields.

Keywords: Adaptation, Climate change, CO_2, ensemble modelling, meta-analysis, yield

1. Introduction

Many studies on the impact of climate change on crop yields, mainly through increased temperatures, changing rainfall patterns and increasing CO_2 concentration have been published in recent years. They are based on the results of experiments (Ainsworth and Long 2005, Long et al. 2006, Zhao et al. 2016, Zhao et al. 2017a), on simulations from single or ensemble of mechanistic crop models (Asseng et al. 2013, Bassu et al. 2014, Makowski et al. 2015), or on statistical or machine learning models (Crane-Droesch 2018, Lobell & Asseng 2017, Lobell et al. 2011, Roberts et al. 2017). These studies provide a better understanding of the impact of climate change on yields, in particular, of the magnitude of the so-called "fertilizing" effect of atmospheric CO_2 concentration on biomass production (Long et al. 2006). It is now well established that C3 crops (e.g., wheat, soybean, rice) benefit more from CO_2 concentration increase (Ainsworth and Long 2005; Fitzgerald et al. 2016; Long et al. 2006) than C4 crops (e.g., maize, sorghum). However, in practice, the effect of CO_2 on crop yields is often ignored when assessing impact of climate change on crop yield of C3 crops, both in scientific papers (Zhao et al. 2017a, b) and in reports presenting results of foresight studies on climate change (FAO 2018).

Climate change impacts crop yields through other factors than CO_2, in particular through temperature and rainfall changes. The rate of crop development and growth strongly responds to temperature (Bonhomme et al 1994, Bonhomme 2000, Soltani and Sinclair 2012). Under conditions of increased temperature, the sum of temperature required for development will be met more rapidly, hence reducing the amount of intercepted solar energy and penalizing potential plant growth (Brisson and Levrault 2010). In addition to its effect on the length of the growth cycle, temperature can have deleterious effects on crops when it becomes higher than some thresholds, penalizing yields (Hunt et al. 2018) or accelerating plant senescence by altering its photosystem (De la Haba et al. 2014) or reproductive processes (Lizaso et al 2018). Several studies have shown that the effect of rainfall on yields depends on various factors, related to its total amount and distribution within the growing season, soil characteristics, in particular initial soil water conditions, useful soil reserve, and soil rooting depth (Schlenker and Lobell 2010; Ray et al. 2015, Lobell and Asseng 2017). Rainfall effects vary according to agricultural practices, in particular to irrigation but also to the specific water requirements of species and varieties. In fact, various adaptation strategies can be implemented by farmers to mitigate the negative effects of temperature and rainfall changes on yields, including irrigation (Li and Troy 2018, Saadi et al. 2015), varietal improvement (Olesen et al. 2011, Nuccio et al. 2018) or changes in harvesting or sowing dates (Caubel et al. 2018).

Although the potential effects of each of these factors have been discussed in a number of separate studies, only a few syntheses have been published to provide quantitative estimates of crop yield changes resulting from changes in temperature, CO_2, and rainfall with or without adaptation strategy. Two meta-analyses published in 2014 synthetized results of several studies (Challinor et al. 2014, Wilcox and Makowski 2014) but these two papers did not include the most recent studies based on ensemble of crop models or global experimental datasets.

The objective of our work is to provide a quantitative synthesis of the effects of changes in temperature, CO_2 concentration and precipitation on crop yields from key scientific sources of information. In our analysis, we estimate the yield losses or gains associated with different levels of temperature increase, CO_2 increase, and changes in precipitation patterns, while taking the crop photosynthetic pathway and adaptation strategies into account. We report these effects both individually (i.e., for one variable at a time, with all others set to zero) and in combination. Based on our results, we are hence able to disentangle the effects of temperature, CO_2, rainfall and adaptation.

Given the high variability of estimated yield responses between sites or between models (Asseng et al. 2013, Bassu et al. 2014, Li et al. 2015, Makowski et al. 2015), we chose to focus only on bibliographic references that present the results from several sources of information in the same analysis (e.g., three or more models). Our synthesis thus includes results from ensembles of crop models (such as those from the AgMip project, Rosenzweig et al. 2014) and from meta-analyses (e.g., Challinor et al. 2014, Wilcox and Makowski 2014, Zhao et al. 2016, Zhao et al. 2017a). The articles included in our analysis are systematically selected according to a procedure based on explicit criteria. The data extracted from these articles are analyzed using statistical models commonly used in meta-analysis. The levels of uncertainty associated with our estimates are systematically presented to allow for a transparent assessment of the robustness of our conclusions.

By adopting this approach, we are able to synthesize a large number of studies each using several sources of information to estimate the impact of climate change on yields for a group C3 species as a whole and for four major C3 and C4 crops separately (i.e., maize, wheat, soybean, rice), and to analyze uncertainties associated. Our synthesis is based on aggregated estimates provided by simulations of model ensembles and meta-analyses. As these aggregated estimates are generally less uncertain than those provided by individual studies or models (Koricheva et al. 2013, Wallach et al. 2016, 2019), our synthesis is expected to produce robust conclusions that could be relevant for foresight studies on climate changes, such as those produced by the Intergovernmental Panel on Climate Change or the FAO.

2. Material and method

2.1. Systematic literature review

A bibliographic search was conducted in the web of science according to the following research equation:

TITLE: ((Climat* and (change* or event* or condition* or factor* or variability or regime*)) or future or trend* or projecti* or "warming" or forecast* or 2030 or 2040 or 2050 or 2100)

AND TITLE: (Crop or Cereal* or Maize or corn or wheat or rice or barley or sorghum or oat* or rye or triticale or "Sugar plant*" or sugarbeet or sugarcane or beet* or "sugar cane" or Oilcrop* or oleaginous or proteaginous or "oilseed crop*" or Rape* or Soya* or soybean* or Sunflower or "Protein crop*" or pulse* or pea* or "faba bean*" or lupin* or alfalfa or Forages or Grass or fodder or pasture* or canola or bean or grass* or "grain legume*")

AND TOPIC: (meta-analys* OR (meta NEAR analys*) OR meta-model* OR (model* NEAR inter-comp*) OR (model* NEAR intercomp*) OR (model* NEAR ensemble*))

NOT TITLE: (peak or beetle)

This bibliographic search allowed us to retrieve 113 articles as of 14/05/2018.

2.2. Study selection

To be selected, an item must meet the following criteria: (i) it must involve an analysis of the climate change impact on crop yield, (ii) it must present the results of at least three different yield estimation methods and/or at least three different crop models, (iii) it must present yield values and the characteristics of the climate change scenarios tested (temperature change, CO_2, precipitation). After application of the selection criteria, the final corpus contains 16 review articles, published between 2008 and 2018 (Supplementary 1). The crops represented are wheat (6 items), maize (5), soya (5), rice (7), barley (1) and grassland (1). Depending on the case, these studies are carried out on the scale of a large geographical region (e.g. Europe), a country, or a local site. The most represented countries are China (4 articles), Brazil (4 articles), USA (3 articles), India (3 articles) and France (2 articles). In total, 15 distinct geographical areas covering both temperate and tropical regions are concerned. The results published in the articles are based on mechanistic (11) or statistical (5) modelling. Two articles analyze a set of experiments. Some articles use several approaches. The number of selected articles is relatively small, but each of them includes several individual studies (3 to 346) and several scenarios.

2.3. Data extraction

The following information has been extracted from the selected articles:

- article references (title, authors, date of publication)
- geographical coordinates for site studies or countries or regions

- the crop species concerned
- scenarios of changes in temperature, precipitation and CO_2
- the future horizons considered and the reference period
- the average impacts of climate change on yields (relative change in yield in % of baseline estimated by combining all available individual models/studies)
- information about the uncertainty of the average impacts reported in the articles (standard deviations or confidence intervals)
- the number of individual studies or models analyzed
- the adaptation strategies considered (change of sowing dates, irrigation, varietal improvement, when tested).

Data were extracted from the text or tables of the selected articles. When the data was not directly accessible, the web plot digitizer software was used to extract it from the figures. Finally, some missing data were retrieved directly from the authors. The total number of relative yield change values extracted from the 16 items is 310 (about 40% in temperate areas, 44% in tropical areas, 16% in both). These data are presented in Figure 1 as a function of changes in temperature, precipitation, and CO_2 concentrations considered in the selected articles. The majority of the relative change in yield values are between -10% and +10%. Note that, for maize and rice, the number of scenarios of increasing precipitation is very small (two and one, respectively), and that no scenario of decreasing precipitation is considered in the selected references for these two crops. The file including the data is available on request.

2.4. Statistical analysis

The objective of our statistical analysis is to estimate the relative change in yield due to climate change (Y) as a function of changes in temperature (T), precipitation (P), metabolic pathways of carbon fixation (i.e., C3 or C4 plants), atmospheric CO_2 concentration (C) and adaptation to climate change (i.e., change in planting date, varietal choice, and/or irrigation). Given the available data, a global binary variable indicating the application (or not) of adaptation strategies was considered (I), without distinguishing between different types of adaptation.

The analysis is performed with a mixed model including a random effect associated with the different studies (defined by the combinations Articles*Sites because the same article can contain several sites). The random effect allows for the heterogeneity between the different studies included in our database. This type of model is often used to manage heterogeneity in meta-analysis (i.e., quantitative synthesis of data collected in different situations). A global model was adjusted for all C3 crops, and other models were adjusted species by species for wheat, maize, soybean and rice. As the only C4 species included in our database is maize, it was not necessary to define a C4 model in addition to the maize model.

The model for C3 crops (as a group) is defined by:

$$Y_{ij} = a_{Ti}T_{ij} + a_P P_{ij} + a_C C_{ij} + a_{CT} C_{ij} T_{ij} + a_A I_{Aij} + \varepsilon_{ij} \qquad (1)$$

Y_{ij} is the relative change in yield in % with respect to site reference i for scenario j, a_{Ti} corresponds to the effect of the increase of one degree Celsius on yield for study i, a_P is a parameter describing the effect of the 1% increase in precipitation on yield, a_C is a parameter describing the effect of increasing by one ppm of CO_2, a_A is the parameter corresponding to the effect of adapting to climate change, a_{CT} is a parameter describing the interaction between the effect of increasing temperature and of increasing CO_2. Variable I_{Aij} is a dummy variable equal to 1 for situations where adaptation is present, and equal to zero otherwise. The variables T_{ij}, P_{ij} and C_{ij} are the changes of temperature, rainfalls and CO_2 concentrations on site i and scenario j, respectively. The sites considered are well suited for each crop, and our model does not cover regions out of the current cropping area of the respective species. The temperature effect a_{Ti} is assumed to vary from one study to another according to a Gaussian distribution $a_{Ti} \sim N(\mu_T, \sigma_T^2)$, with μ_T the global expected value of a_{Ti} and σ_T the between-study standard deviation of a_{Ti}. This random term recognizes that the effect of temperature on yield is likely to vary depending on the characteristics of the environment and crop, but also on the method used (e.g., selected crop models). The term ε_{ij} is a random error distributed according to a Gaussian distribution $\varepsilon_{ij} \sim N(0, \tau_{ij}^2)$, describing intra-study variability, with τ_{ij} the residual standard deviation for study *i* and scenario *j*. The values of τ_{ij} are assumed to be proportional to the standard deviations extracted from the selected articles in order to give less weight to the most uncertain studies.

Our statistical model cannot be used to simulate the effects of a specific heat stress or drought occurring at certain stages or on certain date because it does not explicitly take into account the dates of occurrence of heat and water stresses. However, the parameters of our statistical models are estimated from data mostly generated by process-based crop models that do simulate the timing of these stresses (albeit imperfectly). Thus, the estimated parameter values of our model are indirectly dependent on the dates of occurrence of heat and water stresses and their corresponding crop growth stages.

Several variants of the model (1) were tested under the following assumptions: (i) the effects of precipitation, CO_2, and adaptation vary between studies (such as the temperature effect a_{Ti} presented above), (ii) interactions exist between temperature and precipitation, and between precipitation and CO_2. These variants of the global model (1) were not retained; either they could not be adjusted to the data because of identifiability problems (model too complex compared to available data), or they led to higher AIC values (Akaike information criterion) reflecting a less optimal compromise between likelihood and complexity than that offered by the initial model, or they included non-statistically significant effects. The residual analysis does not reveal any particular issue (Supplementary 2). Quality of fit is similar for both considered sources of data (i.e., model ensembles and meta-analyses), and is better for wheat (R^2=0.85), maize (R^2=0.84) and soybean (R^2=0.89) than for rice (R^2=0.5). The lower quality of fit obtained for rice is due to the relatively large residuals obtained for temperature change of +6°C. Results obtained for this level of temperature change should thus be interpreted with caution for rice. We tried to fit the model for each continent separately, but the results were not conclusive due to a lack of data.

The species-by-species analyses were carried out using the model (1) by estimating its parameters based on the data reported specifically for the species in question. For some species, simplified versions of the model (1) were selected because they led to a reduction in the AIC criterion. Depending on the crop species, the effects of P_{ij}, $C_{ij}T_{ij}$ interaction and/or I_{Aij} adaptation were significant or not (Supplementary 3). The interaction between temperature change and CO_2 change was significant ($p<0.001$) for the C3 model and for the rice model. This means that, in these models, the effect of CO_2 depends on the level of temperature change. Since the interaction parameter here is negative, the positive effect of CO_2 on yield decreases as the temperature change increases.

The parameters μ_T, σ_T , a_P, a_C, a_A et a_{CT} were estimated by restricted maximum likelihood using the R lme4 package. All the estimated parameter values of the selected models are available in Supplementary 3. Once the parameters estimated, the global C3 model and the models selected species by species were used to compute the relative change in yield resulting from temperature increases of +0, +2, +3, +4°C, for CO_2 content increases of +0, +100, and +200ppm, precipitation decreases of 0 and -10%, with and without adaptation to climate change. The proposed models can easily be reused to test other temperature and CO_2 combinations than those considered here. In particular, it is possible to compute the frontier describing the minimum levels of CO_2 concentration increase requested to achieve a yield gain. Thus, based on model (1), a yield gain is expected when the CO_2 concentration increase exceeds the value calculated from

$$\frac{-1}{a_C + a_{CT}T_{ij}}\left(\mu_T T_{ij} + a_P P_{ij} + C_{ij} + a_{CT} C_{ij} T_{ij} + a_A I_{Aij}\right) \qquad (2)$$

Uncertainty was analyzed by computing 95% confidence intervals by bootstrap for all relevant quantities.

3. Results

In this section we present first the results of the marginal effects of changes in temperature, precipitation, CO_2 and adaptation (3.1) and then the combined effects of these factors (3.2).

3.1. Marginal effects of changes in temperature, precipitation, CO_2 and adaptation

The estimated values of the parameters μ_T, a_P, a_C, a_{CT}, and a_A respectively describe the marginal effects of temperature, precipitation, CO_2 concentration, CO_2-temperature interaction, and climate change adaptation. Each marginal effect quantifies the impact on yield of a unit increase in one of the factors taken individually, i.e., without taking the effect of the other factors into account (all set equal to zero). The estimated values of these effects are presented in Figures 2 and 3.

For temperature (Figure 2A), the estimated values range from -1.42% (for rice, C3) to -4.52% (for maize, C4) yield for an increase of +1°C. The overall estimate for all C3 crops is -2.40%. The estimated values are all significant ($p<0.05$) except for soybean where the estimated impact of temperature is highly uncertain.

For CO_2 (Figure 2B), the effect of an increase of +1ppm is significant and positive in all cases, but is significantly lower for maize (C4) (+0.02% yield per ppm, or 2% for 100 ppm) than for C3 crops. In average over all C3, the effect is about +9% for +100ppm (+0.09 per ppm). The interaction between temperature and CO_2 is significant for rice (Figure 2C). This interaction is negative, indicating that the positive effect of CO_2 is hampered by temperature increases. For example, this interaction induces an additional rice yield decrease of -0.02% for +1ppm and +1°C or, equivalently, -2% for +100ppm and +1°C.

The effect of a 1% increase in growing season cumulated rainfall on crop yield is significant and positive for the group of C3 crops (+0.27%), as well as for wheat (+0.43%) and soybean (+0.32%) separately (Figure 2D). For maize, this effect is close to zero and not significant, partly because maize is either cultivated in regions exhibiting rainy growing seasons or irrigated by default in most of the selected studies. For rice, the uncertainty is high and does not allow to robustly conclude.

The effect of adaptation (all types of adaptation combined) (Figure 3) is significant when all C3 crops are analyzed simultaneously (+7.25%) and for wheat (+10.4%). The effect is close to zero for maize. For rice and soybean, the results are very uncertain and do not allows us to conclude.

3.2. Estimation of the combined effect of temperature and CO_2 changes

The model (1) was used to estimate the effects of different combinations of temperature and CO_2 concentration increases, with/without adaptation, and with/without a decrease in precipitation for all C3 crops altogether (Figures 4 and 5). Without adaptation, significant C3 yield gains of +5.1 to +7.8% (depending on whether rainfall is reduced or not) are obtained when the temperature increase is limited to +2°C and associated with a +200ppm increase in CO_2 (Figure 4A,B). On the other hand, yield losses ranging from -5.1 to -12.2% are estimated in case of a temperature increase of +4°C combined with a 10% decrease in precipitation (Figure 4B).

For C3, the increase in CO_2 has a positive effect on yield, but this positive effect could be partly offset by stronger temperature increase (Figure 5). This is due to the interaction between temperature and CO_2, estimated at -0.01% for +1°C and +1ppm for all C3 crops combined (Figure 2). When temperature increase reaches +4°C, the interaction effect equals -0.04% and partially compensates for the positive CO_2 effect estimated for C3 at +0.09% per ppm. Thus, the level of yield increase due to the positive effect of CO_2 on photosynthesis is smaller at +4°C than at +2°C (Figure 5).

As we said before, adaptation could have a strong effect on yields (+7.25% for C3 in Figure 3). The effect of a +2 and +3°C temperature increase combined with respectively a +100 and +200ppm CO_2 concentration increase become positive and significantly different from zero when adaptation is considered and assuming no or small rainfall decrease (Figure 4C compared to 4A and 4D compared to 4B).

The selected statistical model for maize (C4) includes a temperature effect and a CO_2 effect, but no precipitation effect, interaction or adaptation (not significant, see Figures 2-3). The absence of effect of precipitation on maize yields is unexpected and could be due to the limited number of scenarios considering water stress in our dataset. For this crop, the combined effect of temperature and CO_2 increases is systematically negative; estimated yield losses range from -4.6% to -17.3% depending on the scenario considered (Figure 6). The estimated losses for +4°C systematically exceed -13% but the levels of uncertainty obtained for this temperature increase are high and significantly higher than those obtained for +2 and +3°C.

For wheat (C3), the selected model includes all the effects of model (1) except the temperature/CO_2 interaction which is not significant (Figure 2). When there is no adaptation, the temperature increase is associated with significant yield gains if the CO_2 increase exceeds 200ppm, but it can lead to yield losses when the CO_2 increase is lower (Figure 7AB). Losses are higher in the event of a 10% decrease in rainfall, but despite the negative effect of a rainfall decrease, the yield loss for wheat is not statistically significant when combined with an increase of +4°C and 200ppm of CO_2 (Figure 7B). When an adaptation strategy is applied, no significant yield loss is estimated for wheat, with the only exception of a – physically unlikely - situation corresponding to a temperature increase of +4°C but without any CO_2 increase (Figure 7CD). For a CO_2 increase of +200ppm associated with a temperature increase of +4°C, a yield gain of 9 to 13% is estimated for wheat if adapted.

Based on the fitted maize and wheat models, we computed the minimum levels of CO_2 increase requested to obtain a positive yield change (yield gain) for +0 to +6°C (Figure 8) and we determined frontiers of CO_2 increase level above (below) which a yield gain (loss) is more likely than not (Eq.2). Here, we assume that no adaptation strategy is applied. Results show that the CO_2 frontier obtained for maize is well above the one obtained for wheat. Thus, at +2°C, an increase in CO_2 concentration of more than +300 ppm would be necessary to obtain a yield gain in maize crops. But, for wheat without adaptation, a yield gain is expected as soon as the CO_2 concentration increases by +50ppm at +2°C and by +150ppm at +4°C (Figure 8). The frontier is even lower for wheat in case of adaptation (not shown).

For soybean (C3), the selected model includes temperature, CO_2 and precipitation effects, but no adaptation or temperature/CO_2 interaction effects (no significant effect at 5%, see Figures 2-3). The estimates obtained are quite similar to those obtained for wheat without adaptation with slightly lower losses and slightly stronger gains for the same temperature and CO_2 combinations (Figure 9). For CO_2 increases of +200ppm, the estimated yield gain exceeds 10% for +2°C, even if precipitation decreases by 10%. The gain also exceeds 10% for a temperature increase of +3°C if rainfall is not reduced. On the other hand, soybean yield gain becomes not statistically significant at +4°C (Figure 9).

For rice (C3), the selected model includes temperature, CO_2, temperature/CO_2 interaction and adaptation effects, but no precipitation effect (non-significant effect, see Figure 2). Without adaptation, yield losses of -3 to -5% are estimated for a temperature increase of +4°C, but a yield gain is estimated when CO_2 increases by +100 ppm and temperature increases by +2°C (Figure 10A). A slight gain is also estimated if temperature increases by +3°C and CO_2 by +200 ppm. With adaptation, no significant yield loss is estimated for temperature increases less than or equal to +4°C; yield gains can even reach 15% if the temperature only increases by +2°C and the CO_2 content increases by +200ppm or more (Figure 10B).

4. Discussion

The difference in CO_2 yield response between C3 and C4 plants is consistent with known photosynthesis mechanisms. C4 plants (e.g., maize, sorghum, millet, and sugar cane) have a mechanism for supplying CO_2 to leaf sites where it is fixed on sugars and it is therefore the concentration of photosynthetic enzymes that limits photosynthesis and not the concentration of CO_2. Their photosynthesis rate hence does not strongly respond to CO_2 variations at values higher than current concentration levels. On the contrary, under optimal growing conditions, C3 plants do not have these concentration processes in the leaf and are instead limited by atmospheric CO_2 concentration (Ainsworth 2008, Gao et al 2015). However, to benefit from the positive effect of increasing CO_2 concentrations, C3 plants require a concomitant increase in nitrogen supply from the soil (Weigel and Manderscheid 2012, Manderscheid et al 2010). If nitrogen supplies are not adjusted, then the positive impact of CO_2 increase is reduced (Lakshmi et al 2017), except for leguminous plants that use part of the photosynthesized sugars to feed their nitrogen fixing symbionts (Li et al 2017, Matsunami et al, 2009, Oikawa et al 2010). In addition, for C3 crops and in particular for rice, we found a negative interaction between CO_2 and temperature change revealing that the positive effect of CO_2 on yield is partly offset by an increase in temperature. For rice, the negative interaction between temperature and CO_2 may come from the fact that the increase in CO_2 itself generates a temperature increase in the rice vegetation cover (Li et al.

2015). The divergent effects of CO_2 between C3 and C4 estimated in our study are consistent with the results of Webber et al. (2018) who indicated that climate change could result in yield losses for grain maize but gains for winter wheat.

The ability of adaptation strategies to mitigate the potential negative impact of climate change is discussed in a number of published studies (Challinor et al., 2014; Li and Troy, 2018; Lipper et al., 2014; Wilcox and Makowski, 2014). The strong effect of adaptation that we found on wheat yields is partly due to the meta-analysis of Challinor et al (2014) which reports a high estimated value for this parameter. Irrigation (when allowed by local water availability) is a direct way to protect against climate change induced droughts (Li and Troy 2018). However, irrigation can increase greenhouse gas emissions through energy use, creating a negative feedback on the long term (Lipper et al. 2014). In addition, water availability and water quality (e.g. salinization) are expected to decrease in some areas. An increase in the quantity of water used for irrigation can also generate water use conflicts, e.g., as in California (Grantham and Viers 2014). Its use can be improved by more efficient technologies such as precision irrigation and more efficient deficit irrigation strategies (Wolfe et al. 2018).

Varietal improvement is another adaptation strategy and mostly relies on the use of earlier or later varieties, the modification of the photoperiod (Olesen et al. 2011) or, more rarely, the use of drought-tolerant varieties (Nuccio et al. 2018). Farmers can also adapt to climate change by changing sowing dates, harvesting dates or plant density without necessarily changing the varieties themselves (Caubel et al. 2018). These types of adaptation can be already observed in many parts of the world, for example for French vines with increasingly early harvest dates (Webb et al. 2012, Jones et al. 2005) and for maize in central United States with increasingly early planting dates (Kucharik 2008).

The effectiveness of a few adaptation strategies has been assessed in previous studies (Basso et al. 2015, Challinor et al. 2014, Wilcox and Makowski 2014), including changes in sowing dates, crop varieties or irrigation. The results of these studies show that these strategies partially offset the negative impacts of climate change on crop yields. Other more systemic adaptation strategies exist; they are based on profound changes in agricultural systems e.g., adoption of soil conservation systems (Powlson et al. 2016) or systems based on agroforestry (Verchot et al. 2007), changes in the composition of rotations or substitution between species (Olesen et al. 2011).

It is important to keep in mind that the effectiveness of these strategies depends on the socio-economic context, and may present heterogeneous results at the global level (Hoegh-Guldberg et al. 2018). In modeling studies, adaptation strategies are tested under optimal conditions, and simulated benefits should thus be considered as potential. Practical or social constraints could reduce the effectiveness of adaptation strategies such as irrigation, and could limit farmers' ability to obtain high yields in the future. Also, extreme weather events and development of pests and diseases induced by climate change could reduce the expected benefit of adaptation strategies (Gouache et al., 2013; Webber et al., 2018).

Our approach has several limitations. We present here only a single global statistical model for each crop species, without any regional differentiation. We attempted to fit our statistical models for each continent separately, but the confidence intervals were very large and the estimated values were not informative. Note that our global statistical models could nevertheless be implemented regionally using regional climate data as inputs. Spatialized yield gain/loss resulting from climate change are available in a number of published reports but these studies usually rely on a small number of model outputs. For example, the report of the Joint Research Center (Donatelli et al., 2012) assesses the effects of several climate change scenarios on maize, wheat, rice, rape and sunflower yields in Europe. Some of their results have been taken up and completed in Donatelli et al (2015). This study was carried out both at national level and at the level of NUTS2 regions for all countries of the European Union. Two climate models HadCM3 ("warm scenario") and ECHAM5 ("cold scenario") were used, but only one crop model (BIOMA) was run. No adaptation strategy was considered. Yield projections were made at time horizons close to 2020 (+45ppm CO2) and 2030 (+65ppm CO_2) compared to a reference period corresponding to 1996-2005. For maize, yield simulations indicate a gain of +10% and a loss of -9% for the "cold" and "warm" scenarios, respectively. Apart from sunflower, the average losses are therefore somewhat low, and close to zero for maize and rice, -1% for wheat and -2.5% for rapeseed. These average values are close to those obtained for the +2°C and +100ppm CO_2 scenario for wheat and rice in our own study. However, these averages hide significant regional disparities within Europe.

Another limit of our study is that it covers a limited number of crop species. Only four major crop species are indeed considered here, namely wheat, maize, soybean, and rice. Some previous studies assessing climate change impacts consider a higher number of crop species, but others studies present aggregated results for large groups of crop species. For example, in the report by Müller et al (2010), yield projections are performed on average over a wide range of crops (wheat, rice, maize, millet, millet, peas, sugar beet, sweet potato, soya, groundnut, sunflower, rape) but simulated yields are averaged over all species and are not presented crop by crop. The results obtained for C3 and C4 plants are therefore not presented separately in this report. About thirty climate scenarios are considered and yields are simulated with the LPJmL model directly at the global scale. Two series of simulations are carried out successively, first without any effect on yields of CO_2 concentration increase, and then taking its effect into account. With CO_2 effect, the results show an average yield gain of 12.4% worldwide. On the other hand, without CO_2 effect, an average loss of -6.5% was estimated. This result is consistent with the strong positive effects of CO_2 on the yields estimated in our study for C3 plants.

In our analysis, the effects of temperature, precipitation and CO_2 on crop yields are calculated for a large variety of soil types in different geographical areas. Yield variations presented in our study should therefore be interpreted as average responses and it is important to keep in mind that local values of these responses may be significantly different from the average values under particular soil conditions (Kersebaum and Nendel, 2014). This is particularly true for yield response to precipitation, which is known to be dependent on initial soil water conditions, soil water holding capacity and on plant rooting depth (He and Wang, 2019) and may hence differ from aggregate values across several soil types (Lobell and Burke 2010). It has been shown that the local sensitivity of yields to changes in precipitation may differ from aggregate values across several soil types (Lobell and Burke 2010). In addition, in our study, we were unable to explore in detail the effect of rainfall changes on maize and rice yields due to the limited number of scenarios considering rainfall changes for these two crops. For rice and maize, the uncertainty is high and does not allow for robust conclusions on the effect of rainfall changes on yields.

Our approach does not directly quantify yield losses due to pests and diseases. However, the effects of climate variables on pests and diseases are multiple and are difficult to estimate. Relative air and soil humidity impact the survival and reproduction of pests and diseases

(Roos et al. 2011). Winter temperatures can have a significant impact on the survival of pathogens and insect pests (Gouache et al. 2013, Bale et al. 2002, Roos et al. 2011). Additional effects on the spatial distribution of insect populations cannot be ruled out (Bale et al. 2002). Recently, it has been shown that climate change could strongly impact the level of crop destruction by insects (between 10 and 25% additional losses for wheat, maize and rice per degree Celsius of warming) via an effect of temperature on insect metabolism (Deutsch et al. 2018).

Despite these limitations, we were able to establish simple analytical functions quantifying the individual and combined effect of temperature, CO_2, precipitation and adaptation of practices on yields of several major crop species. Our results show that it is not reasonable to overlook the effect of CO_2 on yields when studying the effect of climate change on crop production. Yet, this effect was disregarded in several recent articles (Zhao et al. 2017a,b) and reports (FAO, 2018). Thus, FAO (2018) estimates the impacts of climate change on the yields of different types of crops by 2050 at a global scale. The estimated impacts are derived from FAO-IIASA GAEZ simulations obtained using a set of climate data from five different climate models. RCP scenarios 4.5, 6 and 8.5 were considered successively and these scenarios correspond to temperature increases of about 2.5, 3.5 and 4.5°C respectively. The results of these models suggest that climate change will mainly have negative impacts on yields, with reductions of about 5% globally by 2050 compared to 2012 for all crops combined. According to this report, the effect of climate change is negative on wheat yields, including in Europe. However, it is important to note that these results were obtained while neglecting the CO_2 effect, which has a positive effect on yields, particularly on wheat yields, as shown in our study. We believe that our simple models could be used in future foresight studies to take CO_2 effect on crop yields into account.

5. Conclusion

Our work is based on a quantitative synthesis of a wide range of studies assessing the impact of climate change on crop yields and could be relevant for future foresight studies on climate change.

For C3 plants, our results show that the positive effects of adaptation (+7.25% for all C3) and CO_2 (+9% for +100ppm for all C3) are high enough to offset the negative effects of a temperature increase, even at +4°C (-2.4% for +1°C). On the other hand, for maize (the only C4 plant represented in our database), the low positive effect of CO_2 and the absence of significant effect of adaptation strategies lead to yield losses, in the order of -10% for +4°C. Our results thus clearly demonstrate that effect of CO_2 should not be overlooked when studying climate change impacts on crop yields.

Our analysis also highlights the need for more reliable estimates of the effects of key factors influencing crop yields, in particular of climate change adaptation strategies. The effects of adaptation are somewhat uncertain, especially for soybean and rice, but also for maize, where the absence of a significant adaptation effect is probably at least partly due to the limited data available. The mechanisms underlying the interaction between temperature and CO_2 should also be studied more precisely, in particular for rice, a crop for which this interaction is significant.

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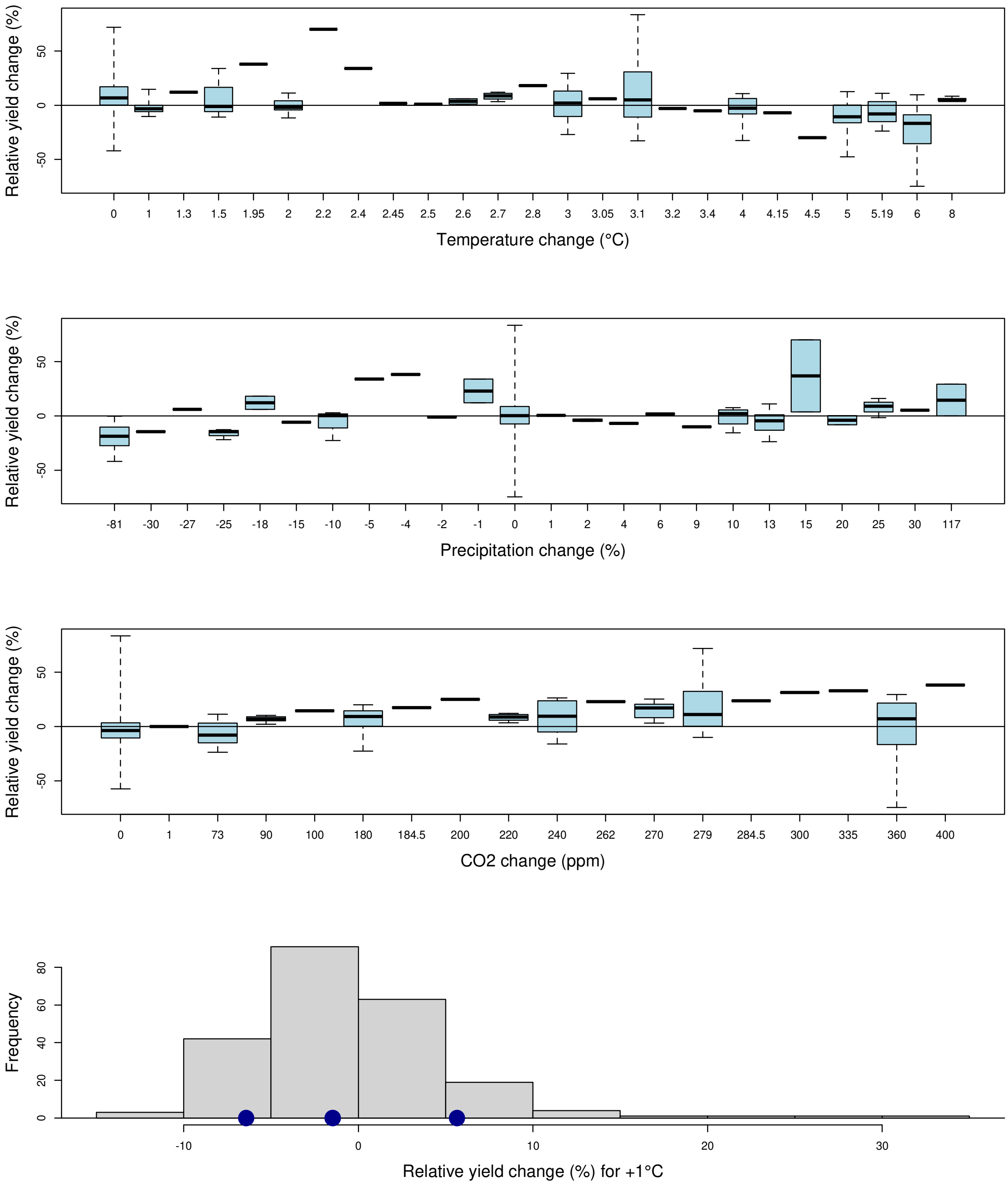

Figure 1. Data from the literature. Relative change of yield (%) as a function of a temperature increase from 0 to +8°C, a change in precipitation from about -100 to +100%, an increase in CO2 concentration up to +400ppm compared to the reference period considered in the studies. Each box describes the minimum, 1st quartile, median, 3rd quartile, and maximum values determined through all available data. When only one data is available, it is indicated by a horizontal black dash. Low: distribution of relative yield changes for +1°C, median and quartiles of the distribution (blue dots).

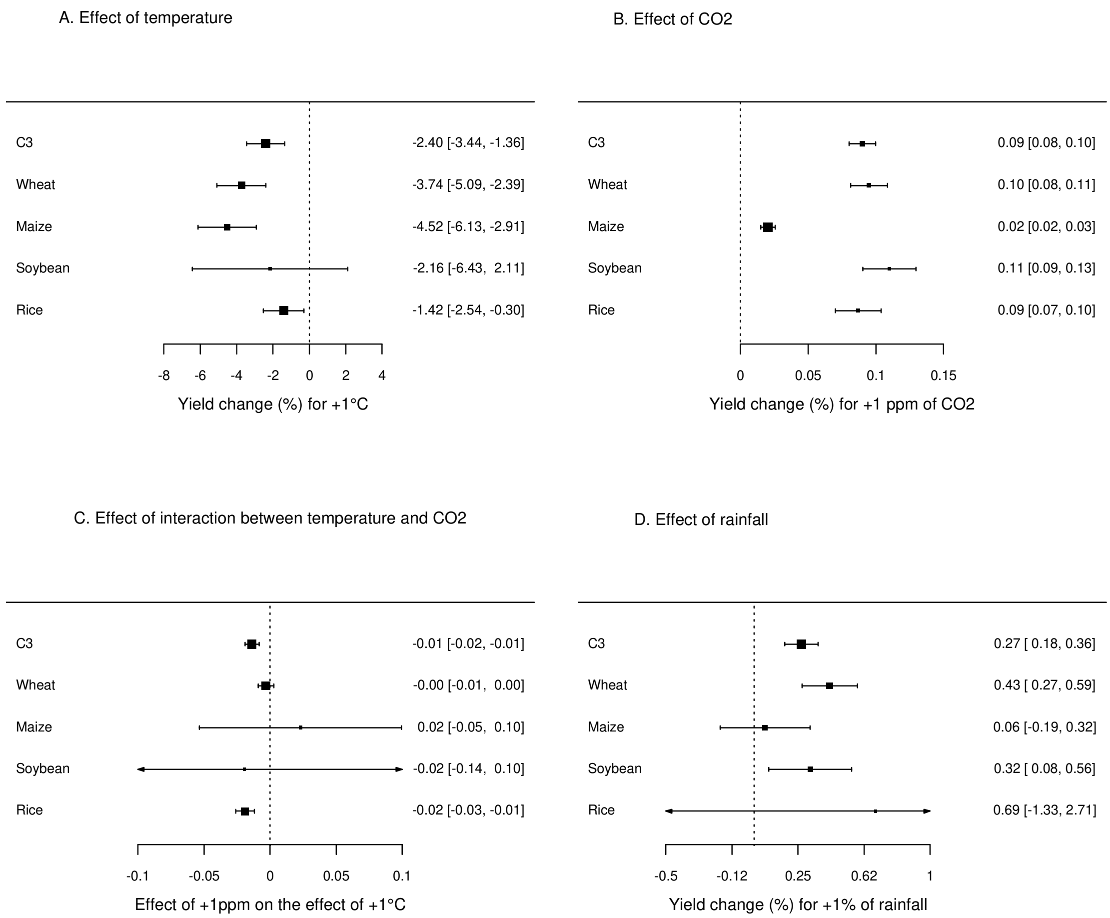

Figure 2. Marginal effects (regardless of the level of adaptation) on yield of temperature (A), CO_2 (B), temperature-CO_2 (C) interaction, and precipitation (D) for all C3 crops combined and for each major species (wheat, maize, soybean, rice). The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. Each estimated value is obtained by increasing the corresponding factor by one unit with all others set equal to zero. The size of the square is proportional to the accuracy of each estimate. Numerical values are presented on the right.

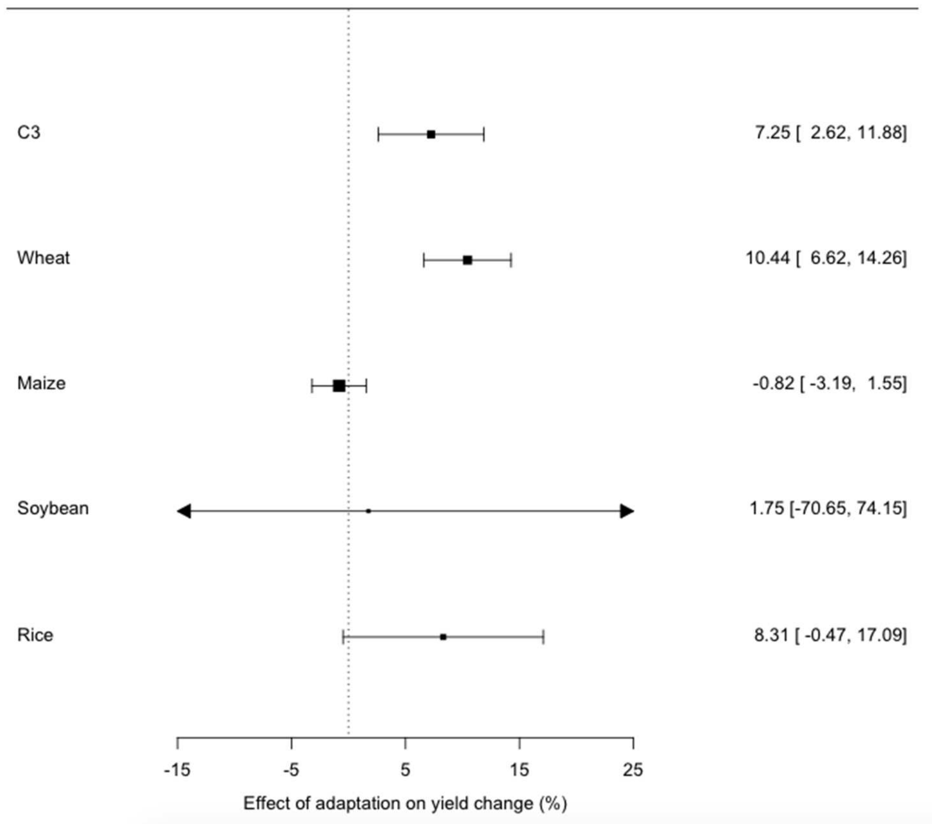

Figure 3. Estimated parameter values quantifying the effect of climate change adaptation on relative yield variation for all C3 crops combined, and for major species. The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right.

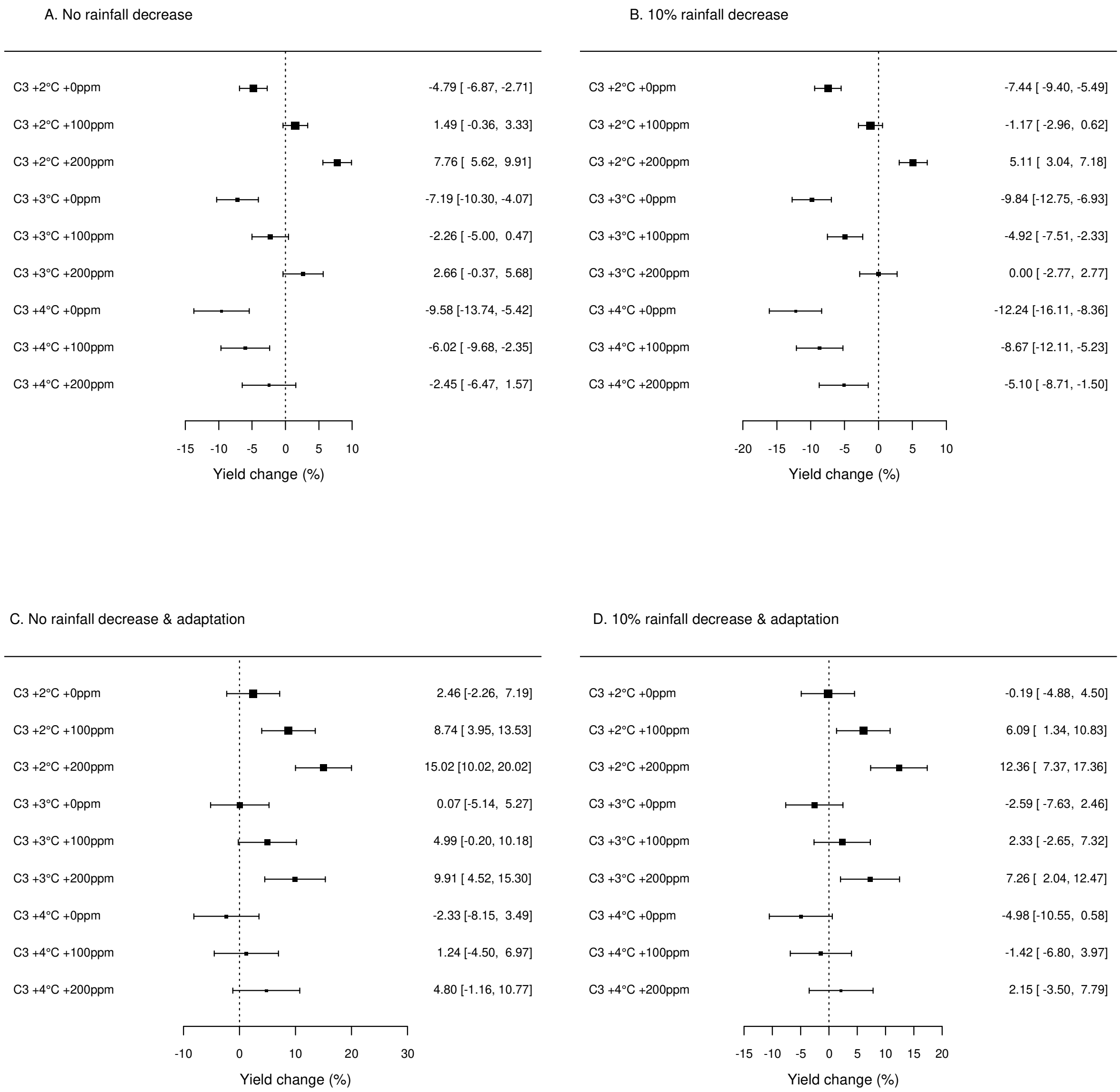

Figure 4. Combined effects of different levels of temperature (+2, +3, +4°C) and CO_2 concentration increase (+0, +100, +200ppm) on C3 crop yields. No decrease in precipitation and no adaptation (A), 10% decrease in precipitation without adaptation (B), no decrease in precipitation with adaptation (C), 10% decrease in precipitation with adaptation (D). The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right of the graphs.

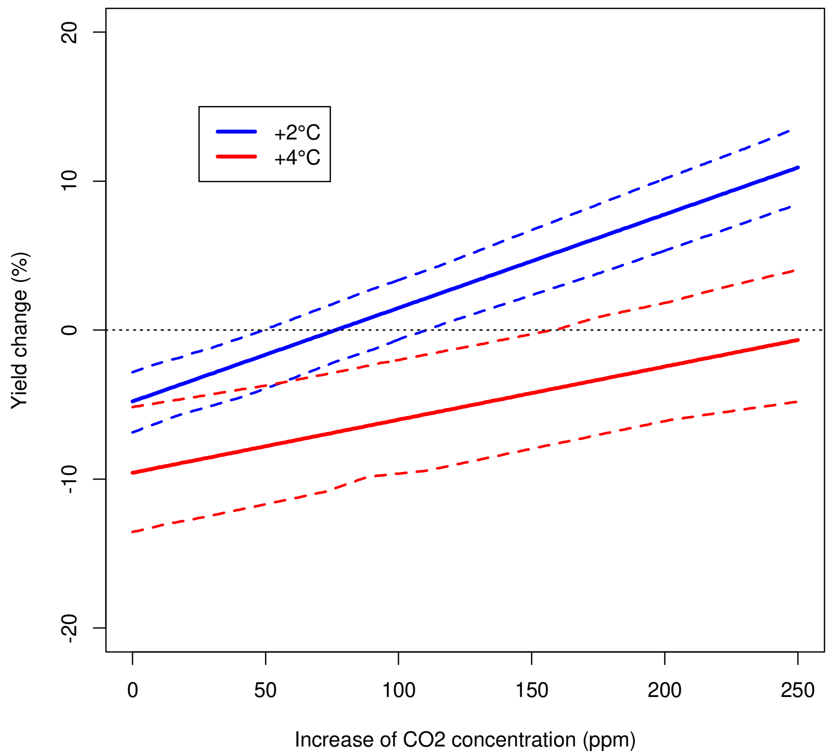

Figure 5. Response of the relative change in C3 crop yield to an increase in CO_2 concentration (+0 to +250ppm) for two levels of temperature increase (+2 or +4°C), without decrease in precipitation and without adaptation. The dashed lines represent the 95% confidence intervals. The effect of CO_2 is smaller for large temperature increases.

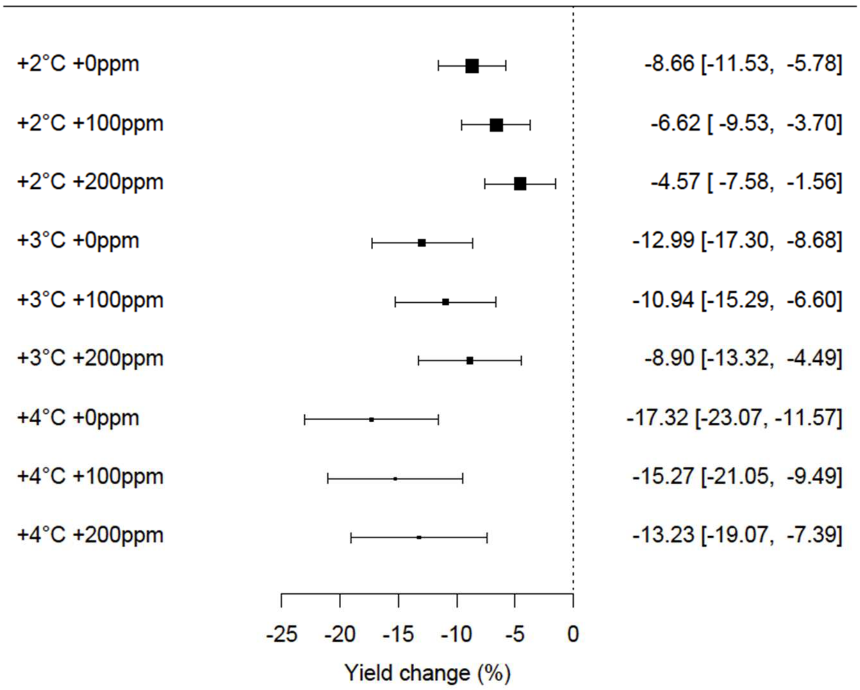

Figure 6. Effect of different levels of temperature and CO_2 concentration increase on maize yields. Note that some combinations are physically unlikely (e.g., an increase of +4°C for 0 ppm). The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right.

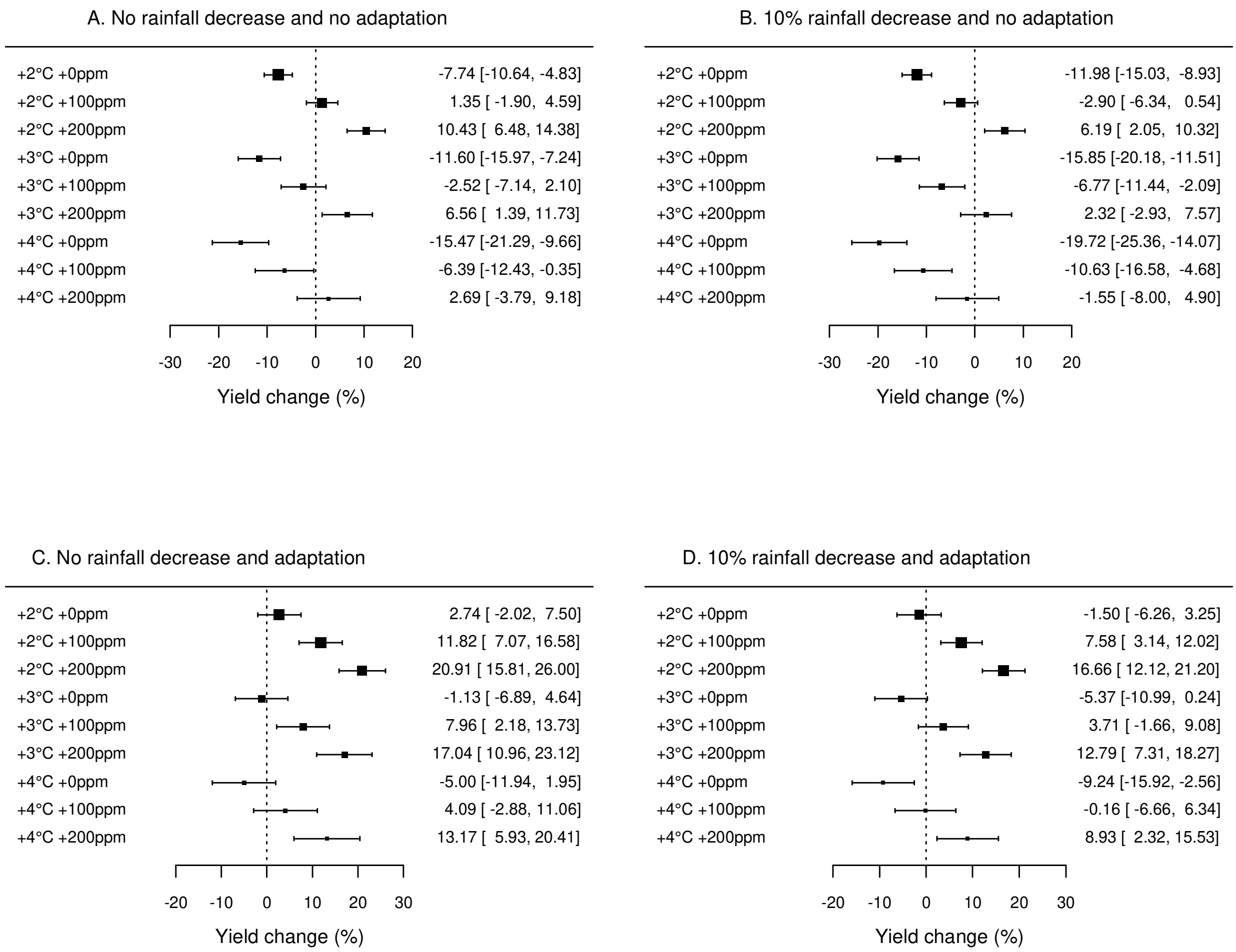

Figure 7. Effect of different levels of temperature increase (+2, +3, +4°C), CO_2 content (+0, +100, +200ppm) and precipitation on wheat yields. No decrease in precipitation and no adaptation (A), 10% decrease in precipitation without adaptation (B), no decrease in precipitation with adaptation (C), 10% decrease in precipitation with adaptation (D). The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right.

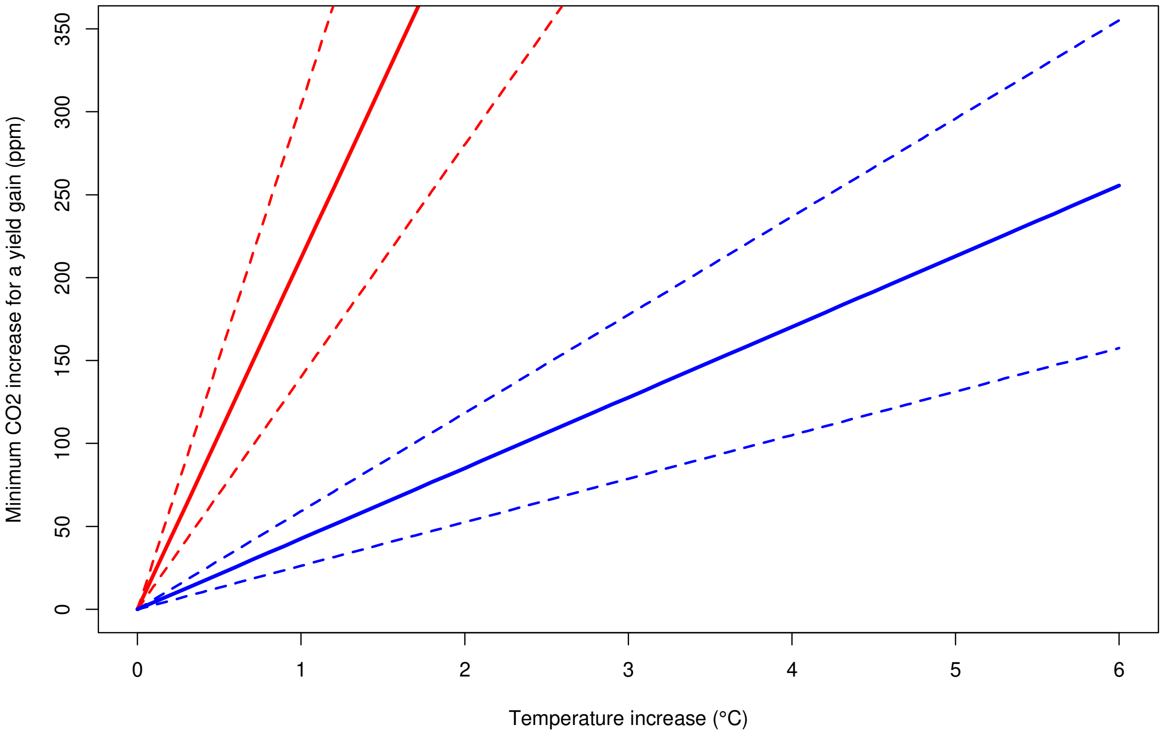

Figure 8. Frontiers of CO_2 increase levels above (below) which a yield gain (loss) is expected for wheat (blue) and maize (red). Dotted lines represent 95% confidence intervals.

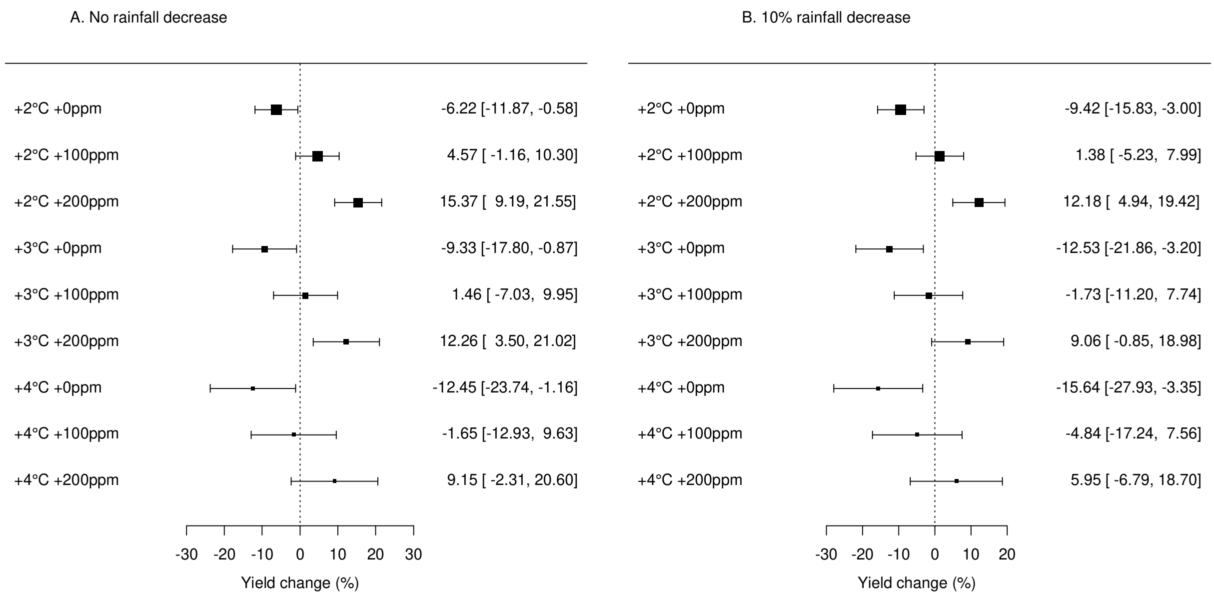

Figure 9. Effect of different levels of temperature increase (+2, +3, +4°C), CO_2 content (+0, +100, +200ppm) and precipitation on soybean yields. No decrease in precipitation (A), 10% decrease in precipitation (B). The effect of adaptation is not presented because it is not significant for the soybean model. The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right.

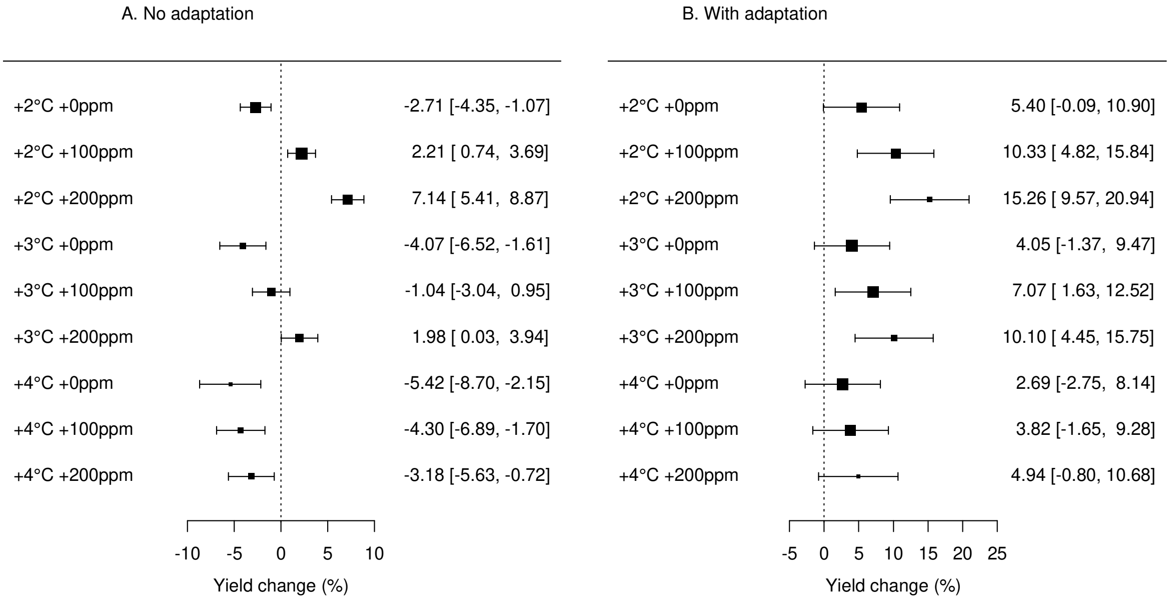

Figure 10. Effect on rice yield of different levels of temperature increase (+2, +3, +4°C), and CO_2 content (+0, +100, +200ppm) with and without adaptation. The effect of a change in precipitation is not presented here because it is not significant. The squares correspond to the estimated values and the horizontal bars represent the 95% confidence intervals. The size of the squares is proportional to the accuracy of the estimates. Numerical values are presented on the right.