

# *Adaptive sowing helps mitigate future wheat losses globally*

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# Earth's Future

## RESEARCH ARTICLE

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### Key Points:

- Moderate warming prompts earlier sowing, while stronger warming delays sowing in most wheat areas
- Adaptive sowing dates coupled with CO<sub>2</sub> fertilization could help mitigate the adverse effects of changing climate on global wheat production
- Latin America and Sub-Saharan Africa will face higher risks of wheat yield reduction than other regions in the future

### Supporting Information:

Supporting Information may be found in the online version of this article.

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# Adaptive Sowing Helps Mitigate Future Wheat Losses Globally

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**Abstract** The escalating effect of climate change on crop yields necessitates urgent adaptation measures. Shifting sowing dates is emerging as one cost-effective adaptation strategy. However, the implications for global wheat yields are unclear. Here, we use an optimality-based model, assuming farmers select sowing dates to maximize yields, to quantify changes in wheat sowing dates and potential grain yields by the 2090s under two climatic scenarios (SSP126 and SSP370). We find that the optimal wheat sowing dates are affected by climate change, primarily driven by temperature norms and warming trends. Global warming prompts earlier sowing (10–20 days) and even a switch from spring to winter wheat in cold areas, while strong warming delays sowing (20–40 days). Scenario modeling shows climate change is projected to negatively impact wheat potential yields under both moderate (−2.4%, SSP126) and strong (−7.8%, SSP370) warming scenarios. Adaptive sowing dates coupled with CO<sub>2</sub> fertilization could mitigate these losses and even enhance yields, resulting in a +5.6% increase in potential yield for SSP126 and a +12.4% for SSP370. However, the benefits are not uniformly distributed across regions, with hotter and less developed regions—such as sub-Saharan Africa and Latin America—facing heightened risks of yield decline. Our findings suggest that simple adaptation strategies could help address the challenges posed by climate change for agricultural production and emphasize the need for region-specific adaptation policies to ensure equitable climate resilience in agriculture.

**Plain Language Summary** As climate change increasingly threatens global food production, wheat yields are particularly vulnerable due to global warming and changing climatic conditions. One potential adaptation to offset these threats is adjusting sowing dates, yet the comprehensive global impact of such adjustments has not been thoroughly evaluated. To address this gap, we use an optimality-based modeling approach to assess how wheat sowing dates might shift and how these changes will influence global wheat yields under future climatic conditions. We found that climate change will drive shifts in sowing dates—earlier sowing in cooler regions and later sowing in warmer regions, generally. While climate change is expected to reduce global wheat yields, adaptive sowing dates in combination with increased atmospheric carbon dioxide could mitigate these losses and, in some cases, even improve yields. However, the benefits are not uniformly distributed across the globe. Hotter and less developed regions, such as sub-Saharan Africa and Latin America, may still face substantial declines in wheat yields. These results emphasize the potential of adaptive strategies like sowing date adjustments, while also highlighting the importance of region-specific policies to enhance climate resilience and ensure food security worldwide.

## 1. Introduction

Global food demand is projected to rise by 35%–56% by 2050 (Dijk et al., 2021), driven by the growth of population and changing dietary preferences, with continued growth anticipated (Bajželj et al., 2014; Li et al., 2024). Wheat, a widely cultivated cereal crop, supplies about 20% of the global caloric intake and dietary protein (Erenstein et al., 2022; Shiferaw et al., 2013), playing a pivotal role in alleviating hunger and ensuring global food security (Bajželj et al., 2014; Tilman et al., 2011). Given the ecological and environmental challenges posed by the expansion of arable land (Laurance et al., 2014; Zabel et al., 2019), future increases in global wheat production will predominantly rely on yield intensification to achieve potential yield (Mueller et al., 2012)—the maximum attainable under specific climatic conditions.

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Recent studies have demonstrated that wheat yields are increasingly affected by changing climate (Challinor et al., 2014; Jägermeyr et al., 2021; Rosenzweig et al., 2014). Elevated atmospheric CO<sub>2</sub> enhances crop carbon assimilation and water-use efficiency through its effects on light use efficiency, canopy light interception and stomatal behavior (Ainsworth & Long, 2021; Fitzgerald et al., 2016; O’Leary et al., 2014), contributing to increased grain yields but potentially at the expense of grain quality, including protein content (Asseng et al., 2019). Rising temperatures accelerate phenological development, shorten growth cycles, and intensify water stress, thereby adversely affecting grain yields (Asseng et al., 2015; Kadam et al., 2014). The combined impacts of these processes ultimately determine wheat yields. Despite the enhancement of wheat production by increased atmospheric CO<sub>2</sub> concentration (Ainsworth & Long, 2021; Jägermeyr et al., 2021; Rezaei et al., 2023), significant adverse impacts related to climate change have also been demonstrated by experiments (X. Wang et al., 2020), large-scale statistical analyses (Asseng et al., 2015; Challinor et al., 2014), and modeling (Jägermeyr et al., 2021; Rosenzweig et al., 2014). Various adaptation strategies have been implemented in response to increasingly adverse conditions, including improved irrigation and fertilization management (Agnolucci et al., 2020; Cai et al., 2023; X. Wang et al., 2021), cultivar switching (Minoli et al., 2022; Rising & Devineni, 2020), and crop redistribution (Sloat et al., 2020; Z. Wang et al., 2022). However, there are limitations to these adaptations, and they are not universally applicable across all wheat-growing regions (Challinor et al., 2014; Grigorieva et al., 2023). Enhancements in water and fertilizer management, for example, are associated with higher costs and may lead to negative environmental consequences (Liu & Yang, 2022). Furthermore, the efficacy of these measures may be constrained by ongoing climate change (Liu & Yang, 2022; Ma et al., 2021). Cultivar switching and crop redistribution necessitate technological advances that may not be possible in underdeveloped regions (Clark et al., 2023). There are also socio-economic and cultural barriers to the adoption of these strategies (Clark et al., 2023; Liu & Yang, 2022; Xiao et al., 2024), particularly in regions dominated by smallholder farming with low productivity—areas expected to experience significant population growth in the coming decades (Janssens et al., 2020; X. Wang et al., 2022). Thus, there is an urgent need to develop low-cost, universally applicable, and sustainable adaptation strategies.

Wheat phenology is primarily driven by climate during the growing season, but yields are also influenced by farmers' decisions about sowing dates (Collins & Chenu, 2021; Hunt et al., 2019; McDonald et al., 2022; Minoli et al., 2022). Drawing on extensive agricultural experience, farmers plant at the most favorable time of the year to maximize yield (Liu & Yang, 2022; Minoli et al., 2022). However, with climate change, the optimal period for wheat sowing is shifting (Dadrasi et al., 2024; He et al., 2015; Olesen et al., 2012). Wheat sowing dates have changed significantly across many regions of the world in recent decades (Hunt et al., 2019; Olesen et al., 2012; Tao et al., 2022). Numerous studies have demonstrated the benefits of these adjustments at local and regional scales—for example, earlier sowing has increased wheat yields in Australia (Collins & Chenu, 2021; Hunt et al., 2019), and timely planting has substantially enhanced wheat productivity in eastern India (McDonald et al., 2022). By adjusting sowing dates, farmers can avoid periods of extreme temperatures, drought, and other adverse weather conditions that could otherwise reduce yields (Dadrasi et al., 2024; Hunt et al., 2019). This strategy leverages existing knowledge and resources, avoiding the need for substantial investments in new technology or infrastructure and making it accessible even in economically constrained regions. Consequently, shifting sowing dates could be a universally applicable and cost-effective adaptation strategy to mitigate the adverse impacts of future climate changes on wheat production (Dadrasi et al., 2024; Minoli et al., 2022).

Models provide a tool for assessing the effects of climate change and adaptation strategies on crops, as well as for predicting future changes in yield (Jägermeyr et al., 2021; Timlin et al., 2024). However, until recently, global crop models have predominantly relied on fixed, observed sowing dates (Rabin et al., 2023). Consequently, the potential shifts in wheat sowing dates under future climate scenarios, and their interactions with climate variability and CO<sub>2</sub> fertilization in determining global wheat production, remain poorly quantified. Some efforts have been made to explore dynamic simulations of optimal sowing dates based on climatic conditions, including rule-based farmer decisions (Minoli et al., 2022; Waha et al., 2012) and maximum yield-based optimization principles (Qiao et al., 2023), to simulate global wheat sowing dates. These approaches reproduce current patterns with minimal discrepancies from observations. Given the ongoing intensification of climate change and its potential effects on crop yields, more effort is required to understand the potential impacts of changing sowing dates in response to climate, and how this interacts with climatic factors and CO<sub>2</sub> fertilization to influence crop yields globally.

In this study, we investigate adaptive responses to changing climate by shifting sowing dates and evaluate the benefits of this strategy in mitigating the adverse impacts of future climate change, focusing specifically on wheat.

We use an eco-evolutionary optimality (EEO) based model for wheat (Qiao et al., 2020, 2021, 2023) to simulate optimal sowing dates annually from 2015 to 2099 and a historical baseline in 2000. We then apply the PC model to simulate the spatiotemporal variation of maximum potential of wheat yields across eight scenarios, combining different climate scenarios (SSP126 and SSP370), sowing scenarios (fixed sowing dates and climate-optimized sowing dates), and CO<sub>2</sub> scenarios (fixed CO<sub>2</sub> and year-by-year CO<sub>2</sub> changes). Finally, we quantify the impacts of climate change, CO<sub>2</sub> fertilization, and adaptive sowing dates on potential future yield changes. The study aims to (a) predict how wheat sowing dates should change with climate, (b) simulate the spatiotemporal variation of potential wheat yields under different scenarios, (c) quantify future potential yield changes at both global and regional scales, and (d) identify the dominant factors controlling these potential yield changes.

## 2. Materials and Methods

### 2.1. The Wheat Growth Model

The EEO-based wheat model (PC model) provides a robust tool for simulating wheat growth, and accurately predicts yield, as well as its response to environmental variables at both site-specific and global scales, by integrating three core modules—phenological development, photosynthetic carbon uptake, and biomass partitioning (Qiao et al., 2020, 2021, 2023). The phenological development module builds on the process-based global crop model LPJmL4 (Schaphoff et al., 2018), simulating the processes of wheat development via a temperature-dependent scalar which represents the ratio (0–1) of accumulated thermal units to the potential requirement (PHU, °C days) from planting to maturity. To enhance the representation of PHU and reduce dependency on cultivar- and location-specific parameters, an empirical scheme incorporating photoperiod and chilling effects was developed and calibrated using global observations of wheat phenology (Qiao et al., 2023). This module also predicts leaf area index (LAI) dynamics, interpolating daily LAI from a seasonal maximum value. This seasonal maximum value is determined by a mass-balance approach accounting for carbon and water limitations, taking the minimum of the two.

The photosynthetic carbon uptake module estimates wheat photosynthesis through a universal productivity scheme (Stocker et al., 2020; H. Wang et al., 2017), which estimates gross primary productivity based on environmental conditions, including climate, soil water, and atmospheric CO<sub>2</sub> concentration. This scheme integrates the FvCB model (Farquhar et al., 1980) with two EEO principles—the “least-cost” hypothesis (Prentice et al., 2014) and the “coordination” hypothesis (H. Wang et al., 2017). These frameworks capture the acclimation of stomatal behavior and carboxylation efficiency to environmental variability on weekly to monthly timescales, incorporating recent advances in understanding photosynthetic optimization (Harrison et al., 2021).

The biomass allocation module (Qiao et al., 2020, 2021) simulates the partitioning of photosynthetically assimilated carbon into biomass and ultimately grain yields, regulated by water and nitrogen stress. The allocated ratio of assimilation to aboveground biomass varies with water availability, quantified using a moisture index. Finally, wheat yield is derived from aboveground biomass through a non-linear yield function that incorporates cultivar variability as a random effect.

### 2.2. The Optimality Principle to Predict Wheat Sowing Dates

A maximum yield-based optimality principle was applied to simulate optimal wheat sowing dates, assuming that farmers select sowing dates in the potential sowing season (PSS) to maximize yields. The PSS is defined as the period when climate conditions are suitable for sowing, with harvest occurring when the heat accumulation required for maturity is met. This approach reflects the adaptability of farmers to long-term local climates and aligns with crop modeling practices that use historical management as inputs (Minoli et al., 2022). Here, wheat yields were calculated using the EEO-based PC model for every date in the PSS, and the optimal date was identified as the one yielding the highest productivity at each location.

The PSS is influenced by local temperature and rainfall seasonality. A temperature index, the mean temperature of the coldest month (MTCO), determines whether wheat is sown in autumn or spring, with the thresholds of  $-10^{\circ}\text{C}$  and  $5^{\circ}\text{C}$ . MTCO below  $-10^{\circ}\text{C}$  precludes autumn sowing due to cold damage, while MTCO above  $5^{\circ}\text{C}$  favors spring sowing by preventing winter dormancy (Waha et al., 2012). This classification yields three temperature zones: cold (MTCO  $< -10^{\circ}\text{C}$ ), temperate ( $-10^{\circ}\text{C} \leq \text{MTCO} < 5^{\circ}\text{C}$ ), and warm (MTCO  $\geq 5^{\circ}\text{C}$ ). In warm regions with monsoonal climates, a rainfall seasonality index (DI), based on the difference between maximum and

minimum monthly rainfall (threshold: 150 mm), identifies areas where sowing follows the retreat of the monsoon (Sperber et al., 2012). The global patterns of MTCO and the associated seasonality types for wheat sowing are shown in Figure S8 in Supporting Information S1.

Global simulations of sowing season show distinct patterns across climatic zones. In cold areas, wheat is typically sown in late spring to minimize the risk of frost damage, with crops completing their growth cycle without dormancy. In temperate regions, wheat sown in autumn undergoes winter dormancy, while spring-sown crops bypass dormancy. In warm, non-monsoonal regions, sowing is largely unconstrained by climate, whereas in monsoonal regions, it occurs after the cessation of heavy rainfall.

### 2.3. Data Description and Processing

*Global climate data:* We used historical reanalysis climate data and future climate projections for baseline simulations and projections, respectively. Historical climate forcing for 1998–2002 was obtained from WFDE5 (Cucchi et al., 2020), which provided hourly data at 0.5° spatial resolution. Hourly values were averaged over 24 hr to produce daily climate inputs. Future climate forcing was derived from bias-corrected CMIP6 projections provided by protocol 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP-3b). These data sets, at 0.5° spatial and daily temporal resolution, included projections from five primary CMIP6 climate models (UKESM1-0-LL, IPSL-CM6A-LR, MRI-ESM2-0, MPI-ESM1-2-HR, and GFDL-ESM4) under three Shared Socioeconomic Pathways (SSP126, SSP370, and SSP585). We focused on SSP126 and SSP370 scenarios, as the SSP585 scenario is now considered implausible (Hausfather & Peters, 2020). The mean climate forcing from the five primary models was calculated for SSP126 and SSP370 to serve as inputs for future projections (Figures S1–S4 in Supporting Information S1). Additionally, we conducted separate simulations using outputs from the high-sensitivity (UKESM1-0-LL) and low-sensitivity (GFDL-ESM4) models (Figure S5 in Supporting Information S1) to evaluate the effects of climate sensitivity on simulations.

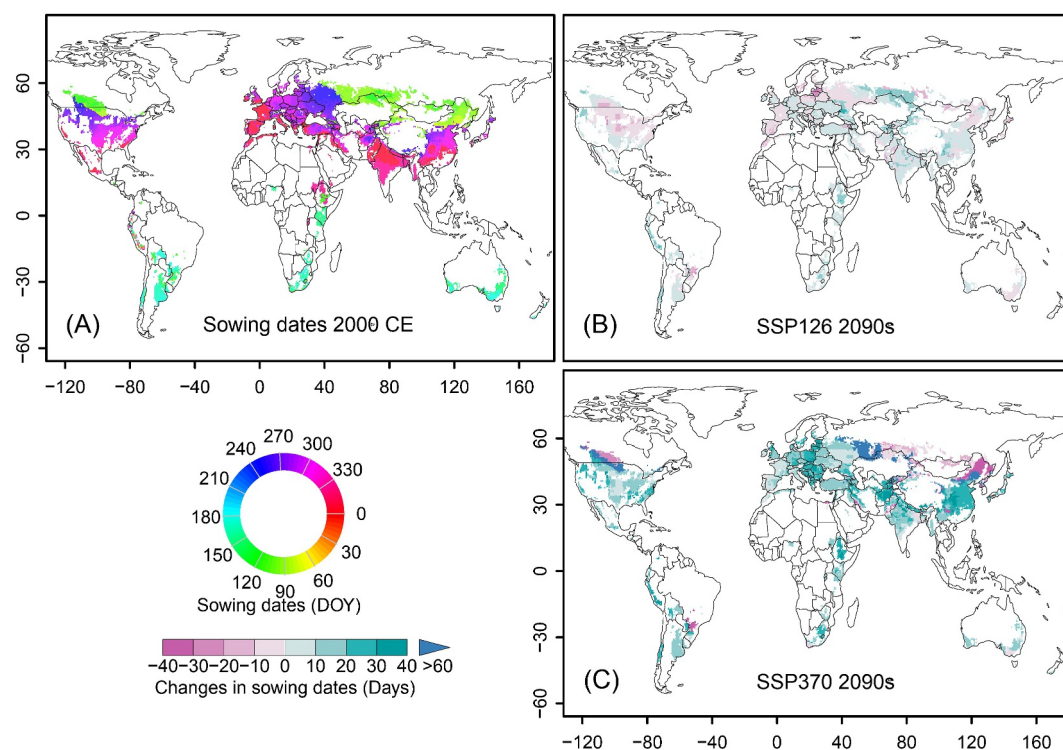
Key climatic variables, specifically downward shortwave radiation flux ( $\text{W m}^{-2}$ ), air temperature ( $^{\circ}\text{C}$ ), specific humidity ( $\text{kg kg}^{-1}$ ), precipitation ( $\text{kg m}^{-2} \text{s}^{-1}$ ), and atmospheric pressure (Pa), were extracted from the historical and future climate forcing data sets. Daily data were used to derive additional variables needed as the inputs to the wheat growth model, including vapor pressure deficit, derived from atmospheric pressure, temperature and specific humidity, and daily photosynthetic photon flux density (PPFD), derived from downward shortwave radiation (Meek et al., 1984). These daily data were pre-processed into weekly values for input to the PC model. Weekly values were computed as the means of daily data, except for PPFD, which was summed over each week.

*Atmospheric CO<sub>2</sub> concentration:* The annual atmospheric CO<sub>2</sub> concentrations for the historical period were sourced from the US National Oceanic and Atmospheric Administration. Future CO<sub>2</sub> levels for the SSP126 and SSP370 scenarios (Figure S5c in Supporting Information S1) were derived from scenario projections associated with the Shared Socioeconomic Pathways (Riahi et al., 2017).

*Global wheat areas:* The global land grid for wheat cultivation (Figure S6 in Supporting Information S1) was defined based on the wheat growing map from EARTHSTAT, which integrates census-based statistics with remote sensing data (Ray et al., 2012). EARTHSTAT gives the proportion of wheat-harvested area at 5-min resolution ( $\sim 0.083^{\circ}$ ), which we resampled to a resolution of 0.5°. For the projections, we assumed a constant global wheat distribution and did not account for climate-driven shifts in suitable cultivation areas.

*Global wheat irrigation information:* Irrigation data was sourced from a global data set (MIRCA2000) of monthly irrigated and rainfed crop areas (Portmann et al., 2010), which reports the area of each type within 0.5° grid cells. For cells with both types, we assigned the dominant system. Specifically, if the irrigated-to-rainfed ratio exceeded 1, the cell was treated as fully irrigated for modeling purposes.

*Global historical wheat sowing dates:* We used two widely used global data sets, MIRCA2000 (Portmann et al., 2010) and Sacks et al. (2010), to construct a data set of global historical wheat sowing dates. Both data sets provide wheat sowing information at a 0.5° grid resolution centered around the year 2000. We supplemented and corrected these data sets using country-specific information from published literature and reports, particularly for regions such as Russia, China, and South America. Details of the integration and correction process are given in Qiao et al. (2023). The final data set, after integration and corrections, provides the historical baseline (Figure S7b in Supporting Information S1) for scenario modeling and as a reference for quantifying future changes.



**Figure 1.** Simulated optimal wheat sowing dates. (a) Simulated sowing dates in 2000 CE, and predicted changes in the 2090s under (b) SSP126 and (c) SSP370 scenarios. Negative values indicate earlier, and positive values indicate delayed sowing compared to 2000 CE.

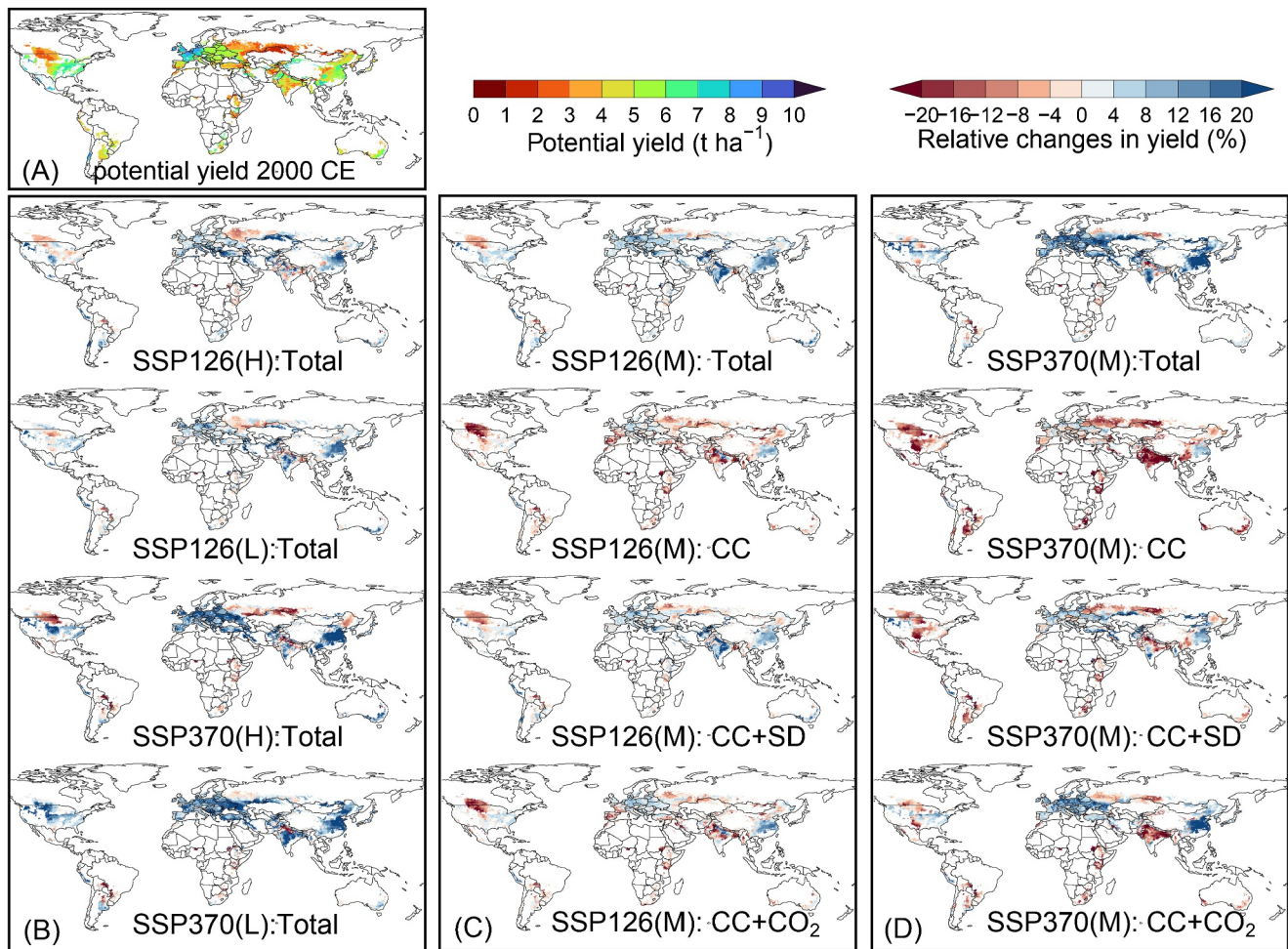
## 2.4. Design of Modeling Experiments for Future Projections

To evaluate the individual and combined impacts of climate change, changing sowing date, and atmospheric CO<sub>2</sub> levels on wheat growth and potential grain yields, we designed eight modeling experiments. The potential yield was defined as the maximum attainable under specific climatic conditions, which means water stress in irrigated wheat-growing areas and nutrient stress in both irrigated and rainfed wheat-growing areas were eliminated to approximate potential yield. The eight modeling experiments integrated two climate change scenarios (SSP126 and SSP370), two sowing scenarios (fixed sowing dates for the year 2000 and climate-optimized sowing dates), and two CO<sub>2</sub> scenarios (fixed CO<sub>2</sub> levels and year-by-year CO<sub>2</sub> changes). We ran each experiment across current wheat growing areas at 0.5° × 0.5° resolution from 2015 to 2099 to assess the effects of climate change, CO<sub>2</sub> fertilization, and changing sowing dates on future potential wheat yields. We also simulated the historical baseline of potential wheat yields and sowing dates (centered on the year 2000, averaged over 1998–2002) to establish a reference for quantifying future changes (Figure S7 in Supporting Information S1). Subsequently, we quantified the contribution of individual factors (temperature, radiation, precipitation, atmospheric CO<sub>2</sub> concentration, and sowing date adaptation) to the simulated changes in potential yield by holding all but one factor constant. This allowed us to identify the dominant drivers of variations in potential yield in each grid cell.

## 3. Results

### 3.1. Simulated Changes in Wheat Sowing

The season suitable for wheat sowing is altered under the stronger, SSP370 projection. The mean temperature of wheat areas globally is projected to increase by >4°C by the 2090s, and high-latitude wheat-growing regions of the Northern Hemisphere experience a 6°C warming (Figures S1 and S5 in Supporting Information S1). As a result, the winter temperature limitation on planting is reduced. Many high latitude regions, including central North America, southern Russia, Kazakhstan, and some regions in northern China, currently typified by spring wheat cultivation due to low winter temperatures (Figure 1a), become progressively more suitable for planting winter wheat (Figure 1c and Figure S8 in Supporting Information S1). The comparatively minor warming under the SSP126

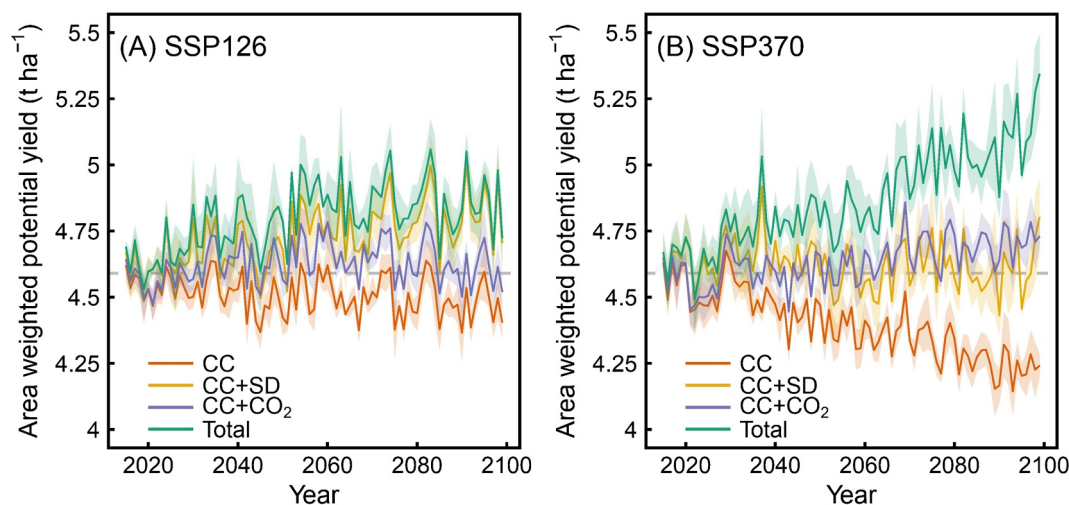


**Figure 2.** Simulations of potential wheat yield and its changes for multiple scenarios. (a) Simulated potential wheat yield in 2000 CE projected using (b) outputs of high- (H) and low- (L) sensitivity climate model respectively, and the mean level (M) of five climate models under (c) SSP126 and (d) SSP370 scenarios, accounting for the combined effects of climate change, shifting sowing dates and CO<sub>2</sub> fertilization. “CC” represents the modeling scenario with climate change alone, “CC+SD” includes the additional effect of sowing dates adaptation, “CC+CO<sub>2</sub>” includes the additional effects of CO<sub>2</sub> concentration, and “Total” reflects the combined effects of all three factors.

scenario, does not lead to a shift in the season suitable for sowing wheat (Figure 1b and Figure S8 in Supporting Information S1). However, the optimal timing of planting is shifted. Wheat sowing at regions north of >30°N is advanced by ~10 days under mild warming (SSP126) and by >20 days under stronger warming (SSP370). In northeastern China, the optimal sowing date is advanced by >30 days. In contrast, in areas where winter temperature is not currently a limitation, warming delays wheat sowing. The delay increases with the level of warming: from 0–10 days under SSP126 (Figure 1b) to 20–40 days under SSP370 (Figure 1c) compared to the timing in 2000 CE.

### 3.2. Yield Response to Changing Climate and Sowing Dates

Future climate change (CC scenario) adversely affected potential wheat yields under both the moderate (SSP126, Figures 2c and 3a) and stronger (SSP370, Figures 2d and 3b) warming scenarios. Potential yields are projected to decline in the CC scenario (Figures 2c and 2d), except in some regions of China and Europe where increased radiation had a positive effect on potential yield (Figures S1c and S4 in Supporting Information S1). Elsewhere, the decline in potential yield is related to the degree of warming: the overall decline under SSP370 is –7.8%, larger than for SSP126 (–2.4%). Adjustments to sowing dates (CC + SD scenario) reduce these adverse effects (Figures 2c, 2d, and 3 and Table S1 in Supporting Information S1) as does the increase in CO<sub>2</sub> concentration (CC + CO<sub>2</sub> scenario)

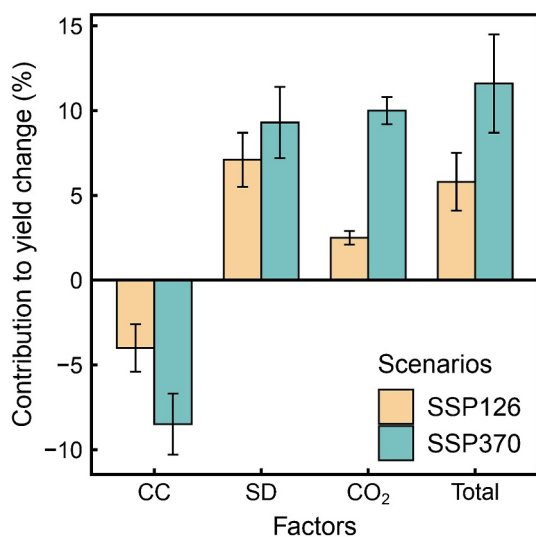


**Figure 3.** Projected interannual variations in area-weighted potential wheat yield under (a) SSP126 and (b) SSP370 scenarios. “CC” represents the modeling scenario with climate change alone, “CC+SD” includes the additional effect of sowing dates adaptation, “CC+CO<sub>2</sub>” includes the additional effects of CO<sub>2</sub> concentration, and “Total” reflects the combined effects of all three factors.

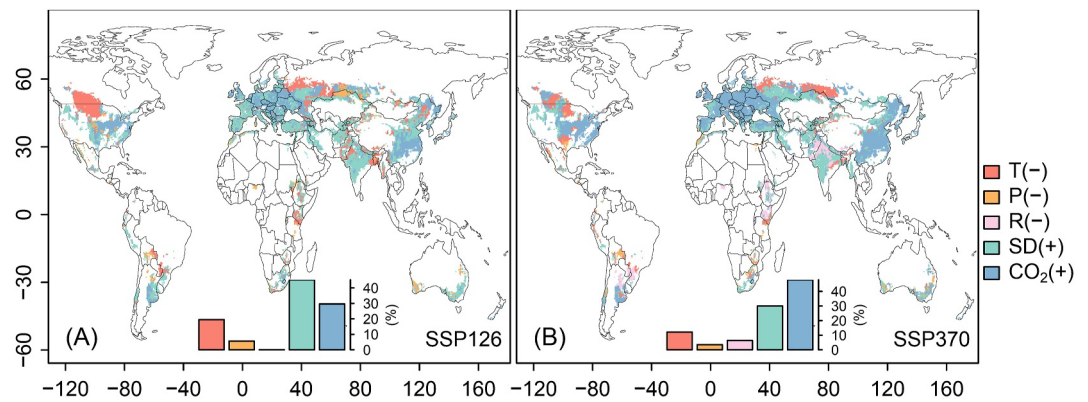
under SSP370 (Figure 3b). Under the CC + SD scenario, the average of global potential wheat yield by the 2090s is 4.83 and 4.63 t ha<sup>-1</sup> for the SSP126 and SSP370 scenarios, respectively (Table S1 in Supporting Information S1). Similarly, under the CC + CO<sub>2</sub> scenario, potential wheat yields are 4.6 t ha<sup>-1</sup> and 4.72 t ha<sup>-1</sup> for the SSP126 and SSP370 scenarios, respectively, by the 2090s. There is an interaction between these two drivers such that the combined impact of changing sowing dates and CO<sub>2</sub> fertilization under climate change (Total scenario) is larger than the impact of either in isolation under climate change (Figures 3 and 4 and Table S1 in Supporting Information S1).

Thus, by the 2090s, these experiments show an overall increase in potential wheat yield relative to 2000 CE of +5.6% and +12.4% under the SSP126 and SSP370, respectively, compared to the scenario taking account of climate change alone (Figure 4). The improvement in potential yield is dominated by the positive benefits of CO<sub>2</sub> fertilization over ca 47.92% of grid cells and by the positive benefits of shifting sowing dates over ca 29.97% of the wheat growing areas globally, particularly under the stronger scenario (Figure 5).

The effects of climate change, adaptive sowing and CO<sub>2</sub> fertilization on potential yield are geographically distinct (Figures 5 and 6). In tropical regions, including Sub-Saharan Africa and Latin America, baseline temperatures already exceed the optimum for wheat growth. Further warming under SSP370 reduces photosynthetic carbon assimilation and accelerates phenological development. Combined with changes in precipitation and radiation, these factors impose multiple constraints on wheat production, contributing to potential yield declines. In parts of the tropics such as India and East Africa, where seasonal rainfall is already high, additional precipitation can further limit yields by reducing incoming solar radiation (Figure S1 in Supporting Information S1). In Oceania, particularly Australia, where wheat is predominantly rainfed, rising temperatures coupled with declining rainfall are projected to reduce yields. CO<sub>2</sub> fertilization, however, can improve water-use efficiency and partially offset the adverse effects of warming and reduced precipitation (Figures S1–S4 in Supporting Information S1). Benefits are expected in temperate regions such as China, Europe, and the United States, where wheat production is dominated by winter cultivars grown under



**Figure 4.** The contribution of different factors to global potential yield changes in the 2090s under SSP126 and SSP370 scenarios. The values represent the mean  $\pm$  standard error for each grid where wheat cultivation. “CC” indicates the individual contribution of climate change, “SD” indicates the individual contribution of sowing dates adaptation, “CO<sub>2</sub>” indicates the individual contribution of CO<sub>2</sub> changes, and “Total” indicates the combined effects of all three factors.



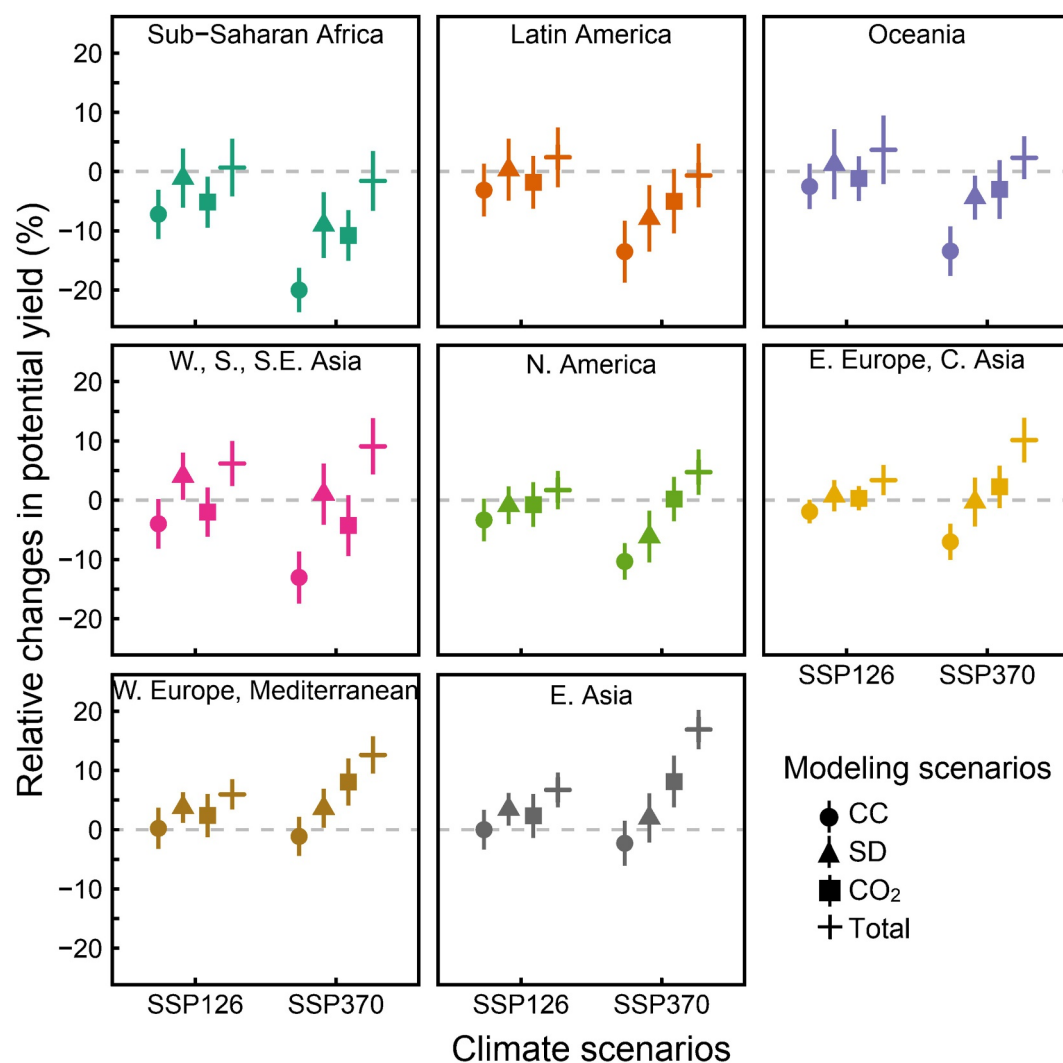
**Figure 5.** The dominant factor driving potential yield changes under (a) SSP126 and (b) SSP370 scenarios. The (+) symbol means positive effects, and the (−) symbol means negative effects. The bar shows the proportion of grid cells dominated by each factor.

relatively cool baseline temperatures (Figure S8 in Supporting Information S1). Warming-induced delays in sowing dates partially offset the negative effects of rising temperatures on growing-season shortening. Together with enhanced CO<sub>2</sub> fertilization under the SSP370 scenario, these adjustments are projected to support yield gains in these regions (Figures 2d, 5, and 6). However, in some high-latitude regions where spring wheat predominates, including Canada and the Siberian region of Russia, projected temperature increases exceeding 6°C (SSP370 scenario) markedly accelerate crop development (Figure S2 in Supporting Information S1), shorten the growing season, and lead to yield declines. Overall, wheat production in cooler regions such as East Asia, Europe, and the United States is projected to benefit more from future CO<sub>2</sub> fertilization and adaptive shifts in sowing dates. In contrast, hotter regions, such as Latin America and sub-Saharan Africa (Figures 2b–2d), are expected to experience larger declines in potential yield of −20% and −13.5%, respectively, under the SSP370 scenario (Figure 6). The combined effect of shifts in sowing date and CO<sub>2</sub> fertilization offset the adverse effects of climate change in hotter regions, but this is not sufficient to produce the overall increase in potential yields compared to 2000 seen in other regions of the world (Figure 6).

#### 4. Discussion

We have shown that projected future climate changes have an adverse impact on potential yields in current wheat-growing areas, consistent with previous studies (Agnolucci et al., 2020; Jägermeyr et al., 2021; Qiao et al., 2021; Rosenzweig et al., 2014). Under SSP370, the overall reduction in potential wheat yield is approximately −7.8%. This is weaker than the ensemble estimates from multi-crop models, which focus on actual yield rather than the maximum potential (Jägermeyr et al., 2021). This discrepancy arises because some of the yield loss is offset by eliminating water and nutrient stress. Our simulations indicate that future changes in CO<sub>2</sub> concentration have positive effects on potential yields and hence mitigate the effects of climate change, consistent with a recent meta-analysis of experimental and modeling studies showing the positive effect of CO<sub>2</sub> on crop yields (Toreti et al., 2020). Our simulations show a +5.6% increase compared to yields in 2000 CE under the SSP126 scenario and a +12.4% increase under the SSP370 scenario. The positive impact of CO<sub>2</sub> may be reduced under nutrient stress (Toreti et al., 2020), a factor not considered in our simulations, and thus the benefits of increased CO<sub>2</sub> may not be realized in less-developed countries where fertilizer use is sub-optimal. However, the simulated changes in climate also have an impact on the potential window for sowing, advancing the optimal timing for planting spring wheat in cold regions, delaying the planting of winter wheat in temperate and warm regions, and leading to a shift from spring to autumn planting in many parts of the high northern latitudes. Thus, relative to the technological advances, economic investments, and environmental costs associated with fertilization, irrigation optimization, and cultivar substitution, a relatively simple adjustment in sowing date has the potential to mitigate the adverse effects of future climate changes.

Our optimality-based assumption that farmers will act to increase wheat yield by adjusting sowing dates to reflect changing environmental conditions is supported by observations of changes in wheat planting in recent decades, widely reported from China (He et al., 2015; Tao et al., 2012), India (Lobell et al., 2013), USA (Olmstead &



**Figure 6.** Regional statistics of the mean changes in potential wheat yields. “CC” represents the modeling scenario with climate change alone, “CC+SD” includes the additional effect of sowing dates adaptation and “CC+CO<sub>2</sub>” includes the additional effects of CO<sub>2</sub> concentration. “Total” reflects the combined effects of all three factors. The regional classifications are shown in Figure S9 in Supporting Information S1.

Rhode, 2011), Europe (Olesen et al., 2012), and Australia (Collins & Chenu, 2021; Hunt et al., 2019). Both local field records and large-scale remote-sensing provide evidence that farmers are already adapting wheat sowing to changing climatic conditions (Dadrasi et al., 2024; He et al., 2015; Hunt et al., 2019; Lobell et al., 2013; Olesen et al., 2012). Importantly, our simulations captured these observed shifts across the main wheat-growing regions (Table S2 in Supporting Information S1), increasing confidence in projections of future changes in sowing dates.

The simulated reduction in potential yield varies regionally, with some of the largest changes occurring in hotter and less-developed regions, including Latin America and Sub-Saharan Africa. Background temperatures during the growing season already exceed the optimum for wheat growth, and further warming is expected to reduce photosynthetic carbon assimilation while accelerating phenological development and intensifying water stress, thereby contributing to substantial yield declines (Agnolucci et al., 2020; Asseng et al., 2015). This disproportionate impact on tropical regions has been reported in a previous study (Pequeno et al., 2021). These are regions where technological solutions, such as switching to high yield cultivars more suited to high temperatures, introducing irrigation or increasing fertilizer use, may not be accessible and where change to sowing dates provides a low-cost and environmentally friendly approach to mitigation. Encouraging change in the timing of planting would be a contribution toward the United Nations Sustainable Development Goal of “No Hunger”

(SD2) but will require both improved projections of near-term climate changes and the adoption of a modeling approach that allows the identification of optimal planting seasons and dates.

Most crop models used to assess the effects of future climate changes on crops either use prescribed planting dates for specific crops or simple environmental rules for determining the sowing date (Minoli et al., 2019, 2022; Rabin et al., 2023). There is an urgent need to improve this modeling capacity to improve the reliability of model projections (Timlin et al., 2024). Our optimality-based approach may provide a workable alternative method to investigating how simple management changes could offset the adverse effects of climate change, and if employed with near-time climate scenarios could inform recommendations on optimal sowing windows for crops.

In this research, we have focused on analyzing potential yield changes in the current global distribution of wheat cultivation. In some of these areas, wheat is planted as one crop in a rotation (e.g., China: wheat-maize rotation). The sowing dates in a rotational system may not be optimal for any individual crop, since the overall aim is to maximize total crop yield rather than the yield of each specific crop (Tsai et al., 1987; Xiao et al., 2024). It would be useful to extend the current model to other common cereal crops, such as barley, rice, millet, sorghum or maize, to facilitate consideration of yields in rotational systems. Finally, it is clear that future climate change will shift the areas that are climatically suitable for key crops, for example, allowing wheat to be grown further north than it is currently (Ceglar et al., 2019; King et al., 2018). Although machine learning-based and statistical approaches have been used to project future expansions in wheat sowing areas, the underlying climate-driven mechanisms remain poorly understood from a process-based perspective (Cong et al., 2025; Guo et al., 2024). Notably, most existing crop models do not explicitly account for changes in the climatic niche governing crop distribution. Accordingly, we have not taken possible changes in wheat-growing areas into account in this study, partly because such changes depend strongly on technological factors, including the availability of agricultural machinery, and partly because expansion into new cultivation zones may not be a viable option for farmers in most regions of the world. Nevertheless, it would be valuable to explore the impact of changing, or indeed increasing, the area of wheat cultivation on global yields by coupling crop models with land-use or land-system models. Given this, our optimality-based modeling approach makes it clear that the effects of changing climate and management on crop yields are complex and vary geographically, and thus provides a tool for better understanding the consequences of future climate change and for designing management options to manage these consequences.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Availability Statement

Data used in this study are all publicly available. The global wheat-growing map was sourced from the website of EARTHSTAT ([www.earthstat.org/harvested-area-yield-4-crops-1995-2005](http://www.earthstat.org/harvested-area-yield-4-crops-1995-2005)). Historical baseline global wheat sowing dates were integrated from data sets by Sacks et al. (2010) and MIRCA2000 data set proposed by Portmann et al. (2010), which also provided irrigation information. Historical climate forcing were sourced from WFDE5 (Cucchi et al., 2020) and future climate forcing was obtained from CMIP6 projections provided the ISIMIP-3b Project (Lange & Büchner, 2021) for future scenarios analyses. Annual atmospheric CO<sub>2</sub> concentrations are available in Lan et al. (2025), with future projections based on Shared Socioeconomic Pathways provided by ISIMIP-3b.

### References

- Agnolucci, P., Rapti, C., Alexander, P., Lipsis, V. D., Holland, R. A., Eigenbrod, F., & Ekins, P. (2020). Impacts of rising temperatures and farm management practices on global yields of 18 crops. *Nature Food*, 1(9), 562–571. <https://doi.org/10.1038/s43016-020-00148-x>
- Ainsworth, E. A., & Long, S. P. (2021). 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, 27(1), 27–49. <https://doi.org/10.1111/gcb.15375>
- Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., et al. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, 5(2), 143–147. <https://doi.org/10.1038/nclimate2470>
- Asseng, S., Martre, P., Maiorano, A., Rötter, R. P., O'Leary, G. J., Fitzgerald, G. J., et al. (2019). Climate change impact and adaptation for wheat protein. *Global Change Biology*, 25(1), 155–173. <https://doi.org/10.1111/gcb.14481>
- Bajželj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E., & Gilligan, C. A. (2014). Importance of food-demand management for climate mitigation. *Nature Climate Change*, 4(10), 924–929. <https://doi.org/10.1038/nclimate2353>
- Cai, S., Zhao, X., Pittelkow, C. M., Fan, M., Zhang, X., & Yan, X. (2023). Optimal nitrogen rate strategy for sustainable rice production in China. *Nature*, 615(7950), 73–79. <https://doi.org/10.1038/s41586-022-05678-x>

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- Ceglar, A., Zampieri, M., Toreti, A., & Dentener, F. (2019). Observed northward migration of agro-climate zones in Europe will further accelerate under climate change. *Earth's Future*, 7(9), 1088–1101. <https://doi.org/10.1029/2019ef001178>
- Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4(4), 287–291. <https://doi.org/10.1038/nclimate2153>
- Clark, B., Xia, L., Robock, A., Tilmes, S., Richter, J. H., Visionsi, D., & Rabin, S. S. (2023). Optimal climate intervention scenarios for crop production vary by nation. *Nature Food*, 4(10), 902–911. <https://doi.org/10.1038/s43016-023-00853-3>
- Collins, B., & Chenu, K. (2021). Improving productivity of Australian wheat by adapting sowing date and genotype phenology to future climate. *Climate Risk Management*, 32, 100300. <https://doi.org/10.1016/j.crm.2021.100300>
- Cong, J., Zhao, C., Asseng, S., Wang, X., Müller, C., Jägermeyr, J., et al. (2025). Potential expansion of wheat planting areas driven by climate warming offsets yield losses and enhances global production. *One Earth*, 9(1), 101464. <https://doi.org/10.1016/j.oneear.2025.101464>
- Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Lange, S., Schmied, H. M., et al. (2020). WFDE5: Bias-adjusted ERA5 reanalysis data for impact studies [Dataset]. *Earth System Science Data*, 12(3), 2097–2120. <https://doi.org/10.5194/essd-12-2097-2020>
- Dadrasi, A., Soltani, E., Makowski, D., & Lamichhane, J. R. (2024). Does shifting from normal to early or late sowing dates provide yield benefits? A global meta-analysis. *Field Crops Research*, 318, 109600. <https://doi.org/10.1016/j.fcr.2024.109600>
- Dijk, M. V., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, 2(7), 494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Erenstein, O., Jaleta, M., Mottaleb, K. A., Sonder, K., Donovan, J., & Braun, H.-J. (2022). Wheat improvement. *Food Security in a Changing Climate*, 47–66. [https://doi.org/10.1007/978-3-030-90673-3\\_4](https://doi.org/10.1007/978-3-030-90673-3_4)
- Farquhar, G. D., Caemmerer, S. V., & Berry, J. A. (1980). A biochemical model of photosynthetic CO<sub>2</sub> assimilation in leaves of C3 species. *Planta*, 149(1), 78–90. <https://doi.org/10.1007/bf00386231>
- Fitzgerald, G. J., Tausz, M., O'Leary, G., Mollah, M. R., Tausz-Posch, S., Seneweera, S., et al. (2016). Elevated atmospheric [CO<sub>2</sub>] can dramatically increase wheat yields in semi-arid environments and buffer against heat waves. *Global Change Biology*, 22(6), 2269–2284. <https://doi.org/10.1111/gcb.13263>
- Grigorieva, E., Livenets, A., & Stelmakh, E. (2023). Adaptation of agriculture to climate change: A scoping review. *Climate*, 11(10), 202. <https://doi.org/10.3390/cli11100202>
- Guo, X., Zhang, P., & Yue, Y. (2024). Global wheat planting suitability under the 1.5°C and 2°C warming targets. *Frontiers in Plant Science*, 15, 1410388. <https://doi.org/10.3389/fpls.2024.1410388>
- Harrison, S. P., Cramer, W., Franklin, O., Prentice, I. C., Wang, H., Brännström, Å., et al. (2021). Eco-evolutionary optimality as a means to improve vegetation and land-surface models. *New Phytologist*, 231(6), 2125–2141. <https://doi.org/10.1111/nph.17558>
- Hausfather, Z., & Peters, G. P. (2020). Emissions – The ‘business as usual’ story is misleading. *Nature*, 577(7792), 618–620. <https://doi.org/10.1038/d41586-020-00177-3>
- He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W., et al. (2015). Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agricultural and Forest Meteorology*, 200, 135–143. <https://doi.org/10.1016/j.agrformet.2014.09.011>
- Hunt, J. R., Lilley, J. M., Trevaskis, B., Flohr, B. M., Peake, A., Fletcher, A., et al. (2019). Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change*, 9(3), 244–247. <https://doi.org/10.1038/s41558-019-0417-9>
- Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., et al. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, 2(11), 873–885. <https://doi.org/10.1038/s43016-021-00400-y>
- Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., et al. (2020). Global hunger and climate change adaptation through international trade. *Nature Climate Change*, 10(9), 829–835. <https://doi.org/10.1038/s41558-020-0847-4>
- Kadam, N. N., Xiao, G., Melgar, R. J., Bahuguna, R. N., Quinones, C., Tamilselvan, A., et al. (2014). Chapter three agronomic and physiological responses to high temperature, drought, and elevated CO<sub>2</sub> interactions in cereals. *Advances in Agronomy*, 127, 111–156. <https://doi.org/10.1016/b978-0-12-800131-8.00003-0>
- King, M., Altdorff, D., Li, P., Galagedara, L., Holden, J., & Unc, A. (2018). Northward shift of the agricultural climate zone under 21st-century global climate change. *Scientific Reports*, 8(1), 7904. <https://doi.org/10.1038/s41598-018-26321-8>
- Lan, X., Tans, P., & Thoning, K. W. (2025). Trends in globally-averaged CO<sub>2</sub> determined from NOAA Global Monitoring Laboratory measurements version 2025-01 [Dataset]. <https://doi.org/10.15138/9n0h-zh07>
- Lange, S., & Büchner, M. (2021). ISIMIP3b bias-adjusted atmospheric climate input data (v1.1) [Dataset]. *ISIMIP Repository*. <https://doi.org/10.48364/isimip.842396.1>
- Laurance, W. F., Sayer, J., & Cassman, K. G. (2014). Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution*, 29(2), 107–116. <https://doi.org/10.1016/j.tree.2013.12.001>
- Li, Y., He, P., Shan, Y., Li, Y., Hang, Y., Shao, S., et al. (2024). Reducing climate change impacts from the global food system through diet shifts. *Nature Climate Change*, 14(9), 943–953. <https://doi.org/10.1038/s41558-024-02084-1>
- Liu, B., & Yang, Y. (2022). Large benefits of timely planting. *Nature Food*, 3(7), 495–496. <https://doi.org/10.1038/s43016-022-00553-4>
- Lobell, D. B., Ortiz-Monasterio, J. I., Sibley, A. M., & Sohu, V. S. (2013). Satellite detection of earlier wheat sowing in India and implications for yield trends. *Agricultural Systems*, 115, 137–143. <https://doi.org/10.1016/j.agry.2012.09.003>
- Ma, C.-S., Zhang, W., Peng, Y., Zhao, F., Chang, X.-Q., Xing, K., et al. (2021). Climate warming promotes pesticide resistance through expanding overwintering range of a global pest. *Nature Communications*, 12(1), 5351. <https://doi.org/10.1038/s41467-021-25505-7>
- McDonald, A. J., Keil, A., Srivastava, A., Craufurd, P., Kishore, A., Kumar, V., et al. (2022). Time management governs climate resilience and productivity in the coupled rice–wheat cropping systems of eastern India. *Nature Food*, 3(7), 542–551. <https://doi.org/10.1038/s43016-022-00549-0>
- Meek, D. W., Hatfield, J. L., Howell, T. A., Idso, S. B., & Reginato, R. J. (1984). A generalized relationship between photosynthetically active radiation and solar Radiation1. *Agronomy Journal*, 76(6), 939–945. <https://doi.org/10.2134/agronj1984.00021962007600060018x>
- Minoli, S., Egli, D. B., Rolinski, S., & Müller, C. (2019). Modelling cropping periods of grain crops at the global scale. *Global and Planetary Change*, 174, 35–46. <https://doi.org/10.1016/j.gloplacha.2018.12.013>
- Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A., & Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. *Nature Communications*, 13(1), 7079. <https://doi.org/10.1038/s41467-022-34411-5>
- Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490(7419), 254–257. <https://doi.org/10.1038/nature11420>
- O'Leary, G. J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C., et al. (2014). Response of wheat growth, grain yield and water use to elevated CO<sub>2</sub> under a free-air CO<sub>2</sub> enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology*, 21(7), 2670–2686. <https://doi.org/10.1111/gcb.12830>

- Olesen, J. E., Børgesen, C. D., Elsgaard, L., Palosuo, T., Rötter, R. P., Skjelvåg, A. O., et al. (2012). Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food Additives & Contaminants: Part A*, 29(10), 1527–1542. <https://doi.org/10.1080/19440049.2012.712060>
- Olmstead, A. L., & Rhode, P. W. (2011). Adapting North American wheat production to climatic challenges, 1839–2009. *Proceedings of the National Academy of Sciences of the United States of America*, 108(2), 480–485. <https://doi.org/10.1073/pnas.1008279108>
- Pequeno, D. N. L., Hernández-Ochoa, I. M., Reynolds, M., Sonder, K., MoleroMilan, A., Robertson, R. D., et al. (2021). Climate impact and adaptation to heat and drought stress of regional and global wheat production. *Environmental Research Letters*, 16(5), 054070. <https://doi.org/10.1088/1748-9326/abd970>
- Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling [Dataset]. *Global Biogeochemical Cycles*, 24(1), GB1011. <https://doi.org/10.1029/2008gb003435>
- Prentice, I. C., Dong, N., Gleason, S. M., Maire, V., & Wright, I. J. (2014). Balancing the costs of carbon gain and water transport: Testing a new theoretical framework for plant functional ecology. *Ecology Letters*, 17(1), 82–91. <https://doi.org/10.1111/ele.12211>
- Qiao, S., Harrison, S. P., Prentice, I. C., & Wang, H. (2023). Optimality-based modelling of wheat sowing dates globally. *Agricultural Systems*, 206, 103608. <https://doi.org/10.1016/j.agsy.2023.103608>
- Qiao, S., Wang, H., Prentice, I. C., & Harrison, S. P. (2020). Extending a first-principles primary production model to predict wheat yields. *Agricultural and Forest Meteorology*, 287, 107932. <https://doi.org/10.1016/j.agrformet.2020.107932>
- Qiao, S., Wang, H., Prentice, I. C., & Harrison, S. P. (2021). Optimality-based modelling of climate impacts on global potential wheat yield. *Environmental Research Letters*, 16(11), 114013. <https://doi.org/10.1088/1748-9326/ac2e38>
- Rabin, S. S., Sacks, W. J., Lombardozzi, D. L., Xia, L., & Robock, A. (2023). Observation-based sowing dates and cultivars significantly affect yield and irrigation for some crops in the community land model (CLM5). *Geoscientific Model Development*, 16(24), 7253–7273. <https://doi.org/10.5194/gmd-16-7253-2023>
- Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature Communications*, 3(1), 1293. <https://doi.org/10.1038/ncomms2296>
- Rezaei, E. E., Webber, H., Asseng, S., Boote, K., Durand, J. L., Ewert, F., et al. (2023). Climate change impacts on crop yields. *Nature Reviews Earth & Environment*, 4(12), 831–846. <https://doi.org/10.1038/s43017-023-00491-0>
- Riahi, K., Vuuren, D. P. V., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Rising, J., & Devineni, N. (2020). Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5. *Nature Communications*, 11(1), 4991. <https://doi.org/10.1038/s41467-020-18725-w>
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., et al. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, 111(9), 3268–3273. <https://doi.org/10.1073/pnas.1222463110>
- Sacks, W. J., Deryng, D., Foley, J. A., & Ramankutty, N. (2010). Crop planting dates: An analysis of global patterns [Dataset]. *Global Ecology and Biogeography*, 19(5), 607–620. <https://doi.org/10.1111/j.1466-8238.2010.00551.x>
- Schaphoff, S., Bloh, W. V., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., et al. (2018). LPJmL4—A dynamic global vegetation model with managed land—Part 1: Model description. *Geoscientific Model Development*, 11(4), 1343–1375. <https://doi.org/10.5194/gmd-11-1343-2018>
- Shiferaw, B., Smale, M., Braun, H.-J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Security*, 5(3), 291–317. <https://doi.org/10.1007/s12571-013-0263-y>
- Sloat, L. L., Davis, S. J., Gerber, J. S., Moore, F. C., Ray, D. K., West, P. C., & Mueller, N. D. (2020). Climate adaptation by crop migration. *Nature Communications*, 11(1), 1243. <https://doi.org/10.1038/s41467-020-15076-4>
- Sperber, K. R., Annamalai, H., Kang, I.-S., Kitoh, A., Moise, A., Turner, A., et al. (2012). The Asian summer monsoon: An intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Climate Dynamics*, 41(9–10), 2711–2744. <https://doi.org/10.1007/s00382-012-1607-6>
- Stocker, B. D., Wang, H., Smith, N. G., Harrison, S. P., Keenan, T. F., Sandoval, D., et al. (2020). P-model v1.0: An optimality-based light use efficiency model for simulating ecosystem gross primary production. *Geoscientific Model Development*, 13(3), 1545–1581. <https://doi.org/10.5194/gmd-13-1545-2020>
- Tao, F., Zhang, L., Zhang, Z., & Chen, Y. (2022). Climate warming outweighed agricultural managements in affecting wheat phenology across China during 1981–2018. *Agricultural and Forest Meteorology*, 316, 108865. <https://doi.org/10.1016/j.agrformet.2022.108865>
- Tao, F., Zhang, S., & Zhang, Z. (2012). Spatiotemporal changes of wheat phenology in China under the effects of temperature, day length and cultivar thermal characteristics. *European Journal of Agronomy*, 43, 201–212. <https://doi.org/10.1016/j.eja.2012.07.005>
- Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 108(50), 20260–20264. <https://doi.org/10.1073/pnas.1116437108>
- Timlin, D., Paff, K., & Han, E. (2024). The role of crop simulation modeling in assessing potential climate change impacts. *Agrosystems, Geosciences & Environment*, 7(1), e20453. <https://doi.org/10.1002/agg2.20453>
- Toreti, A., Deryng, D., Tubiello, F. N., Müller, C., Kimball, B. A., Moser, G., et al. (2020). Narrowing uncertainties in the effects of elevated CO<sub>2</sub> on crops. *Nature Food*, 1(12), 775–782. <https://doi.org/10.1038/s43016-020-00195-4>
- Tsai, Y. J., Mishoe, J. W., & Jones, J. W. (1987). Optimizing multiple cropping systems: Simulation studies. *Agricultural Systems*, 25(3), 165–176. [https://doi.org/10.1016/0308-521x\(87\)90018-7](https://doi.org/10.1016/0308-521x(87)90018-7)
- Waha, K., Bussel, L. G. J. V., Müller, C., & Bondeau, A. (2012). Climate-driven simulation of global crop sowing dates. *Global Ecology and Biogeography*, 21(2), 247–259. <https://doi.org/10.1111/j.1466-8238.2011.00678.x>
- Wang, H., Prentice, I. C., Keenan, T. F., Davis, T. W., Wright, I. J., Cornwell, W. K., et al. (2017). Towards a universal model for carbon dioxide uptake by plants. *Nature Plants*, 3(9), 734–741. <https://doi.org/10.1038/s41477-017-0006-8>
- Wang, X., Meng, X., & Long, Y. (2022). Projecting 1 km-grid population distributions from 2020 to 2100 globally under shared socioeconomic pathways. *Scientific Data*, 9(1), 563. <https://doi.org/10.1038/s41597-022-01675-x>
- Wang, X., Müller, C., Elliot, J., Mueller, N. D., Ciais, P., Jägermeyr, J., et al. (2021). Global irrigation contribution to wheat and maize yield. *Nature Communications*, 12(1), 1235. <https://doi.org/10.1038/s41467-021-21498-5>
- Wang, X., Zhao, C., Müller, C., Wang, C., Ciais, P., Janssens, I., et al. (2020). Emergent constraint on crop yield response to warmer temperature from field experiments. *Nature Sustainability*, 3(11), 908–916. <https://doi.org/10.1038/s41893-020-0569-7>
- Wang, Z., Yin, Y., Wang, Y., Tian, X., Ying, H., Zhang, Q., et al. (2022). Integrating crop redistribution and improved management towards meeting China's food demand with lower environmental costs. *Nature Food*, 3(12), 1031–1039. <https://doi.org/10.1038/s43016-022-00646-0>

- Xiao, L., Wang, G., Wang, E., Liu, S., Chang, J., Zhang, P., et al. (2024). Spatiotemporal co-optimization of agricultural management practices towards climate-smart crop production. *Nature Food*, 5(1), 59–71. <https://doi.org/10.1038/s43016-023-00891-x>
- Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., & Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nature Communications*, 10(1), 2844. <https://doi.org/10.1038/s41467-019-10775-z>

## References From the Supporting Information

- Ahmad, S., Abbas, G., Ahmed, M., Fatima, Z., Anjum, M. A., Rasul, G., et al. (2019). Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan. *Field Crops Research*, 230, 46–61. <https://doi.org/10.1016/j.fcr.2018.10.008>
- Chakraborty, D., Sehgal, V. K., Dhakar, R., Ray, M., & Das, D. K. (2019). Spatio-temporal trend in heat waves over India and its impact assessment on wheat crop. *Theoretical and Applied Climatology*, 138(3–4), 1925–1937. <https://doi.org/10.1007/s00704-019-02939-0>
- Croitoru, A.-E., Holobaca, I.-H., Lazar, C., Moldovan, F., & Imbroane, A. (2012). Air temperature trend and the impact on winter wheat phenology in Romania. *Climatic Change*, 111(2), 393–410. <https://doi.org/10.1007/s10584-011-0133-6>
- Fatima, Z., Ahmed, M., Hussain, M., Abbas, G., Ul-Allah, S., Ahmad, S., et al. (2020). The fingerprints of climate warming on cereal crops phenology and adaptation options. *Scientific Reports*, 10(1), 18013. <https://doi.org/10.1038/s41598-020-74740-3>
- Hossain, A., & Silva, J. A. T. D. (2012). Phenology, growth and yield of three wheat (*Triticum aestivum* L.) varieties as affected by high temperature stress. *Notulae Scientia Biologicae*, 4(3), 97–109. <https://doi.org/10.15835/nsb437879>
- Hu, Q., Weiss, A., Feng, S., & Baenziger, P. S. (2005). Earlier winter wheat heading dates and warmer spring in the U.S. Great Plains. *Agricultural and Forest Meteorology*, 135(1–4), 284–290. <https://doi.org/10.1016/j.agrformet.2006.01.001>
- Liu, Y., Chen, Q., Ge, Q., & Dai, J. (2018). Spatiotemporal differentiation of changes in wheat phenology in China under climate change from 1981 to 2010. *Science China Earth Sciences*, 61(8), 1088–1097. <https://doi.org/10.1007/s11430-017-9149-0>
- Luo, Q., O'Leary, G., Cleverly, J., & Eamus, D. (2018). Effectiveness of time of sowing and cultivar choice for managing climate change: Wheat crop phenology and water use efficiency. *International Journal of Biometeorology*, 62(6), 1049–1061. <https://doi.org/10.1007/s00484-018-1508-4>
- Oteros, J., García-Mozo, H., Botey, R., Mestre, A., & Galán, C. (2015). Variations in cereal crop phenology in Spain over the last twenty-six years (1986–2012). *Climatic Change*, 130(4), 545–558. <https://doi.org/10.1007/s10584-015-1363-9>
- Rezaei, E. E., Siebert, S., Hüging, H., & Ewert, F. (2018). Climate change effect on wheat phenology depends on cultivar change. *Scientific Reports*, 8(1), 4891. <https://doi.org/10.1038/s41598-018-23101-2>
- Sadras, V. O., & Monzon, J. P. (2006). Modelled wheat phenology captures rising temperature trends: Shortened time to flowering and maturity in Australia and Argentina. *Field Crops Research*, 99(2–3), 136–146. <https://doi.org/10.1016/j.fcr.2006.04.003>
- Wang, Z., Chen, J., Tong, W., Xu, C., & Chen, F. (2018). Impacts of climate change and varietal replacement on winter wheat phenology in the North China Plain. *International Journal of Plant Production*, 12(4), 251–263. <https://doi.org/10.1007/s42106-018-0024-0>
- Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F., et al. (2013). Observed changes in winter wheat phenology in the North China Plain for 1981–2009. *International Journal of Biometeorology*, 57(2), 275–285. <https://doi.org/10.1007/s00484-012-0552-8>
- Xiao, D., Tao, F., Shen, Y., & Qi, Y. (2016). Combined impact of climate change, cultivar shift, and sowing date on spring wheat phenology in Northern China. *Journal of Meteorological Research*, 30(5), 820–831. <https://doi.org/10.1007/s13351-016-5108-0>