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Publication Date

2022-12-01

DOI

10.1016/j.agrformet.2022.109230

Site-specific field management adaptation is key to feeding the world in the 21$^{\text{st}}$ century

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Abstract

Rapid climate change and growing population threaten global food security across the globe. Several studies have proposed early planting, increased irrigation, and increased fertilizer applications as climate adaptation strategies, yet none have considered combined and site-specific field management strategies as a comprehensive solution. Here, we analyzed non-irrigated wheat yield responses to climate change and field management adaptation using a mechanistic crop model evaluated against observed global non-irrigated wheat-yield over 3-year intervals spanning 13 years at 3,749 sites (RMSE=36 gC m^{-2}). Early planting with later-maturing varieties provided the most benefit to future yields among the proposed field management adaptation strategies. Improved water use efficiency from increased CO_2 led to relatively low benefits of additional irrigation. We estimated that spatially heterogeneous adaption strategies had the potential to improve global wheat yields by 91% by 2100 compared to the present day. The yield improvements from combined field adaptation strategies were larger than the sum of improvements from the individual strategies. These synergistic benefits were shown to result from complementary processes regulating nutrient and water uptake, physiological tolerance to heat stress, and internal carbon

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Preprint submitted to Agricultural and Forest Meteorology *September 22, 2022*

and nutrient cycling.

Keywords: Wheat, Yield, Climate change, Adaptation

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1. Introduction

Ensuring global food security is one of the most significant challenges facing humanity in the 21$^{\text{st}}$ century, owing to ongoing climate change and rapid human population growth (Gerland et al., 2014). Population growth, accompanied by a spread of prosperity to developing countries (dietary changes from plant-based food to animal-based food, requiring more livestock feed), lead to a rapidly growing demand for crop production (Bodirsky et al., 2015; Shepon et al., 2018). In particular, the world's supply of grain needs to approximately double by the 2050s to avoid potential food shortages (Alexandratos and Bruinsma, 2012). Among cereal grain crops (e.g., rice, wheat, maize, millet, and sorghum), wheat is the most widely consumed (McWilliam, 2012), a primary source of protein in developing countries (Braun et al., 2000), and an alternative livestock feed in regions where stable yields of maize cannot be achieved (Shiferaw et al., 2013). However, despite its essential role in providing human nutrition, wheat production is currently challenged. Expected 21$^{\text{st}}$ century changes in regional precipitation, temperature, and drought due to climate change increase the uncertainty in projecting and improving wheat yields.

Several studies (Morison, 1998; Drake et al., 1997; Xu et al., 2016) found that increases in atmospheric CO_2 resulted in enhanced rates of photosynthesis and reduced stomatal opening, especially for C3 plants, such as wheat. The increased CO_2-induced stomatal response improves drought tolerance without a penalty to CO_2 assimilation. However, elevated CO_2 concentrations would also lead to deterioration of wheat grain quality and reduced yields under nutrient limititations (Kimball et al., 2001; Ainsworth and Long, 2005). Warming can negatively affect wheat yields due to heat stress. Akter and Islam (2017) reported that warming could reduce grain number and size by disturbing assimilate supply and shortening the duration of grain filling. However, Xiao et al. (2010) found that, based on a field experiment, the increased temperature would improve wheat yields by advancing grain filling stages to more favorable seasons (cooler and wetter periods). Changes in precipitation patterns undoubtedly affect wheat yields based on the availability of soil water during wheat development cycles (Heng et al., 2007). Summarizing, these observational studies indicate that wheat yield responses to climate change are highly heterogeneous across different geographic regions and meteorological conditions.

The rate of climate change now exceeds the worst-case climate scenario (Christensen et al., 2018), Representative Concentration Pathway 8.5 (RCP8.5), included as part of the last Intergovernmental Panel on Climate Change report (van Vuuren et al., 2011). Although world governments have set a much lower goal for warming (UNFCCC, 2015), risks to 21^{st} century food production remain large. Accordingly, studies investigating the impacts of climate change on wheat production and adaptation strategies are increasingly important for global food security. Recent studies have explored several factors expected to affect global wheat production, including (i) CO_2 fertilization (Allen et al., 2020), (ii) warming (Asseng et al., 2015; Zhao et al., 2017), (iii) early planting (Hunt et al., 2019), (iv) growing season management (Iizumi et al., 2019; Minoli et al., 2019a,b), and (v) agricultural input intensifications (Liu et al., 2018; Muller et al., 2018). Impacts of changes in climate patterns on wheat yields have been examined at the site level, focusing on site-specific management and design practices (e.g. Ainsworth and Long (2005)).

In this study, we build on these results by further evaluating a well-tested mechanistic crop model (*ecosys*, Methods), demonstrating that the model accurately represents observed yields and observations from CO_2 enrichment studies and global observations over 3-year intervals spanning 13 years at 3,749 sites. We then used the model to explore climate and management effects on spatially-explicit 21$^{\mathrm{st}}$ century global wheat yields. *Ecosys* is an appropriate model for our study because it mechanistically links phenological stage transitions, gross and net primary production, soil N and P biogeochemistry, and plant and soil thermal and hydrological processes (Grant et al., 1999, 2011), thereby allowing elucidation of the complex set of processes affecting yield responses to climate change. The overall objective of this study is to analyze management adaption strategies commonly proposed to improve crop yields under climate change, including planting date with later-maturing varieties, irrigation, and fertilizer application (Lobell et al., 2011; Adams et al., 1990; Rosenzweig and Parry, 1994; Elliott et al., 2014; Asseng et al., 2015).

2. Materials and Methods

2.1. Model

Fodor et al. (2017) classified existing crop models into four major groups: (1) environmental index-based, (2) statistical, (3) niche-based, and (4) process-based models. The level of complexity incorporated into process-based models has important implications for the interpretation of modeled projections. While the discussion of whether a model inter-comparison approach or a single model analysis with uncertainty estimates is superior will likely continue in the literature, we argue here that both approaches can help to improve scientific understanding of the relevant processes and predictability of crop growth. In this context, we chose *ecosys* because of (1) its reasonable level of soil and plant module complexity; (2) its ability to mechanistically couple above- and below-ground processes for whole system C, N, and P cycle projections; and (3) its long-published record of accurately projecting agricultural and natural ecosystem C, N, and P dynamics. In this study, we did not modify the well-tested model but applied it to 3,749 globally-distributed sites. A detailed description of the model, including field managements, equations, and parameters is provided in the Supplemental Information. The model has been applied in more than 100 peer-reviewed publications, including analyses in agricultural systems (Grant et al., 1999, 2011; Webber et al., 2017; Woo et al., 2019), and has been shown to accurately represent many of the features of these systems analyzed here.

2.2. Climate change adaptation strategies

We implemented acclimation by adjusting the model's temperature sensitivity functions, which are based on Arrhenius functions modified for low- and high-temperature effects (Grant, 2015). The temperature sensitivity functions were shifted upward by 0.3°C per 1°C mean annual temperature increase. Earlier planting was simulated to evaluate synergistic effects with later-maturing varieties and reduce water-limited conditions due to rising temperature (He et al., 2015; Cann et al., 2020). We also considered irrigation as an adaptation strategy to offset drought stress. That is, when soil moisture dropped below the wilting point during growing periods, the difference in soil water content between field capacity and wilting point (i.e., water holding capacity) was applied to the soil as a precision agricultural practice.

2.3. Simulation design and model evaluation

Observed wheat yield, climate, soil, and field management data used in this study are described in Supplementary Information. We considered five years of spin-up periods prior to diagnosis years to reduce computational costs without considerably decreasing the reliability of modeled ecohydrological and biogeochemical dynamics. Model evaluations were performed using the Spatial Production Allocation Model (SPAM, IFPRI (2016, 2019a,b)) dataset. This dataset provided the 1991-2001, 2004-2006, and 2009-2011 average wheat yields, which were hereafter referred to as 2000, 2005, and 2010 observed wheat yields, respectively. We used (i) 2000 and 2005 observed yield data and (ii) early and late harvest dates to explore wheat varieties grown in non-irrigated wheat areas. Eight phenology, morphology, and water-uptake relevant parameters (see Table 1) were chosen based on previous studies (Casadebaig et al., 2016; Zhao et al., 2014). However, since there are hundreds of distinct local wheat varieties around the world (Kenneth and Conee, 2020), we acknowledge this range of parameter values cannot capture the specific wheat cultivar planted at each of the 3,749 gridcells. However, the good comparison between simulated and observed grain yields gives confidence in the model's ability to capture the dominant variability present in the observations. Quasi-random (Sobol) sampling was performed to generate 1,000 virtual crops with the parameters by restricting their ranges based on prior knowledge of wheat varieties. In addition, instead of specifying harvesting dates, we allowed the model to harvest wheat a week after grains were fully ripened to assess growing periods. Then, modeled results were evaluated with observed 2000 and 2005 wheat yields using the root-mean-square error and harvest-date ranges, by which wheat varieties were constructed for each grid. The resulting varieties were then validated with an independent dataset (i.e., 2010 non-irrigated observed wheat yields). We used the normalized standard deviation of yields from 2001 to 2010 to explore parameter uncertainty (Fig. S1). Former Soviet Union, East Asia, and South and South-East Asia regions had the highest uncertainty for modeled yields. These results imply that more yield measurements in these regions could improve global wheat yield projections. These numerical experiments did not consider diseases or weeds, and therefore should be considered as being conducted in well-managed areas. A modeled global projection for averaged wheat yields from 2000 to 2010 is provided in

Table 1: Parameters and their ranges of values used to train *ecosys*. Parameters were chosen based on previous wheat studies (Casadebaig et al., 2016; Zhao et al., 2014; Woo et al., 2020; Grant, 1998, 2013; Grant et al., 2011). Note that seed parameters determine grain potential, not actual grain yields that are determined by CO_2 fixation and allocation during wheat growths. Therefore, actual yields may be smaller than grain potential.

Parameters and descriptions	Range of values
Maximum osmotic potential (MPa)	-4 to -0.6[a]
Shape parameter for stomatal resistance	-8 to -4[b]
Cuticular Rresistance (s m^{-1})	250 to 5000[c]
Potential rate of kernel filling (gC kernel h^{-1})	0.4×10^{-5} to 0.2×10^{-2}[d]
Potential grain kernel mass (gC)	0.01 to 0.06[e]
Potential number of grain kernels per fruiting site	3 to 9
Potential number of fruiting sites per reproductive node	5 to 15
Plant maturity group	5 to 9[b]

[a] Katerji et al. (2005); Schleiff (2005)
[b] Grant et al. (2011)
[c] Jefferson et al. (1989); Stella et al. (2013)
[d] Gbegbelegbe et al. (2017); Zhao et al. (2014)
[e] Arduini et al. (2009); Mitchell et al. (2013); Banowetz et al. (2002); Zhao et al. (2014)

Fig. S2. Because model evaluation is critically important given crop model parameter and structural uncertainty (Xiong et al., 2019), we also evaluated model simulations against a meta-anlaysis of crop CO_2 enrichment studies, focusing in particular on relationships between grain number changes and yields.

After model evaluation, we forced the model with 21st century projections of spatially-explicit drivers (i.e., CO_2, temperature, and precipitation) from the Coupled Model Intercomparison Project 5 (CMIP5) RCP8.5 for the period 2081–2100 (i.e., end-of-century; Methods). We considered seasonal changes in precipitation and temperature (Fig. S3) and atmospheric CO_2 concentration as compared to the baseline (i.e., present-day; 1991-2010) scenario. We evaluated separately (RCP8.5-T, RCP8.5-P, RCP8.5-CO_2) and in combination (RCP8.5) the effects of temperature (T), precipitation (P), CO_2 concentration, and management on non-irrigated wheat yields to explore climate adaptation strategies needed to meet growing food demands in the coming decades (Table 2). Since non-irrigated wheat agriculture accounts for about 63% of wheat area (IFPRI,

Table 2: Climate change and adaptation scenarios used in this study. Changes in seasonal precipitation and mimium and maximum temperature were obtained by comparisons between the 2090s (2081-2100) and recent years (1991-2010). RCP8.5 was used for the 21st century projections.

Scenarios	Description
Climate change scenarios	
RCP8.5-T	Temperature change only
RCP8.5-P	Precipitation change only
RCP8.5-CO_2	CO_2 change only
RCP8.5	All together
Climate adaptation scenarios	
RCP8.5+E	Early planting with later-maturing varieties under RCP8.5
RCP8.5+I	Irrigation under RCP8.5
RCP8.5+F	Fertilizer under RCP8.5
RCP8.5+EIF	All together

2019a, 2016, 2019b), our results are relevant to an assessment of global wheat production.

3. Results

3.1. Wheat yield projection under RCP8.5

To accurately represent the phenological and physiological dynamics of different global wheat varieties, we trained eight *ecosys* parameters (Methods; Table 1) using observed 2000 and 2005 yields at at the 3,749 sites (RMSE=30 gC m^{-2}, Fig. 1a) and then validated the model against independent 2010 yield data (RMSE=45 gC m^{-2}). Overall, the model very accurately represented observed wheat yields (RMSE=36 gC m^{-2}), providing confidence in using the model as a tool for improved understanding and management practices. Previous studies have found that CO_2 fertilization effects on wheat yields could be explained by changes in grain numbers (Broberg et al., 2019). We therefore evaluated *ecosys* projections of these relationships across 3,749 simulated sites under 935 ppm CO_2 concentrations (i.e., RCP8.5 CO_2 levels at 2100) and found excellent agreement with results from two meta-anlayses (Ainsworth and Long, 2005; Broberg et al., 2019) (Pearson's r = 0.97, Fig 1b). However, although controversial, there may be good relationships between grain numbers and yields due to plant resource accumulation processes (Sinclair and Jamieson, 2006; Fischer, 2008; Sinclair and Jamieson, 2008). This observed and modeled agreement should thus be considered as ancillary model validation.

Using current cultivar representations and fertilizer application rates, our global results indicated that elevated CO_2 alone (RCP8.5-CO_2) generally stimulated photosynthesis in the presence of sufficient nitrogen and water-limited environments. We examine the effets of variations to these management strategies in Section 3.4. Specifically, at low ($< 33^{rd}$ percentile) fertilizer application rates, crop yields increased by 1.1 and 0.2% at 550 ppm and 935 ppm, respectively, compared to baseline CO_2 concentration (Fig. 1c). In contrast, at high fertilizer application rates ($> 66^{th}$ percentile), modeled yields increased by 9% and 13% at 550 ppm and 935 ppm, respectively. These modeled results were consistent with observations from Free-Air Carbon dioxide Enrichment (FACE) experiments (Ainsworth and Long, 2005), supporting our mechanistic model-based analysis.

Our results also showed, consistent with observations (Ainsworth and Long, 2005; Broberg et al., 2019), that decreased yields under elevated CO_2 in some gridcells were, in part, caused by N-limiting conditions (Fig. 1c) and reduced duration of pre-anthesis developmental resulting from increased leaf temperature (Fig. 2a). In contrast, some FACE studies have found increased wheat yields under N-limiting conditions, although in many of these experiments, what was characterized as low N inputs were larger than often applied commercially (Kimball, 2016). The modeled increased leaf temperature occurred because of partial stomatal closure in response to elevated CO_2 (Grant et al., 1999), which led to decreased transpiration and therefore decreased latent heat cooling.

An increase in global temperature of approximately 5°C for non-irrigated wheat areas was projected under RCP8.5 by 2081-2100 (Fig. S3). Although the consequences of global warming on wheat yields were dependant on local conditions (e.g., crop varieties, soil properties, and field managements), our results under current management and wheat varieties showed that more than 64% of wheat cultivation areas would experience yield decreases in response to changing temperatures alone (RCP8.5-T), resulting in a 5.5% global yield decrease compared to (simulated) baseline (Fig. 2b). This yield reduction was primarily explained by a substantial advance of mean anthesis date of 6 days per 1°C increase (Fig. S2). An average advancement in the anthesis date of 28 days was modeled from increased temperature alone at end-of-century. However, winter wheat cultivated at high latitude would benefit from warmer temperatures (Fig. 2b) through increased growth and hence grain numbers (Fig. S4), despite hastened development.

About 30% of non-irrigated wheat-growing areas were expected to experience less precipitation and increased risk of drought by the end of the 21^{st} century. Decreases in precipitation alone (RCP8.5-P), especially in Mediterranean and subtropical regions (Fig. S3), led to a 4% yield reduction per 1% precipitation decrease. We also found that non-irrigated wheat yields did not uniformly respond positively to increased precipitation in regions with more than 500 mm annual precipitation (Fig. 2c). Specifically, RCP8.5 precipitation changes alone would lead to a 4.1% reduction in global wheat yields compared to baseline. In wetter regions, this reduction was caused by a decrease in root O_2 concentrations, reducing root growth and thus nutrient uptake (Fig. S5).

Under RCP8.5 end-of-century climate forcing, which included changes in CO_2, temperature, and precipitation (RCP8.5) and no changes to cultivar properties and fertilizer amounts, we found a significant negative relationship between changes in local mean temperature and yields (slope of linear function=-5.65% $^\circ\mathrm{C}^{-1}$, Fig. 2d). This response occured because increased temperatures compressed the wheat pre-grain developmental stages and advanced anthesis dates by an average 29 days compared to baseline (Fig. 2a). Our results also showed that heat stress was a much more important regulator than precipitation in negatively affecting wheat yields with large differences between socioeconomic regions (Fig. 3). Therefore, earlier planting and later-maturing varieties may be essential for climate change adaptation, along with reduced nitrogen and water stresses as discussed above.

Our projected yield responses under RCP8.5 were comparable with results from the IPCC AR4 analysis below 2°C warming (Fig. 2d; i.e., small increases in non-irrigated wheat yields, Easterling et al. (2007)), but were more optimistic in areas with higher expected temperature changes (i.e., lower decreases in yields). Yield projections summarized in the AR4 were constructed using a wide range of future climate changes, including the 1992 IPCC Scenarios (IS92) and the Special Report on Emissions Scenarios (SRES). We found more extensive variations in positive and negative responses to climate change compared to the results summarized in the IPCC AR4, owing to our broader geographical coverage, higher RCP8.5 projected temperatures, and wheat varieties. In addition, we compared our results with the projections of temperature impacts on wheat yields in a recent study (dashed black line in Fig. 2d, Liu et al. (2016)). The slope for average reductions in wheat yields with 1°C global temperature increase projected by our study was consistent with that study. However, our projections were more optimistic than theirs due to the consideration of CO_2 fertilization effects.

3.2. *Implications of projected wheat yield*

Under current management and varieties, CO_2 fertilization alone increased wheat yields by 10% at the global scale (Fig. 4a, inset). Across the nine analyzed socio-economic regions, North America and the former Soviet Union were projected to have relatively low yield increases under enriched CO_2 compared to baseline (low fertilizer rates, Fig. S7). Only the Latin America and Caribbean region, representing 12% of global non-irrigated wheat areas, responded slightly positively to increased temperature alone (Fig. 4b, inset). High fertilizer application rates, especially in China, led to increased wheat yields under precipitation changes only, distinct from other socio-economic regions (Fig. 4c, inset, S7). Importantly, global wheat yields under RCP8.5 were expected to remain essentially unchanged compared to baseline ($< 2\%$ increase) by the end of the 21^{st} century, despite wide variations across socio-economic regions (Fig. 4d, inset).

3.3. *Sensitivity analysis of precipitation and temperature changs on wheat yield*

The magnitude of precipitation and temperature changes across different Global Climate Models (GCMs) is especially large for climate projections at the end of the 21^{st} century. To complement the results on wheat yields under climate change, we explored the impacts of individual projections of temperature and precipitation (i.e., 25^{th} and 75^{th} percentiles evaluated from 39 GCMs for each gridcell) on wheat yields (Fig. 5). These GCMs were used to develop average temperature change (RCP8.5-T), precipitation change (RCP8.5-P), and combined climate change (RCP8.5) scenarios.

We found that a relatively modest increase in temperature alone (global increase in mean temperature of 2.9°C for the case of the 25^{th} percentile temperature change (RCP8.5-T_{25}) and that of 5.0°C under RCP8.5-T) led to a

3.7% yield reduction (Fig. 5a, c, 5.0% yield reduction under RCP8.5-T compared to the baseline). On the other hand, the 75th percentile of temperature change only (RCP8.5-T_{75}) resulted in wheat yield reductions similar to the case under RCP8.5-T due to a negligible difference in global mean temperature increases between RCP8.5-T_{75} and RCP8.5-T (0.2°C, Fig. 5b, c). For the case of precipitation, we found that in areas with precipitation less than 600 mm y^{-1} under baseline conditions, the 25th percentile of precipitation change only (RCP8.5-P_{25}) resulted in decreases in wheat yields compared to the case of RCP8.5-P. The opposite was true for the 75th percentile of precipitation change only (RCP8.5-P_{75}). However, there were very small differences between projected yields under RCP8.5-P_{25} and RCP8.5-P_{75} in areas with precipitation more than 600 mm y^{-1} under the baseline. That is, projections of climate change impacts on wheat yields were highly uncertain especially for areas with precipitation less than 600 mm y^{-1} under baseline conditions due to GCM and scenario uncertainty.

3.4. Twenty-first century adaptation effects on wheat yields

There is no single panacea for mitigating negative impacts of climate change on the wheat productivity necessary to meet rapidly growing food demands. Therefore, we examined three recommended management adaptation techniques (early planting with later-maturing varieties (E), irrigation (I), and additional fertilizer application (F)) to identify the best region-specific combination of field management practices (Fig. 6a, b). Advanced anthesis dates were used as a criterion for exploring the effects of early planting accompanied by later-maturing varieties on wheat yields and thereby ensuring an extended growing season. When anthesis dates were advanced, we planted wheat the estimated advanced days earlier with later-maturing varieties. We estimated that approximately 68% of non-irrigated wheat areas would benefit from this early-planting adaptation strategy, resulting in 38% increase in yields (Fig. 6c), respectively, compared to baseline.

Another adaptation strategy we considered was to use enhanced irrigation to alleviate wheat drought stress. We modeled this strategy by maintaining soil moisture at or above the wilting point during the growing season (Methods). However, because of improved water-use efficiency induced by elevated CO_2 (Fig. 7) and increased precipitation except in subtropical areas, this climate adaptation strategy had a modest effect on wheat growth and yield at the global scale ($\sim$8% increase) although 44% of non-irrigated wheat areas benefitted somewhat from this irrigation adaptation strategy.

We doubled current fertilizer application rates to explore impacts on wheat yields as a guide to agricultural input intensification strategies. Doubing fertilizer application rates enhanced global yield by 16% compared to baseline, most of which was derived from low- and medium-yield regions. The non-linear responses to fertilization application rates are explained by increased nitrogen losses through N_2O and nitrate leaching caused by increased temperature and precipitation that accelerate microbially-mediated processes (e.g., mineralization, nitrification, and denitrification) and subsurface nutrient fluxes.

We showed here that the most effective strategy to meet rising food demands was a combination of region-specific field management techniques (EIF; Fig. 5b illustrates the optimum modeled strategy for each gridcell; Fig. S8 shows the same information for each region). We note synergistic benefits of the three management techniques led to larger total improvements than the sum of improvements from the individual techniques.

4. Discussions

Our analysis of climate change impacts under current management and varieties on wheat yields points to a zero-sum outcome globally, with both negative and positive effects on regional wheat production. Currently, the largest wheat grain exporters are North America and the former Soviet Union, accounting for approximately 34% and 8% of global wheat trade, respectively (d'Amour et al., 2016). However, our results showed that these two regions will experience decreases in wheat yields by the end of the 21$^{\text{st}}$ century under current management and RCP8.5 scenario. The Middle East would then be highly vulnerable to a potential food crisis in light of their strong dependence on food imports from the former Soviet Union (Woertz and Keulertz, 2015; d'Amour et al., 2016), coupled with their low wheat productivity. Our results suggest that it is imperative to focus on wheat-yield improvements (by adapting site-specific field management strategies) in response to climate change.

Ecohydrological models, such as *ecosys*, have been used as powerful tools to assess the impacts of climate change on crop yields and strategies for improving crop yields under climate change (e.g., Zhao et al. (2017); Liu et al. (2018); Woo et al. (2020)). By exploring potential future scenarios, improvements in scientific understanding of food security risks have been introduced to address possible food shortages (Liu et al., 2018). However, at the global scale, there is still a high degree of uncertainty regarding specific representative cultivars at a given gridcell since there are hundreds of local wheat varieties around the world (e.g., Zhao et al. (2014); Kenneth and Conee (2020); Jia et al. (2020)). Casadebaig et al. (2016) evaluated and propagated uncertainty for all plant-related model parameters to identify dominant effects on grain yield. However, computational constraints typically limit the number of parameters that can be evaluated, especially for global yield projections. To resolve this uncertainty issue, we constructed 1,000 virtual wheat cultivars and selected the most representative regional cultivar at each gridcell by using currently available global datasets of global wheat yields and planting and harvesting dates.

Applying a mechanistic modeling approach with a spatial resolution of 1° allowed us to identify heterogeneous solutions to improve end-of-century wheat yields globally. This study provides the first estimation of basic agricultural management strategies for non-irrigated wheat cultivation to levels that are known to be attainable with existing technologies. Our results suggest that previous research has understated the essential role of early planting with later-maturing varieties and additional fertilizer applications for the benefit of wheat productivity. Precision irrigation strategies have limited effects on wheat yields in low to moderately fertile areas, due to expected heat and nitrogen stresses and water use efficiency improvements (stomatal closure under elevated CO_2) by the end of the 21^{st} century. However, although we showed that increased fertilizer application improves yields under end-of-century climate, it also has several negative consequences, including increased N_2O emissions and increased nitrate leaching, which can lead to eutrophication and increases in infant methemoglobinemia (Woo and Kumar, 2019; Wiedmann, 2018). Alternatives to meet future food demands without environmental degradation include site-specific field management strategies and plant engineering for, e.g., nitrogen fixation genes (Bailey-Serres et al., 2019) or modified plant allocation (Woo et al., 2019). Such approaches deserve more attention and research, since, for wheat, only about half of applified fertilizer is acquired by the plant (Gardner and Drinkwater, 2009), and more than half of the energy consumed in agricultural systems is associated with fertilizer production and use (Richardson and Kumar, 2017).

In this study, we did not consider technology advancements for climate change adaptations to improve wheat yields during the 21^{st} century. Over the past several decades there have been several changes in regional farming systems to improve wheat yields and protect the environment. For example, belt-planting-based technologies were implemented in China, leading to an increase in wheat yields of 4% to 14% (Dandan et al., 2013; Bian et al., 2016; Lv et al., 2020). In India, the system of wheat intensification was first practiced in 2006, resulting in wheat yield increases of 18% to 67% compared with conventional farming methods (Abraham et al., 2024). Osman et al. (2016) found that cultivating spring wheat was more practical than winter wheat under temperate humid climate zones (e.g., the Netherlands) due to nitrogen use efficiency and weed control. The use of precision farming technologies in the cultivation of winter wheat has been widely studied and adopted to increase wheat productivity (e.g., Diacono et al. (2013); Segarra et al. (2022)). Changes in farming systems also play an important role in increasing global wheat yields and reducing environmental burdens. Therefore, our estimates should be regarded as conservative. In summary, using a mechanistic crop model evaluated at the global scale against wheat yield observations from 3,749 sites, we found that global wheat productivity under the RCP8.5 scenario and current management techniques would remain essentially the same as present day, with large and offsetting regional differences. We also found that implementing currently achievable management techniques improved end-of-century yield projections by 91%. Further evaluation of field management strategies under uncertain future climate is imperative if societies are to meet rapidly growing food demands in the coming decades.

5. Conclusions

Addressing famine and food shortages are two of the greatest challenges facing mankind due to increases in the world population expected to reach 10 billion by 2050. Over the 21st century, anthropogenic climate change has added, and will continue to add, pressure on food security. By comparing model projections with a very large observational dataset of non-irrigated wheat yields (three periods over 10 years at 3,749 sites), we showed that more than half of wheat-growing areas will experience yield reductions due to climate change. Through synergistic interactions between field management strategies (e.g., early planting, increased irrigation, and increased fertilizer applications), considerable improvements in global wheat yields can be achieved by adopting spatially heterogeneous and combined management strategies.

6. Acknowledgments

The model and parameters used in this study are available at an online repository (doi: 10.5281/zenodo.4489946). Data for model results derived from the original database (such as climate, observed wheat yield, soil properties, and field management), which are shown as figures but are not in the repository, are available upon request from the corresponding author. This work has supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(No. 2021R1C1C1004801) and the Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Scientific Focus Area sponsored by the Earth and Environmental Systems Modeling (EESM) Program under the Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science. This work was also supported by the U.S. Department of Energy grant under Contract No. 16/CJ000/04/08 as part of the Tomographic Electrical Rhizosphere Imaging (TERI) project. Lawrence Berkeley National Laboratory (LBNL) is managed by the University of California for the U.S. Department of Energy under Contract DE-AC02-05CH11231. RFG is the author of the model, *ecosys*,

that was used in this study.

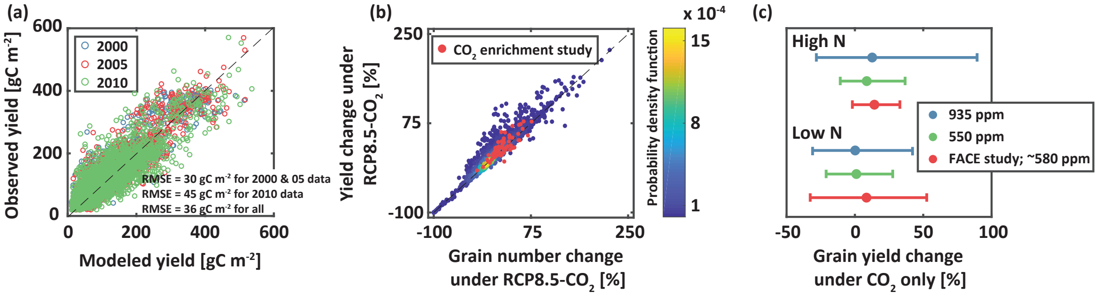

Figure 1: *Ecosys* accurately represented current global wheat yields, grain number effects on yield, and N fertilization effects on CO_2 fertilization. (a) Comparison between projected (x-axis) and observed (IFPRI, 2019a, 2016, 2019b) (y-axis) wheat yields in years 2000 (green), 2005 (red), and 2010 (blue). Root mean square error for the training period (2000 and 2005), validation period (2010), and both are 30, 45, and 36 gCm^{-2}, respectively. (b) Elevated CO_2 effects on grain numbers (x-axis) and yields (y-axis) with color-coded joint probability distribution function. Red dots in (b) represent observations from CO_2 enrichment studies (Broberg et al., 2019). Dashed lines in (a) and (b) indicate 1:1 relation. (c) Influence of nitrogen fertilizer on modeled wheat yields in response to 935 ppm (blue) and 550 ppm (green) of atmospheric CO_2 (bars show the range between 5^{th} and 95^{th} percentiles and circles show their respective means), along with observations (red) from FACE studies conducted at around 580 ppm (Ainsworth and Long, 2005) (±95% confidence interval). The top panel shows cases for high nitrogen fertilizer rates (High N, greater than the 66^{th} percentile of fertilizer rates) while the bottom panel is for low nitrogen fertilizer rates (Low N, lower than the 33^{rd} percentile). A machine in the Intelligent Construction System Core-Support Center of Korea Basic Science Institute Center was partially used in this study.

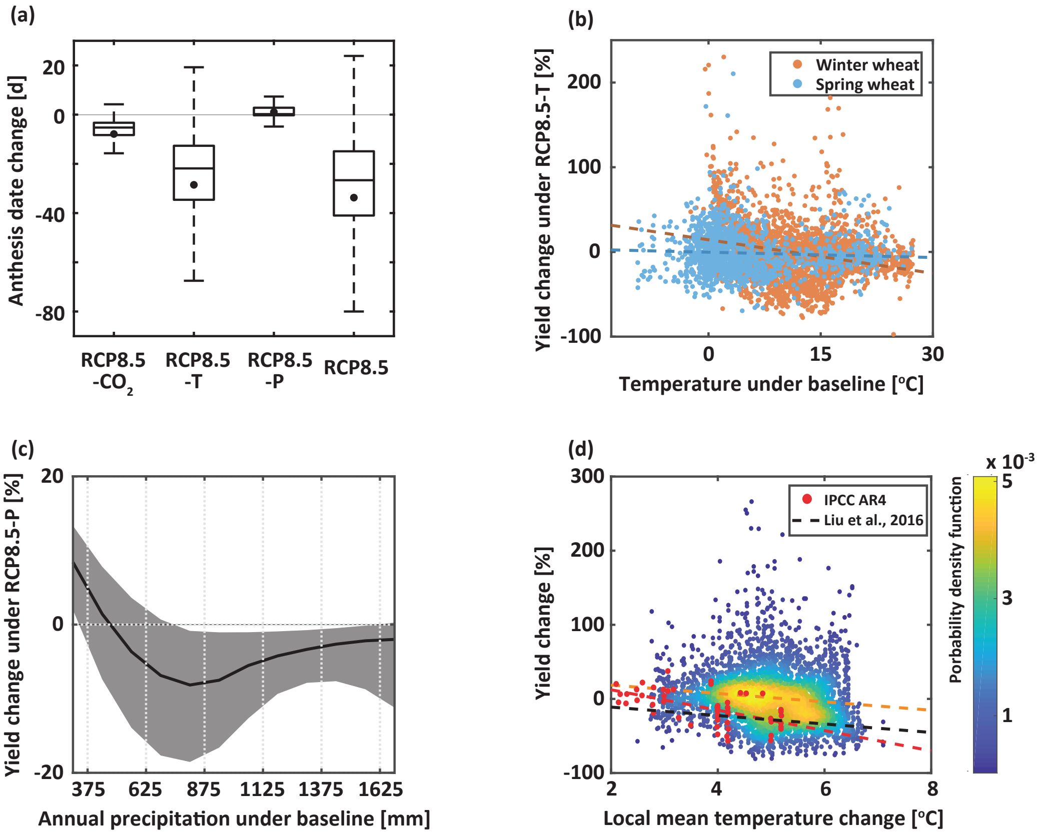

Figure 2: Modeled decreases in wheat yields by 2100 were largely exlained by shortened pre-anthesis period caused by warming and precipitation change. (a) Daily anthesis date changes under CO_2 change only (RCP8.5-CO_2), temperature change only (RCP8.5-T), precipitation change only (RCP8.5-P), and RCP8.5 compared to baseline. The dots in (a) represent the means of independent experiments. (b) Relationship between mean annual temperature under baseline (x-axis) and winter (orange) and spring (blue) wheat-yield changes under RCP8.5-T compared to baseline (y-axis) with their linear regressions (dashed lines). (c) Comparison between annual precipitation under baseline (x-axis) and yield changes under RCP8.5-P (y-axis) for areas that experienced increased precipitation by the end of the 21st century. Multigrid ensemble means (lines) and 25th to 75th percentile intervals (shaded areas) are shown. (d) Influences of local mean temperature changes (x-axis) on relative yield changes under RCP8.5 (y-axis) with color-coded joint probability distribution function compared with IPCC AR4 modeling studies (red dots, Easterling et al. (2007)). Dashed lines show their linear regressions.

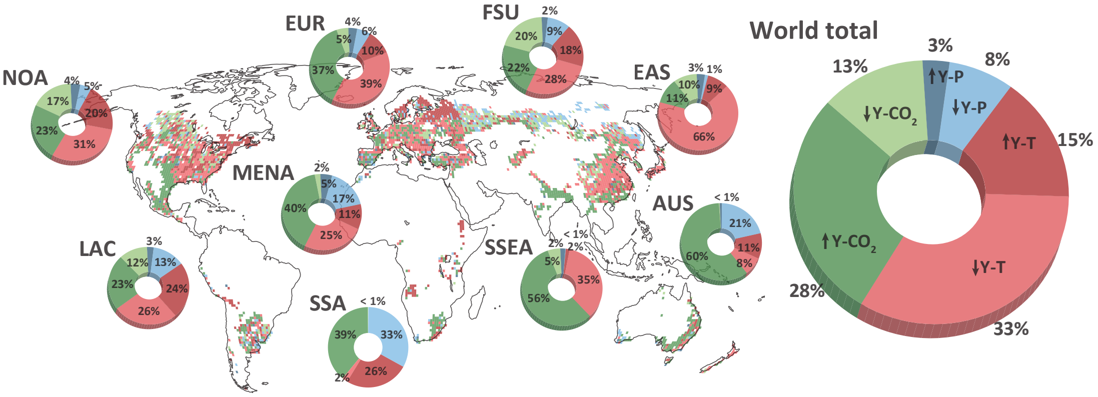

Figure 3: More negative effects of temperature than precipitation on simulated wheat yields. Dominant climate variables (such as CO_2, temperature (T), and precipitation (P)) influenced wheat yields positively (↑Y) and negatively (↓Y) under RCP8.5 compared to baseline (e.g., ↓Y-T: reduced yields under RCP8.5 mainly due to temperature changes) for socio-economic regions (left panel, namely North America (NOA), Latin America and Caribbean (LAC), Europe excluding former Soviet Union (EUR), former Soviet Union (FSU), Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), East Asia (EAS), South and South-East Asia (SSEA), and Australia, New Zealand and Pacific Islands (AUS)) and world total (right panel). Clarification of socio-economic regions is presented in Fig. S6.

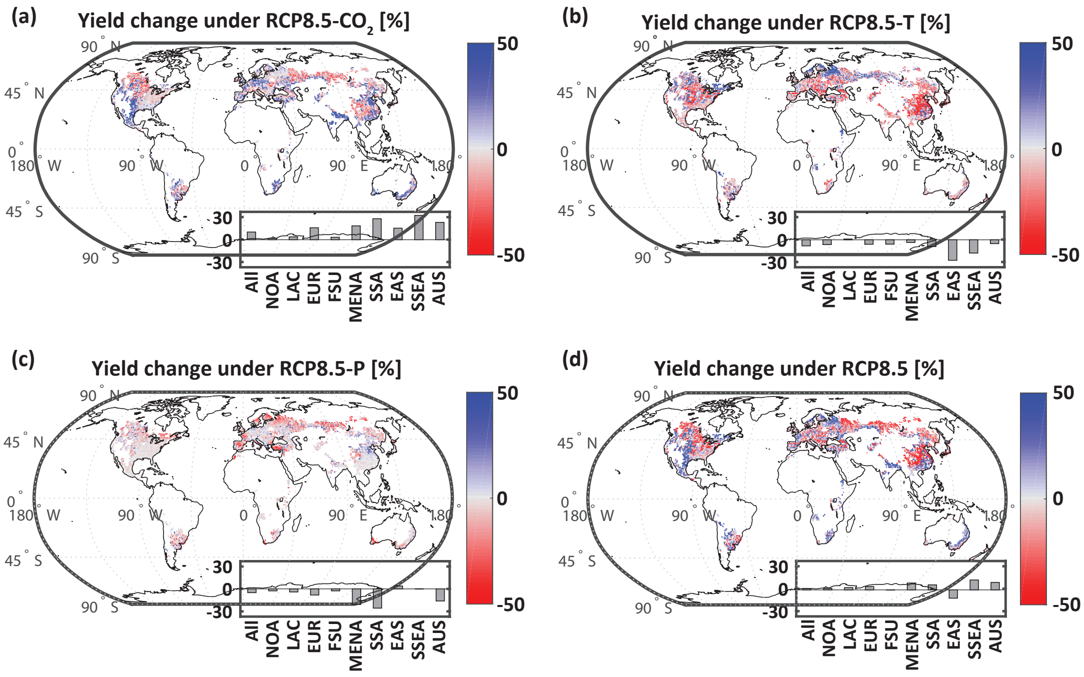

Figure 4: Under current management and crop varieties, global wheat yields under RCP8.5 would remain almost the same by year 2100 compared to baseline. Average wheat yield change by the end of the 21st century under independent experiments of (a, inset) atmospheric CO_2 (RCP8.5-CO_2), (b, inset) temperature (RCP8.5-T), (c, inset) precipitation changes (RCP8.5-P) and (d, inset) RCP8.5 as a percentage of baseline yields (1990-2010 average) under non-irrigated conditions. Insets show relative area-weighted yield changes for socio-economic regions as described in Fig. 3.

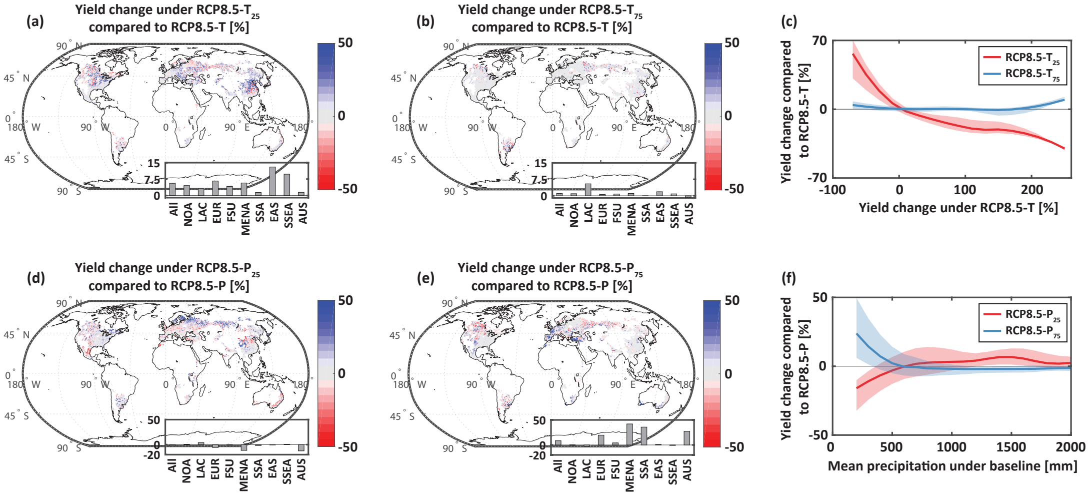

Figure 5: Under current management and crop varieties, uncertainty in projected climate produce large uncertainty in wheat yields, particularly for areas with precipitaiton less than 600 mm under the baseline. Average wheat yield change by the end of the 21st century under independent experiments of (a, inlet) 25th (RCP8.5-T_{25}) and (b, inset) 75th percentiles temperature change alone (RCP8.5-T_{75}) estimated from 39 GCMs for each gridcell. (c) Yield changes under RCP8.5-T_{25} (red) and RCP8.5-T_{75} (blue) were compared to the case of RCP8.5-T. Average wheat yield change by the end of the 21st century under independent experiments of (d, inset) 25th (RCP8.5-P_{25}) and (e, inset) 75th percentiles precipitation change alone (RCP8.5-P_{75}) estimated from 39 GCMs for each gridcell. (f) Relationship between mean annual precipitation under baseline (x-axis) and yield changes under RCP8.5-P_{25} (red) and RCP8.5-P_{75} (blue) compared to the case of RCP8.5-P. In (c) and (f), multigrid ensemble means were presented in lines and 25th to 75th percentile intervals were presented in shaded areas.

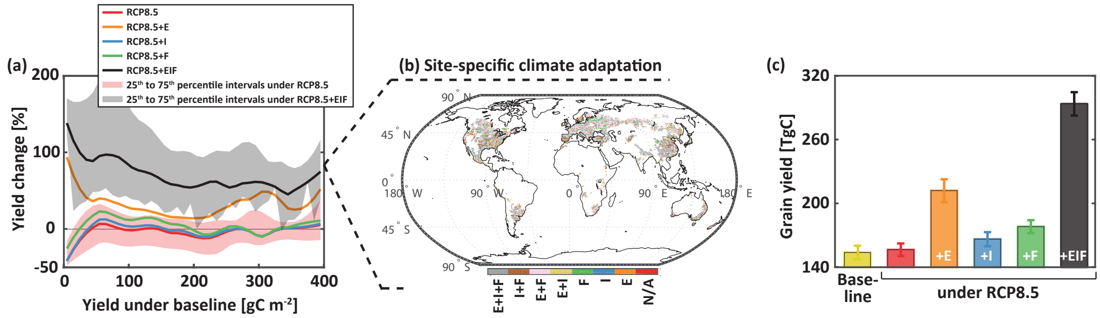

Figure 6: Heterogeneous and diversified climate adaptation strategies would lead to considerable yield improvements. (a) Potential benefits of early planting with later-maturing varieties (E, orange), irrigation (I, blue), fertilizer (F, green), and combinations of them (EIF, black) on global wheat yields under RCP8.5 compared to baseline. Multigrid ensemble means (lines) and 25th to 75th percentile intervals under RCP8.5 and RCP8.5 with combined adaptions (RCP8.5-EIF, shaded areas) are shown. (b) A global projection of the optimum management strategy for each gridcell (see Fig. S8 for details). (c) Global grain yield under baseline and RCP8.5 with four field adaptation strategies (bar colors correspond to legend in panel (a)).

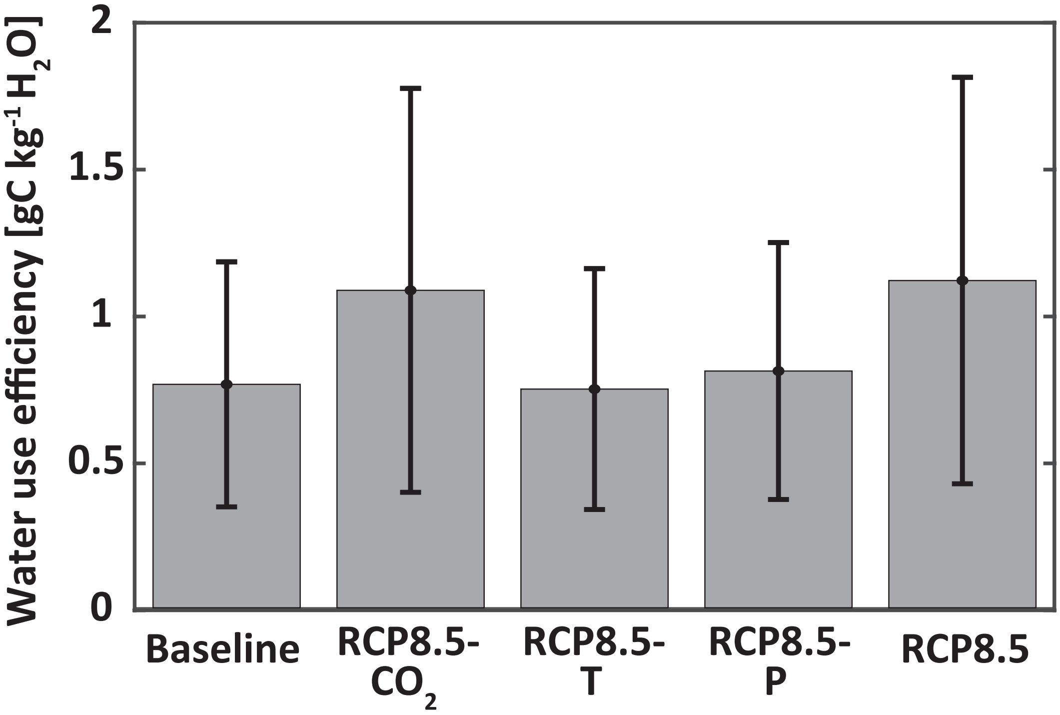

Figure 7: Water use efficiency improvements under RCP8.5 due to stomatal closure under elevated CO_2. Water use efficiency is calculated as harvested grain carbon divided by transpiration under baseline, independent changes in CO_2 (RCP8.5-CO_2), temperature (RCP8.5-T), and precipitation (RCP8.5-P), and RCP8.5. Error bars show standard deviations.

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