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# Global Response Patterns of Major Rainfed Crops to Adaptation by Maintaining Current Growing Periods and Irrigation

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**Key Points:**
- Without agronomic adaptation, the dominant effect of temperature increase is to shorten growing periods and to reduce yields and production
- Adaptation via cultivars that maintain current growing periods under warming can compensate global production losses up to 2 K
- Irrigation would act as intensification rather than true adaptation, as it hardly affects the sensitivity of crop yields to warming

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**Abstract** Increasing temperature trends are expected to impact yields of major field crops by affecting various plant processes, such as phenology, growth, and evapotranspiration. However, future projections typically do not consider the effects of agronomic adaptation in farming practices. We use an ensemble of seven Global Gridded Crop Models to quantify the impacts and adaptation potential of field crops under increasing temperature up to 6 K, accounting for model uncertainty. We find that without adaptation, the dominant effect of temperature increase is to shorten the growing period and to reduce grain yields and production. We then test the potential of two agronomic measures to combat warming-induced yield reduction: (i) use of cultivars with adjusted phenology to regain the reference growing period duration and (ii) conversion of rainfed systems to irrigated ones in order to alleviate the negative temperature effects that are mediated by crop evapotranspiration. We find that cultivar adaptation can fully compensate global production losses up to 2 K of temperature increase, with larger potentials in continental and temperate regions. Irrigation could also compensate production losses, but its potential is highest in arid regions, where irrigation expansion would be constrained by water scarcity. Moreover, we discuss that irrigation is not a true adaptation measure but rather an intensification strategy, as it equally increases production under any temperature level. In the tropics, even when introducing both adapted cultivars and irrigation, crop production declines already at moderate warming, making adaptation particularly challenging in these areas.

**Plain Language Summary** Global warming affects yields of grain crops, which are at the base of human diets. We use crop models to quantify its impacts on global crop production and to assess how adaptation could compensate for the adverse effects. We find that up to 2 K of increased temperature production can be maintained at the current level by using new cultivars, selected to maintain current growing period length under warming. Irrigation, as another management strategy, is shown to have the potential to increase yields in dry regions if water is available. However, models do not indicate that irrigation reduces the crops' sensitivity to warming. We find large differences in the yield response to warming and adaptation across climatic regions. While continental and temperate regions may benefit from higher temperatures but also show sizable adaptation potentials, tropical and arid regions show largest temperature impacts and smaller adaptation potentials. After all, these two crop management

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options appear effective to balance the effects of moderate warming but cannot fully compensate impacts above 2 K of warming.

## 1. Introduction

Productivity of current cropping systems can be severely affected by changes in climatic and weather variables (Challinor et al., 2014; Rosenzweig et al., 2014). Increasing temperature trends have already negatively impacted productivity of agricultural crops over the last decades (Lobell et al., 2011). Multiple methodologies consistently estimate that warming of 1 K causes between 3.1% and 7.4% decline in actual yields of major cereal crops, if no adaptation measures are undertaken (Challinor et al., 2014; Liu et al., 2016; Zhao et al., 2017). Future projections indicate that large portions of current global harvested area will continue experiencing declines in the attainable yields, even under the assumption that management and technology could be transferred between regions, to areas where adaptation to climate change is most needed (Pugh et al., 2016).

Crop yield is a result of several physiological plant processes, many of which are mediated by the ambient temperature, as plants can only partially regulate their own temperature internally (Parent et al., 2010). Experimental evidence has shown that temperature increases up to a certain threshold level are associated with both accelerated rates of crop phenological development (the progress through the life cycle stages of the plant; Hatfield, 2016; Parent & Tardieu, 2012) and growth metabolism (e.g., photosynthesis and respiration; Atkin & Tjoelker, 2003; Von Caemmerer, 2000). If higher metabolic rates enhance primary productivity (biomass) per unit of time, faster phenology also leads to shorter crop growing period durations (time from sowing to maturity), which are often associated with shorter grain-filling periods and thus lower crop yields (Egli, 2011; Hatfield et al., 2011). High temperatures can reduce the net photosynthetic rate, because gross photosynthesis has a lower optimum than mitochondrial respiration (Yamori et al., 2014). High temperatures also reduce the carboxilation rate of Rubisco, increasing photorespiration in $C_3$ species (Ainsworth & Ort, 2010). Extreme temperatures can also permanently damage plant tissues and reduce yields. Grain crops are especially sensitive during the reproductive phase (Hatfield et al., 2018; Porter & Gawith, 1999), undergoing floret sterility and disruption of the pollination process leading to lower grain numbers (Farooq et al., 2011; Hatfield, 2016) and a slower grain filling rate (Rezaei et al., 2015). Although the increase in air temperature alone is not a sufficient condition for increasing the evaporative demand, temperature is among the key drivers of evapotranspiration rates (Donohue et al., 2010). Under nonlimiting water conditions, crop yields are enhanced by high rates of evapotranspiration, due to the coupled exchange of water and $CO_2$, increased by higher stomatal conductance. Vice versa, under limited water availability, if the increased evaporative demand cannot be fulfilled, stomatal conductance and hence yield are reduced (Passioura & Angus, 2010). Furthermore, higher evapotranspiration rates can deplete the soil water content faster, possibly leading to plant water stress (Bodner et al., 2015). The evapotranspiration cooling effect is the main process of canopy temperature self-regulation (Kimball, 2016). Most process-based crop models include temperature response functions on the major physiological rates, while only a few include heat-stress impact mechanisms and the canopy temperature regulation (Asseng et al., 2015; Atkin et al., 2005; Rezaei et al., 2015; Smith & Dukes, 2013; Wang et al., 2017; Webber et al., 2017). Moreover, the combined effects of different stresses, such as temperature and water, which often occur simultaneously, are still poorly understood and pose a challenge for current global crop modeling (Chenu et al., 2017).

Different agronomic management options have been proposed as adaptation strategies against temperature-induced yield losses. Most commonly, these include a shift of sowing dates, choice of cultivars with adjusted phenology, and irrigation (Challinor et al., 2014; Olesen et al., 2011; Parent et al., 2018; Ruiz-Ramos et al., 2018; Semenov et al., 2014; Tack et al., 2017). Sowing dates can be advanced or delayed to match the most favorable thermal conditions and to exploit a longer growing season (Olesen et al., 2012; Sacks et al., 2010; Waha et al., 2012). Cultivars with higher thermal-unit requirements (temperature accumulation above a certain base temperature to reach physiological maturity), different vernalization requirements (exposure to cold temperatures to induce flowering), or altered photoperiod sensitivity (development response to day length) can be used to counteract the shortening of the growing period due to temperature increase (Parent et al., 2018; Sacks & Kucharik, 2011). In turn, shorter maturing cultivars can help avoid terminal heat and water stress (Bodner et al., 2015; Mondal et al., 2013). Irrigation and other management strategies that increase soil moisture have the potential to compensate for the amplified

**Table 1**
*Global Gridded Crop Models (GGCMs) Participating in the Study With Main References*

| GGCM | References |
|---|---|
| CARAIB | Dury et al. (2011) and Pirttioja et al. (2015) |
| GEPIC | Liu et al. (2007) and Folberth et al. (2012) |
| LPJ-GUESS | Lindeskog et al. (2013) and Olin et al. (2015) |
| LPJmL | von Bloh et al. (2018) |
| pDSSAT | Elliott et al. (2014) and Jones et al. (2003) |
| PEPIC | W. Liu, Yang, Folberth, et al. (2016) and W. Liu, Yang, Liu, et al. (2016) |
| PROMET | Mauser and Bach (2009), Hank et al. (2015), and Mauser et al. (2015) |

evapotranspiration demand driven by temperature increase but also to alleviate heat stress and accelerated phenological progress, by cooling the canopy temperature (Siebert et al., 2017; Tack et al., 2017; Webber et al., 2017).

Although some studies assessed these adaptation strategies at local to regional scales (Burke & Emerick, 2016; Parent et al., 2018; Ruiz-Ramos et al., 2018; Semenov et al., 2014), their aggregated effects at the global scale remain an open question. Global projections of climate change impacts usually do not consider the adaptation potentials of agricultural system in response to climate change and might therefore overestimate impacts on crop yields and production.

Crop models allow for the conducting of virtual experiments to study the complex and interdependent biophysical effects of atmosphere and soil processes on crop growth and yield formation. As such, they are widely applied tools for the analysis of climate change impacts on agriculture and play a fundamental role in integrated assessment studies (Rosenzweig et al., 2018). Here we present the first spatially explicit global study of the adaptation potential of the major staple crops to local temperature increase in rainfed systems. We use results from the Global Gridded Crop Model (GGCM) Intercomparison (GGCMI) within the Agricultural Model Intercomparison and Improvement Project (Rosenzweig et al., 2013). The aims of the study are to assess the potential of adaptation in growing period selection and supplementary irrigation to avoid warming-induced reductions in crop yields. To this end, we study how uniform warming scenarios of 1, 2, 3, 4, and 6 K in each grid cell affect crop productivity and growing period duration. We then compare the impacts to a set of scenarios where hypothetical cultivars that maintain the reference growing period through adjusted phenology are introduced. As a second management measure, we study the effect of converting rainfed into irrigated systems. Both interventions are analyzed separately and jointly. Since crop model responses are uncertain and models often show complementary skills (Müller et al., 2017), we employ an ensemble of seven GGCMs to address associated uncertainties. Model simulations are run according to a harmonized protocol, in terms of both weather inputs and agronomic management settings. The analysis is focused on the five major staple crops: maize, winter wheat, spring wheat, rice, and soybean.

## 2. Materials and Methods

### 2.1. Simulation Protocol and Models

Seven GGCM frameworks (CARAIB, GEPIC, LPJ-GUESS, LPJmL, pDSSAT, PEPIC, and PROMET) contributed to this study (Table 1) and followed the GGCMI Phase 2 simulation protocol (refer also to section S1 in the supporting information). The GGCMs are a class of process-based crop simulation models that are built to perform simulations on crop productivity and other agroecological variables at the global scale (Rosenzweig et al., 2014). As other process-based models, they conceptually represent soil-plant-atmosphere biophysical processes, their interactions, and feedbacks. The processes are quantitatively expressed through mathematical functions, and their effects are integrated over time steps, so that the temporal dynamic of, for example, crop growth is explicitly simulated. Different crop species are represented through specific sets of processes, parameters, or functions, which are typically derived on experimental bases (Jones et al., 2017; Muller & Martre, 2019). In the GGCMs, inputs and outputs are grid based and have both spatial (longitude, latitude) and temporal (days, years) dimensions. Inputs include atmospheric $CO_2$, climate, soil, and agronomic management data. They estimate simultaneously multiple crop-specific variables, including yields, biomass production, maturity dates, and cumulative evapotranspiration.

All simulations were run at 0.5° spatial resolution and for 31 years of the historical climate (1980–2010); models with a daily time step used AgMERRA climate data (Ruane et al., 2015), while those with subdaily temporal resolution used ERA-Interim (Dee et al., 2011). We assume that the use of two different climate products does not affect the analysis much, as both data sets are observation based and were treated with the same perturbation approach (see below). Current cropland patterns were selected in model postprocessing. The grid cell- and crop-specific area was obtained from MIRCA2000 (Portmann et al., 2010) data set at 0.5° resolution. The experiment design consisted of separate simulations for five crops (maize, rice, soybean, spring wheat, and winter wheat), under one baseline temperature scenario (T0) and five levels of globally uniform temperature increases (T1, T2, T3, T4, and T6). Moreover, four management settings were simulated, which we call *control management* setting (*T-sensitive growing period* & *Rainfed*) and three *adaptive management* setting (*Fixed growing period* & *Rainfed*, *T-sensitive growing period* & *Irrigation*, and *Fixed growing period* & *Irrigation*). To target specific adaptation strategies, it is necessary to isolate the effect of individual climatic factors, as there is uncertainty in, for example, the temperature sensitivity to increased $CO_2$ and in future correlations between precipitation and temperature patterns (Carter et al., 2016; Schleussner et al., 2018; Zhao et al., 2017). In this study we aimed at isolating the impact of adaptation of crops and agricultural management to temperature increase. Therefore, the atmospheric $CO_2$ mixing ratio was kept constant at 360 ppmv in all simulation years and scenarios (see section 4). To verify whether our conclusions are independent from the $CO_2$ mixing ratio, we repeated the experiment also at 660 ppmv. For the comparison, we rely on a smaller set of GGCM, because GEPIC and PEPIC did not provide the full $CO_2$ offsets simulations (Figure S15). Similarly, precipitation and other climate drivers were unchanged across scenarios. The five artificial warming scenarios were created by perturbing input daily air temperature by five respective offsets (+1, +2, +3, +4, and +6 K).

The model ensemble was harmonized for three key management practices: (1) the growing period, (2) the water supply (rainfed or fully irrigated), and (3) the nitrogen-fertilizer application rate (assumed to be 200 kg $N \cdot ha^{-1} \cdot year^{-1}$ uniformly for each crop and cropping season, applied in two doses: 50% at planting and 50% on a crop- and grid-specific day; see protocol in section S1). The growing period harmonization followed the protocol of GGCMI Phase 1 (Elliott et al., 2015), based on observed growing period data (Portmann et al., 2010; Sacks et al., 2010), gap filled with rule-based (Waha et al., 2012) cropping calendars. Modelers were asked to calibrate the phenology, so that the average (over the 31-year simulation period) growing periods matched the provided crop- and grid-specific sowing and maturity dates. Sowing dates were kept constant at the historical observations. Maturity dates were estimated from observed harvest dates by subtracting crop-specific maturity-to-harvest times (21, 7, 21, 7, and 7 days for maize, rice, soybean, spring wheat, and winter wheat, respectively) from the latter (Elliott et al., 2015). The procedure for the calibration to observed growing periods was individually chosen by each modeling team, which could freely determine phenological parameters such as cardinal temperatures, growing degree days, vernalization, and/or photoperiod requirements, as well as set these as grid-specific or global values. The obtained parametrization was assumed to describe the available historical crop cultivar pool (see details in Tables 2 and S1).

In addition to simulations assuming *control management*, three *adaptive management* scenarios were simulated for each temperature level. Under the *fixed growing period* setting, we assumed the use of different hypothetical cultivars with adapted phenological traits, which maintain the reference growing period under each warming level. This represents a measure to counteract the higher-temperature effect on the phenological development rate, by which the time between sowing and maturity is generally shortened. All GGCMs use thermal time as the main driver of phenological progress (Table 2); therefore, higher air temperature offsets are expected to affect the growing period durations. The *fixed growing period* implementation was simulated by adjusting the crop phenological parameters, so that the average (over the 31-year simulation period) length of the growing period (in days) was the same (as closely as possible) under all T0–T6 scenarios. Therefore, modelers were asked to implement individual solutions to maintain the 1980–2010 mean growing period extent (e.g., precalculating changes in thermal time requirements based on fixed temperature shifts or adjusting by iteration). For models that separate phenology into multiple stages (e.g., sowing-to-anthesis and anthesis-to-maturity), modelers were asked to scale parameters of each stage equally, so that the timing of intermediate stages such as anthesis stayed approximately the same. Under the *irrigation* setting, we assumed the supply of unlimited irrigation water to the crops. Irrigation is studied as an adaptation measure to temperature increase because there are interactions between crop temperature and water supply. Higher air temperatures can increase the rates of evapotranspiration and soil water depletion, while

**Table 2**
*GGCMs Participating in the Study With Main Features of Their Phenological Module*

| GGCM | Temperature response function | Phenological drivers | Perceived Temperature | Phenological phases |
|---|---|---|---|---|
| CARAIB | Lin., Tmin | T(GDD), W | Tair | 1 (S-M) |
| GEPIC | Lin., Tmin, Topt | T(GDD), T(V), DL | Tair | 1 (S-M) |
| LPJ-GUESS | Lin., Tmin, Topt*, Tmax* | T(GDD), T(V) | Tair | 2 (S-A-M) |
| LPJmL | Lin., Tmin | T(GDD), T(V) | Tair | 1 (S-M) |
| pDSSAT | Lin., Tmin, Topt | T(GDD), T(V), DL, W | Tair | Crop specific |
| PEPIC | Lin., Tmin, Topt | T(GDD), T(V), DL | Tair | 1 (S-M) |
| PROMET | Curv., Tmin, Topt, Tmax | T(DVR), T(V), DL, W | Tleaf | 100 (BBCH) |

*Note*. More details are reported in section S2 and Table S1. Temperature response function for phenology (Wang et al., 2017): Lin = linear; Curv. = curvilinear; Tmin = minimum cardinal temperature; Topt = optimum cardinal temperature; Tmax = maximum cardinal temperature; asterisk (*) denotes for spring wheat and winter wheat only. Phenological drivers: T(GDD) = temperature (growing degree days); T(DVR) = temperature (development rate); T(V) = temperature (vernalization); DL = daylength; W = water; N = nitrogen. Perceived temperature: Temperature perceived by the crop, driving phenological and metabolic processes (Tair = air temperature; Tleaf = leaf temperature). Phenological phases: S = sowing; A = anthesis; M = maturity; BBCH = full BBCH. GGCMs = Global Gridded Crop Models.

soil water deficits can reduce evapotranspiration and thus increase the canopy temperature, consequently affecting the phenological development and growth rates. Although not all these effects are included in the GGCMs, each of them represents water-to-temperature interaction in some ways. All the ensemble's GGCMs simulate evapotranspiration by formulas that require temperature as an input variable; thus, temperature increases are expected to modify the crop water demand. Moreover, some GGCMs represent the feedback between water stress and phenology. Particularly, two models include water deficit as directly affecting phenological progress (Table 2). In pDSSAT, water deficit may delay the onset of reproductive growth, while it accelerates the grain filling phase (Jones et al., 2003), while in CARAIB, the water deficit may delay germination. Only the PROMET model includes the indirect effect of soil water status on phenology, through the explicit simulation of the leaves temperature (Table 2). Water deficit results in increased leaf temperature that usually accelerates the phenological progress. Irrigation was assumed to be unconstrained by surface water availability. *Irrigation* was implemented to refill soil water content to field capacity as soon as it fell below a threshold of 90% of field capacity (Elliott et al., 2015). We also tested the combination of *fixed growing period* and *irrigation*.

### 2.2. Model Output Processing

Models reported yearly dry-matter yields (Mg/ha), sowing dates (day of year), and maturity dates (days from planting) for the period 1980–2010, separately for maize, rice, soybean, spring wheat, and winter wheat. Yield failures were reported as 0 Mg/ha, while nonsimulated grids were reported as NA values. Maturity dates of yield failure years were set to NA.

We computed the long-term averages (1981–2009) for yield, sowing date, and maturity date for the period 1981–2009 for each model, temperature offset scenario, and management setting. The first and last years of the simulation time series were excluded to avoid reporting issues relating to completeness of growing periods (Elliott et al., 2015).

Under the reference temperature scenario (T0), the growing periods were assumed to be the same in all management settings, and thus, yields were assumed to be the same as well for the *rainfed* and *irrigation* settings. For efficiency reasons, outputs for T5 were not simulated but derived by linear interpolation between T4 and T6 for each GGCM, crop, and grid cell, independently for each of the management setting (categorical variables). Some individual simulations were not available for all models (Figure S1), and we gap filled missing simulations by linear interpolation of neighboring scenarios (with an exception for rice and soybean for the LPJ-GUESS model that were not simulated at all and for winter wheat for the PEPIC model that was excluded from the analysis due to unreliable simulations of the growing periods). The CARAIB model had only sowing dates harmonized, while the model was not calibrated to match observed harvest dates (see section S2.1 for details), but the simulation with *fixed growing periods* are unaffected.

All GGCM output data are made publicly available at zenodo.org repository. The DOI references are provided in Table 3. For data processing, we used R (R Core Team, 2018) and R-packages for handling netcdf4

**Table 3**
*DOI References for Accessing the Data Used in This Study*

| GGCM | Maize | Soybean | Rice | Winter wheat | Spring wheat |
|---|---|---|---|---|---|
| CARAIB | 2582522 | 2582508 | 2582504 | 2582516 | 2582499 |
| GEPIC | 2582247 | 2582258 | 2582251 | 2582260 | 2582263 |
| LPJ-GUESS | 2581625 | — | — | 2581638 | 2581640 |
| LPJmL | 2581356 | 2581498 | 2581436 | 2581565 | 2581606 |
| pDSSAT | 2582111 | 2582147 | 2582127 | 2582163 | 2582178 |
| PEPIC | 2582341 | 2582433 | 2582343 | 2582439 | 2582455 |
| PROMET | 2582467 | 2582488 | 2582479 | 2582490 | 2582492 |

*Note*. All GGCMs' output data, separated by crop and model, can be found at https://doi.org/10.5281/zenodo/XX, where XX is the value reported in the table. GGCM = Global Gridded Crop Models.

(Pierce, 2015), performing computation (Dowle & Srinivasan, 2017; Wickham, 2011), and plotting results (Wickham, 2009).

### 2.3. Metrics

All GGCMs included in this study simulate crop phenology as a function of temperature (thermal-unit sum and vernalization). We quantified the average impact of globally uniform temperature increase on growing periods and yields across all GGCMs and cropland grid cells by fitting linear regression models for each individual crop (Figures 2a and 2b). To understand whether there is a direct relationship between responses of growing periods and yields to temperature increase, we analyzed the joint distribution of their changes from the reference scenario (T0). We categorized the possible responses into four classes, defined by the sign of change of the two variables, and illustrated their frequency of occurrence within each class and climatic regions (Figure 2c).

To quantify the impact of temperature increase on global production of all crops, we estimated the production change (%) under warming scenarios as compared to the reference temperature scenario (T0). Since here we considered production of crops of relevance for human nutrition, we transform yields from metric tons to their calorie content, as this is the most common metric for quantifying globally available food (Willett et al., 2019). The grid-based global calories production under the management system $m$ and temperature offset $n$ ($P_{m,n}$, equation (1)) was obtained as the sum of production across all crops ($c$) and grid cells ($g$). Within the grid cell $j$, the yield of crop $i$ was multiplied by its calorie content and by its area in that grid.

$$P_{m,n} = \sum_{j=1}^{g}\sum_{i=1}^{c} area_{j,i} \cdot yield_{j,i} \cdot calorie_i. \tag{1}$$

The calorie content values were derived from the FAO (2001) food balance sheet handbook, which reports food composition in terms of weight "as purchased"; therefore, model output yields were converted from dry to fresh matter as from Wirsenius (2000) to obtain the calorie yield per crop and unit of area (Table 4).

**Table 4**
*Crop-Specific Parameters Used for Converting the Crop Yield Model Outputs From Metric Tons of Dry Matter (Mg/ha) to Their Calorie Content (Gcal/ha)*

| Crop | Grain dry matter (% as-purchased) | Calorie content (Gcal/Mg) |
|---|---|---|
| Maize | 88 | 3.560 |
| Soybean | 91 | 3.350 |
| Spring wheat | 88 | 3.340 |
| Winter wheat | 88 | 3.340 |
| Rice | 87 | 2.800 |

*Note*. The grain dry matter (% of as-purchased grain weight) is the yield conversion factor between as-purchased-grain weight and dry-grain weight. The calorie content are the calories per metric ton of as-purchased grain weight.

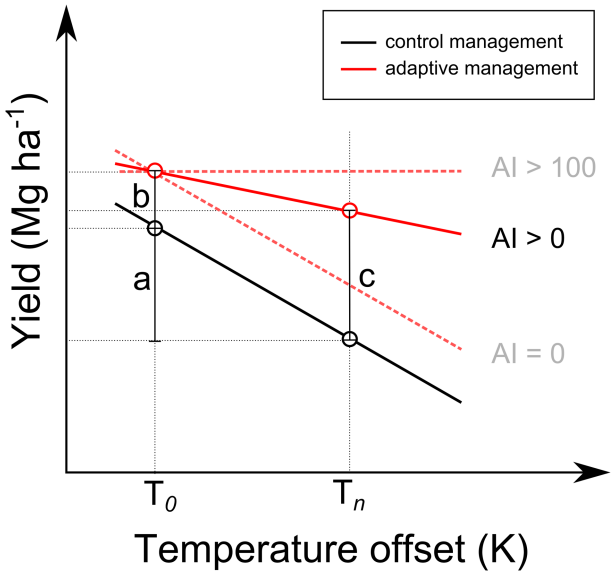


**Figure 1.** Diagram of the Adaptation Index (*AI*) computation (modified from Lobell, 2014). The plot shows the yield (Mg/ha) as a function of increasing temperature between the reference climate and the offset temperature $T_n$ (ranging from T1 to T6). The black and the red lines represent the Yield ~ Temperature response with *control* and *adaptive* crop management, respectively. The red dashed lines delimit the space where *adaptive* management only partially compensate yield losses ($0 < AI < 100$). *AI* is computed as in equation (2) where *a* is the yield impact of the temperature increase from $T_0$ to $T_n$ on yield under *control* management, *b* is the effect that the adaptive management would have under the reference conditions ($T_0$), and *c* is the effect of the *adaptive* management under the offset temperature $T_n$.

To determine whether the simulated adaptation measures are effective, we computed the *Adaptation Index* (*AI*, equation (2); modified from Lobell, 2014) for each grid cell, temperature offset, and *adaptive management* setting as

$$AI = 100 \cdot (c - b)/|a|, \; if \; a < 0, \tag{2}$$

where *a* is the impact of temperature increase on yield under *control management*, *b* is the effect that the *adaptive management* would have under the Reference Scenario T0, and *c* is the effect of the *adaptive management* under increased temperature scenarios (Figure 1). Note that by definition under T0, the *fixed growing period* is equal to *T-sensitive growing period*, and therefore, *b* is zero for this *adaptive management* scenario. Values of *AI* are computed only if *a* is negative; otherwise, temperature increase is considered beneficial. *AI* ranges between $-\infty$ and $+\infty$, with $AI \geq 100$ indicating full compensation or overcompensation of losses (full adaptation), $0 < AI < 100$ indicating partial compensation of losses (partial adaptation), and $AI < 0$ indicating no compensation of losses, meaning either an amplification of damages or that the *adaptive management* can be increasing production, without being impact reducing (intensification), and therefore not a true adaptation measure (Lobell, 2014). *AI* was computed for each single GGCM, and we then computed the median ensemble and uncertainty (range) across GGCMs.

## 3. Results

### 3.1. Crop Phenology Response to Temperature Offsets Without Adaptation

At the global aggregation level, in absence of adaptation measures, the growing period length approximates a negative linear response to increasing temperature from 1 to 6 K (Figure 2). The slope of this relationship (days of growing period lost per Kelvin of warming) is similar across the five simulated crops, ranging from 5.4 (maize) to 3.8 days/K (spring wheat). The spread of growing period length across all GGCMs and all cropland globally does not change fundamentally at higher temperature offsets (whiskers in Figure 2), yet it somewhat increases for soybean and decreases for winter wheat. The general response is similar across the GGCMs as most models simulate shortening growing periods with higher temperatures (Figure S4). Yet some models show smaller sensitivity of the growing period change across crops (PEPIC and PROMET)

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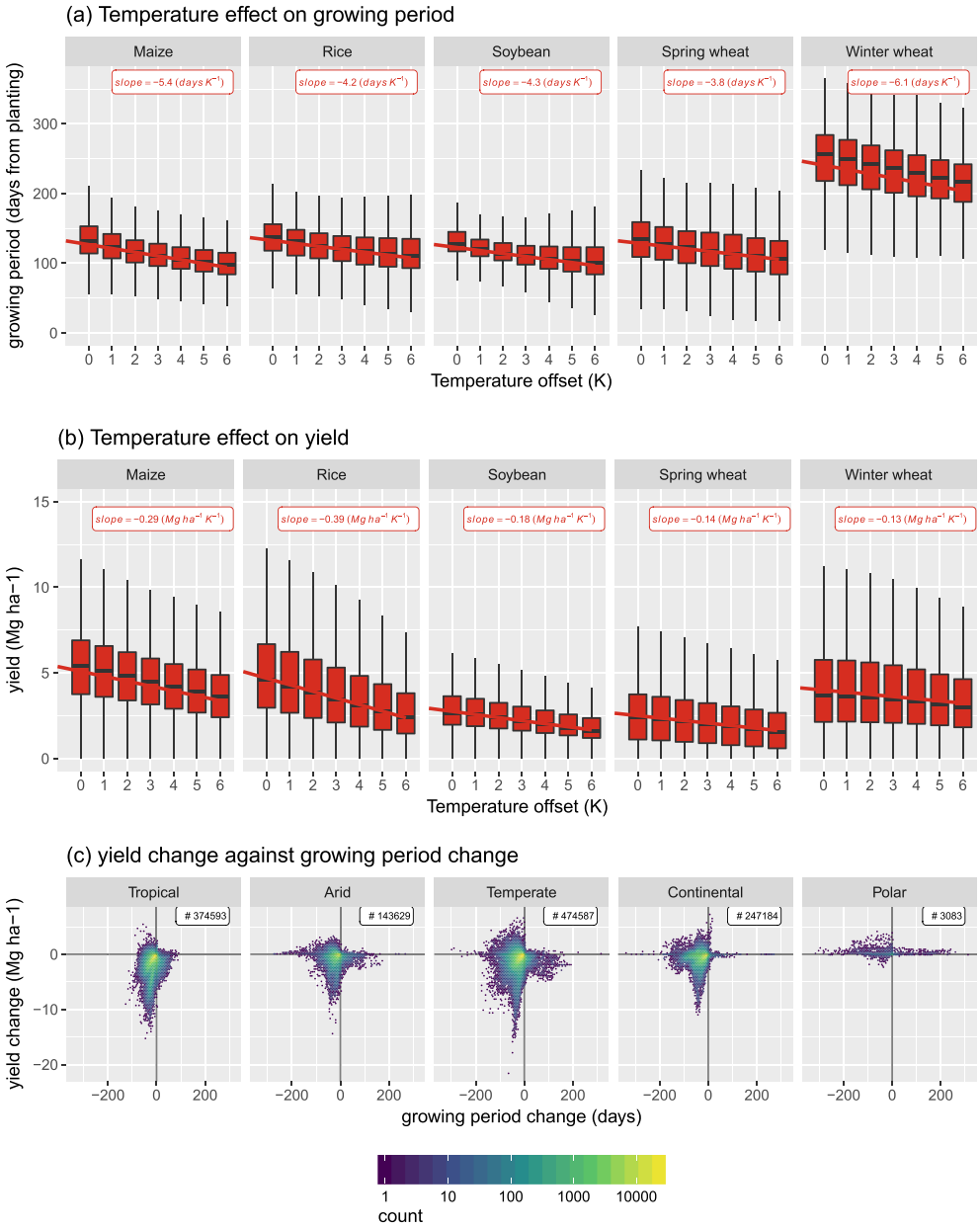


**Figure 2.** Effect of increasing temperature on (a) crop phenology (growing period duration in days from planting) and (b) yield (Mg/ha), separated by the five simulated main staple crops, without any adaptation measure. Each box represents the 25th, 50th, and 75th percentile of all grid cells values of all Global Gridded Crop Models for a specific temperature offset. The whiskers extends from the hinge to the smallest and largest values, no further than 1.5 interquartile range. The red line is the linear regression across simulated values and temperature offsets, and its slope is indicated in each plot. The heat map in (c) displays the relationship between yield changes (Mg/ha) and growing period changes (number of days) for all crops and all temperature offsets, separated by the Koeppen-Geiger climate regions. Changes are calculated as the absolute differences between the reference and the offset scenario. Plot in (a) and (b) includes all cultivated grid cells at all temperature offsets between T1 and T6; note that T5 is not simulated but linearly interpolated from T4 and T6. T5 is not included in (c). Hexagons are colored according to their frequency count.

and, in one case, an opposite sign of change (rice for PROMET). In PROMET, phenology is implemented to slow down at high temperatures above a crop-specific optimum (Table 2), so that warming can also lead to growing periods longer than in the reference temperature scenario. This is the case for LPJ-GUESS (spring and winter wheat) as well, although parametrized with higher optimum thresholds (Table 2), which could be the reason for the nonoccurrence of such increase. In some GGCMs (LPJmL and PROMET), for winter wheat, vernalization requirements are not satisfied as quickly under warming, so that the pheno-

logical development decelerates. Spatial patterns of growing period length at different temperature levels show that its shortening (days) is especially pronounced in cold-temperature limited regions for maize and soybean (Figure S8a), because under warming, more days reach temperatures above the crop-specific base temperatures ($T_{min}$).

### 3.2. Impact of Temperature Offsets on Crop Yield

The crop yield response follows similar patterns as the growing period, with an almost linear decline with temperature at the global aggregation level. Yield declines range between 0.39 $Mg \cdot ha^{-1} \cdot K^{-1}$ for rice and 0.13 $Mg \cdot ha^{-1} \cdot K^{-1}$ for winter wheat (Figure 2b). As opposed to the growing period length, the spread of the GGCMs declines with higher temperature offsets. For rice, soybean, and winter wheat, we also observe narrowing interquartile ranges (Figure 2b) with higher temperature offsets. This reflects a stronger reduction of high yields than of low yields. Indeed, for some regions and models, yields are already null under the baseline climate and cannot decrease further.

Changes in growing period and changes in crop yields do not follow a one-to-one relationship, but in most cases (~69% of all cultivated grid cells, across crops and temperature offsets), shorter growing periods are associated with declining yields (Figures 2c and S8): 69%, 61%, 68%, 69%, and 11% for tropical, arid, temperate, continental, and polar areas, respectively. There are rare cases where decreasing growing periods are associated with increasing yields or where longer growing periods are associated with declining yields. The former can be explained either by the beneficial effect of overall higher growing season temperatures that stimulate primary productivity, as for maize in high latitudes, or by the benefit of a shorter growing season that escapes water stress, if water conditions become more limiting under increased temperatures. Similarly, longer growing periods can lead to yield decline if the growing periods extend into dry season. Longer growing periods with increasing crop yields are, however, basically nonexistent.

### 3.3. Effectiveness of Adaptation Measures

Increasing temperatures decrease global production of all crops almost linearly, except for winter wheat, where decrease only starts at a warming of ~2 K (red line in Figure 3a). Using different cultivars so that the original growing period would be maintained, the total global calorie production of all five crops can be stabilized up to ~2 K and declines with further warming (*fixed growing period* setting; yellow lines in Figure 3a; all crops). Individual crops, however, show different temperature responses. Rice, soybean, and spring wheat show an almost linear decline with any warming. For maize, the *fixed growing period* setting leads to stable global production up to warming of ~3 K. For winter wheat, warming of up to ~4 K is projected to even increase global production and decreases only thereafter. At the global aggregation level, the agreement across GGCMs is reasonable, except for large uncertainty for spring wheat (yellow shaded area in Figure 3a). All models show benefits from the *fixed growing period* setting, compared to *control management*. For all crops except rice, there is always at least one GGCM that simulates increase global production with the fixed growing period setting up to >5 K.

Converting all currently rainfed to irrigated cropland (assuming unlimited water supply; *irrigation* setting) would increase global calorie production by ~20% (blue line in Figure 3a). At such higher level, fully irrigated production would also decline with increasing temperatures at similar rates to rainfed production. Yet the intensification through irrigation could maintain current production levels up to ~4 K at global level across crops. Similar patterns are displayed by all crops, while irrigated winter wheat may be able to maintain current production levels even up to >6 K. In combination, the *fixed growing period* and *irrigation* measures support global calorie production increases up to 4 K temperature offests (green line in Figure 3a) and could maintain current levels across all tested warming levels. For maize, the combined implementation of both measures leads to continuous increases in production across all tested warming levels. Global rice production seems to be the least sensitive to the two adaptation options at any temperature offset. Across the different GGCMs, the effects of irrigation on currently rainfed cropland are generally more uncertain than the effects of warming on rainfed crop production. The size of the response of spring wheat production to introducing *irrigation* to all rainfed areas is highly uncertain across GGCMs, as two models (LPJmL and pDSSAT) project roughly doubled spring wheat production under irrigation, whereas the other models project increases of only 25%. Still, as for the other crops, the uniform decline of irrigated spring wheat production is found by all GGCMs.

The level of warming up to which global production of all crops can increase differs across regions and management scenarios (Figure 3b). Particularly, in the tropics under the *fixed growing period*, global rainfed

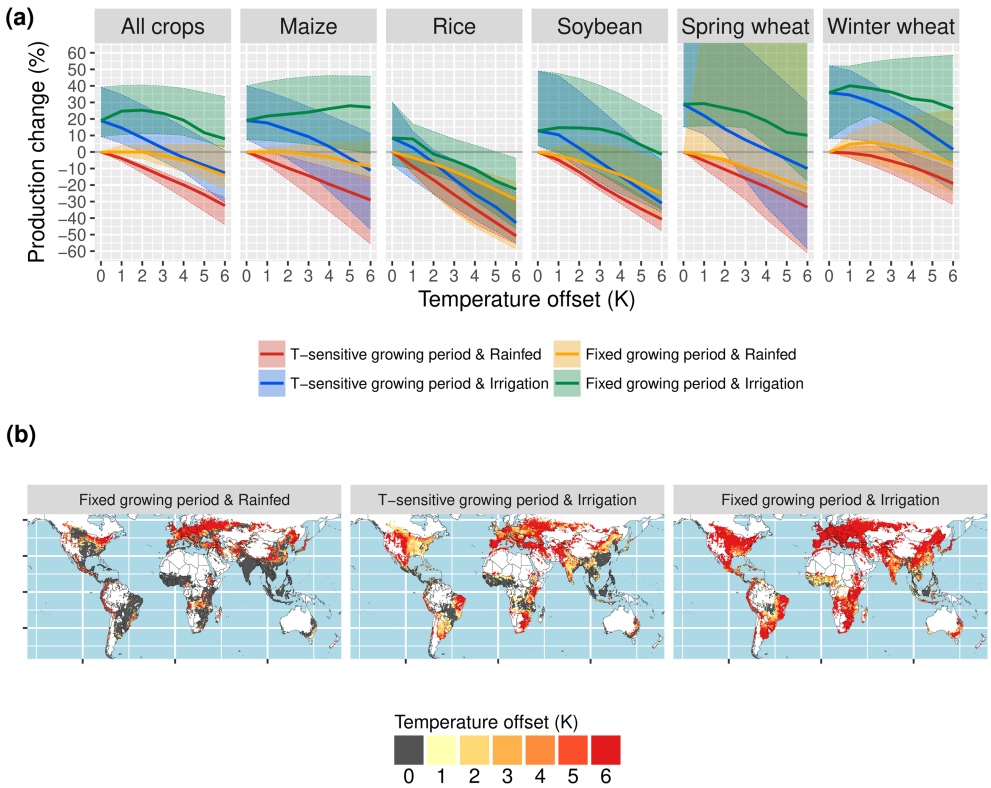


**Figure 3.** Effect of increasing temperatures and four management settings on global calorie production. (a) Calories production change (percent change), shown as an aggregation for each crop. The lines and the shaded areas represent the median and the range of the Global Gridded Crop Models ensemble, respectively. For visualizing the full range of the spring wheat crop, refer to Figure S11. (b) Global patterns of temperature offsets up to which calories production of all crops increases under each *adaptive management* scenario, compared to the *control management* in the baseline temperature scenario (T0).

production is already declining at 1 K of warming, whereas in temperate and continental zones, it increases up to high levels of warming (also 6 K). *Irrigation* would maintain higher production levels up to 6 K in arid regions, where however irrigation expansion would be difficult due to the scarce water resources. In temperate and tropical regions where *irrigation* would likely be more feasible, this measure is effective until moderate warming only or not effective at all like in many tropical areas. Only the combination of *fixed growing period* and *irrigation* maintains crop production above the original level in largest part of the global land. Yet the tropical areas show production declines at 1 to 4 K of warming.

Increases in crop production are in some cases also a direct effect of temperature increase, even in absence of management changes, as in high-latitude regions (dark green in Figure 4a). Although the three management options show potentials to increase crop productivity globally, they are not necessarily true adaptation measures. Particularly, we find that despite the positive effect of *irrigation* in leverage yields, it does not ($AI < 0$) or only partially ($0 < AI < 100$) reduce the negative effect of warming (shortening of the growing period) but rather overcompensate them. The effectiveness of the *fixed growing period* differs across regions (Figure 4a). Figure 4a shows in detail the effectiveness of the *fixed growing period* adaptation for a warming level of 4 K; however, the patterns are very similar across all warming levels tested here (see Figure S13). In temperate and continental regions, there is larger potential for adaptation through the *fixed growing period* than in tropical and arid regions. The *fixed growing periods* measure has hardly any positive effect in arid regions but has the potential to maintain current production levels in continental regions (see Figure S12). In arid regions, the *fixed growing period* measure can lead to amplified damages and would thus be a form of "maladaptation" (orange color in Figures 4a, S13, and S14). The models here capture the typical interaction mechanism between plant phenology and water use. The selection of earlier-maturing cultivars in environments characterized by water shortage is a well-known strategy for avoiding water stress to crops (Bodner

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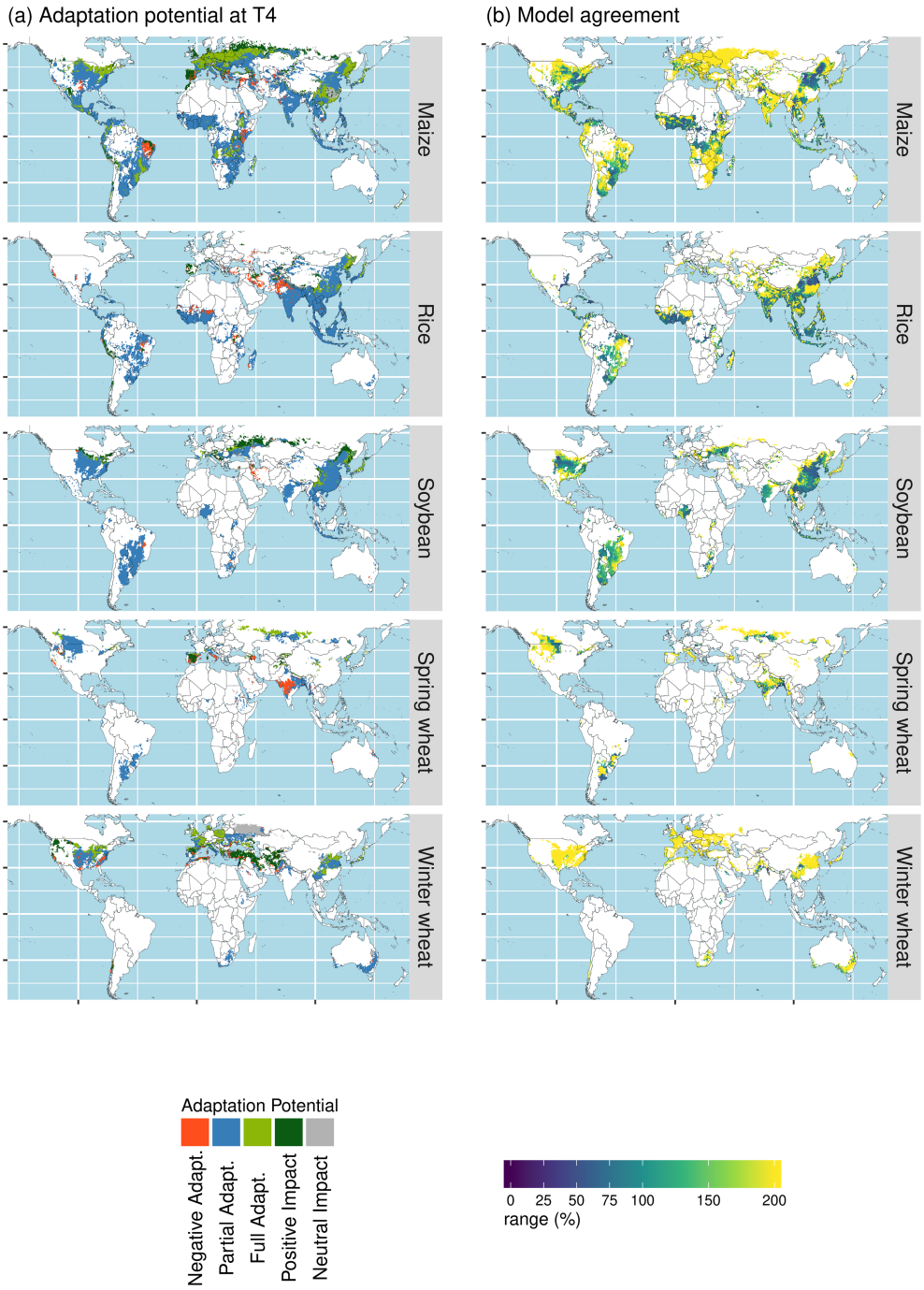


**Figure 4.** Adaptation potential of rainfed crops under a 4 K temperature offset in combination with *fixed growing period* adaptation scenario (a) and model agreement (b). (a) shows Global Gridded Crop Model ensemble medians for (i) negative temperature impact and negative adaptation effect (orange, $a < 0$ & $AI < 0$); (ii) negative temperature impact and positive adaptation effect but with only partial compensations (blue, $a < 0$ & $0 < AI < 100$); (iii) negative temperature impact and positive adaptation effect, with full compensation (light green, $a < 0$ & $AI > 100$); (iv) positive temperature impacts (dark green, $a > 0$); and (v) neutral impacts (gray, $a = 0$). (b) shows the range of $AI$ across Global Gridded Crop Models, only in the grid cells where temperature increase has negative impacts ($a < 0$). Values larger than 200% are constrained to 200% for better visualization. $AI$ and $a$ are computed as in equation (2).

et al., 2015). Under increasing temperatures, the atmospheric water demand increases as well, which cannot be fulfilled by actual evapotranspiration. Extending the growing period therefore worsens water stress, determining a maladaptation effect. There are substantial differences in the global patterns of adaptation effectiveness across the GGCMs (Figures 4b and S13), with a larger agreement on where *fixed growing period* has little adaptation effectiveness, but models often disagree (larger ensemble *AI* range) on the magnitudes of the adaptation effectiveness of the *fixed growing period* measure (Figure 4b).

In tropical regions, *irrigation* has little potential to intensify production, whereas it has substantial potential in arid regions with the highest levels of water stress (see Figure S12). However, availability to realize these potentials are not considered here.

Under higher $CO_2$ mixing ratio of 660 ppmv, temperature impacts with the *control management* are slightly reduced compared to those under 360 ppmv. However, the findings on *fixed growing period* and *irrigation* adaptation potentials hold valid also when assuming higher $CO_2$ mixing ratio (Figures S16–S18). For spring wheat only, the adaptation potential of the *fixed growing period* setting is larger under 660 ppmv than at 360 ppmv, so that global level production can be maintained across all temperature offsets.

## 4. Discussion

Using a large ensemble of GGCMs in a systematic warming experiment, we find that temperature increases lead to continuous reductions in global crop production without compensating adaptation measures, which is in line with previous findings (Challinor et al., 2014; Lobell et al., 2011; Liu et al., 2016; Rosenzweig et al., 2014; Zhao et al., 2017). Our results suggest that this decline is driven by a combination of accelerated phenology and thus shorter growing periods as well as by direct effects on plant growth. As such, selecting cultivars that maintain the original growing period under warming is a viable adaptation measure in most regions, as it reduces or fully compensates negative effects of warming on crop yields. This confirms recent findings in that historical warming already leads to the use of longer maturing cultivars, which in turn contributed to the increasing yield trend in the United States and Europe (Butler et al., 2018; Parent et al., 2018). The response, however, is variable across regions, crops, and GGCMs and thus subject to uncertainties.

In absence of detailed information on crop and cultivar parameters, process-based models applied at global scale have to make critical assumptions. Folberth et al. (2016) highlights how important the assumptions on management aspects are for simulating crop yields. Simulated adaptation potentials at global scale are necessarily affected by coarse model assumptions as well. Previous GGCMI ensemble studies showed that harmonization of management settings (Elliott et al., 2015) can have substantial effects on model performance (Müller et al., 2017); however, only a small set of settings can be harmonized, limited by the availability of global data sets (e.g., fertilizer and growing periods). Recently, Jägermeyr and Frieler (2018) highlighted that the correct timing of the growing season is particularly critical for realistic yield simulation. In this exercise, participating modelers were therefore asked to parametrize crop phenology so that current observed growing periods (Elliott et al., 2015) were reproduced by each model (by calculating required thermal units based on AgMERRA weather data; Ruane et al., 2015). In the simulations without *fixed growing period* adaptation (*T-sensitive growing period* setting), simulated growing periods were allowed to respond to warming, depending on the individual GGCMs' implementation of phenology (Table 2). In the *fixed growing period* adaptation setting, the crop phenology parameters were recalibrated for each warming level, so that the growing period length was roughly unaffected. However, no harmonization was requested for any other cultivar parameters or the functional form of the phenological response to temperature (Table 2). To this end, the ensemble of GGCMs used here reflects a broader variety of cultivars and management systems, which may explain part of the diverse modeled regional response to *fixed growing period* adaptation. Cardinal temperatures of phenological development (Table S1) are considered crop specific (Hatfield et al., 2011), with very little variability within species among genotypes and no acclimation to changes in temperature (Parent & Tardieu, 2012), therefore supporting the use by the GGCMs of crop-specific global parameters in the temperature response function for phenology. On the other hand, photosynthesis and enzyme activity acclimate to higher temperature (Parent & Tardieu, 2012) and cultivars differ in their sensitivity to heat stress. In particular, cultivars that are selected in hot climates are less sensitive to yield losses (Butler & Huybers, 2013), a feature that is not reflected in the GGCMs. Rezaei et al. (2018) suggest that the temperature response in phenology could be flawed by not accounting for changes in cultivar choice in the historic past. Also, Zhu et al. (2019) find that GGCMs often overestimate the response in growing period length compared

to other yield-reducing effects of warming. This uncertainty in regional responses is in contrast to the robust finding of *fixed growing period* adaptation at the global aggregation, where models do not differ much. It remains unclear how the diverse regional responses need to be aggregated. Considering the complex interaction of initial cultivar parameterization for baseline yields and warming effects (Folberth et al., 2016), this requires further research and requires better information on existing management systems globally. In this study we assume the availability of the adapted cultivars to maintain the growing periods. However, it is not clear whether these would actually be available today or in the future, and how large would the effort be for breeding such new cultivars, especially under elevated temperatures (Challinor et al., 2016).

While irrigation comes with substantial potential to lift yields in water-limited regions, therefore buffering temperature-induced adverse effects, converting rainfed to irrigated crop production cannot be considered as a true adaptation measure but rather intensification (Lobell, 2014). This is because the beneficial effect of irrigation is similar under warming and under current conditions. This is surprising, because previous studies suggest that irrigation reduces the direct negative effects of warming on crop yields. Schauberger et al. (2017) find that irrigation buffers against damages from exposure to hot temperatures for maize in the United States and maize yield response to temperature is found to be highly leveraged by soil moisture status (Carter et al., 2016) and thus presumably irrigation in dryer areas. Observed yield declines during historical heat waves and droughts are predominantly attributed to rainfed systems (Jägermeyr & Frieler, 2018). The lack of reproducing this effect in this model ensemble may be due to several reasons. First, only one of the seven GGCMs (PROMET) accounts for the cooling effect of increased transpiration under irrigation by simulating canopy temperature, whereas all other models assume canopy temperature to be equal to air temperature. However, PROMET also shows the same pattern in the response to irrigation and warming as all the other GGCMs: intensification of production through converting rainfed to irrigated production but no benefit on the negative response to warming (see Figure S11). Second, if models tend to overestimate the growing period response to warming, as suggested by Rezaei et al. (2018) and Zhu et al. (2019), it may be that the shortening of the growing season overly dominates the yield response and direct effects of warming on plant growth are underrepresented in the current GGCMs. If canopy temperatures are not accounted for, irrigation cannot affect the simulated length of the growing period and will not show the underrepresented effects on crop growth. Nonetheless, this intensification could compensate for much of the warming-induced damage, at least in regions where irrigation water could be supplied.

We find that the challenge to maintain current productivity levels under warming is particularly large in the tropical and arid climate zones, given that the adaptation of *fixed growing period* has little potential to reduce the negative effects of warming on crop yields and that shifting rainfed to irrigated production has little potential in the tropics and will be severely hampered by water availability in most arid regions. Furthermore, large areas of the tropics are bound to experience climate conditions that have no analogs under current climate conditions (Pugh et al., 2016), so that breeding or designing cultivars for such conditions will be particularly challenging.

Generally, the GGCMI Phase 2 modeling experiment is an artificial setup with several implications for the interpretation of results (Supporting Information S1). First, we study the effects of warming in a uniform manner, that is, all days warmed by exactly the same offset, which is not representative for realistic climate change scenarios. Second, associated impacts from changes in precipitation under climate change are ignored, while direct impacts of elevated atmospheric $CO_2$ mixing ratios are tested in a rather simplistic manner. This can substantially enhance crop growth (Kimball, 2016) but also amplify high temperature damage to crops (Prasad et al., 2006). However, we find that our findings regarding adaptation potential to temperature increase remain valid under both $CO_2$ mixing ratios. Third, we here consider only high-input systems with nitrogen fertilization levels of 200 kg N/ha and no other nutrient limitations (e.g., Phosphorus and Potassium). However, these simplifications seem justified, as we are aiming to understand how warming-induced damages to crop production can be compensated by an adaptation measure that counteracts the phenological acceleration, which is almost exclusively temperature driven. This sensitivity study helps to isolate effects, which are typically difficult to separate in realistic climate scenarios, in which the relationship of changes in temperature, precipitation, and atmospheric $CO_2$ mixing ratios are very model dependent (McSweeney & Jones, 2016). Nevertheless, results from the GGCMI CTWN-A experiment as analyzed here should not be misinterpreted as assessments of adaptation options under realistic climate change scenarios.

The adaptation measure to regain the warming-induced loss of growing period duration considered here is also a simplified theoretical case. As the maintaining of the original growing period is not always beneficial or somewhat shorter or longer growing periods could have even greater potential to adapt to warming, this only represents one specific case of a broader continuum. Also, adaptation in cultivar choice is likely linked to changes in sowing dates to best adapt cropping systems and exploit benefits of a longer growing season, as it is already observed with already contributes to recent yield trends (Butler et al., 2018; Parent et al., 2018). Flexible sowing dates could thus further increase the adaptation potentials shown here as we assume static sowing dates even under extreme temperature offsets. This is especially relevant in regions with temperature seasonality (Waha et al., 2012). Shifting sowing dates has nonetheless its complications, especially for crops with sensitivity to photoperiod and or vernalization, as it could in turn affect the length of the growing period, with importance consequences on the final yields (Abdulai et al., 2012; Hunt et al., 2019). Moreover, we analyze winter and spring wheat separately, therefore maintaining their crop areas static as though they were two different crops. This is a simplification, as these are rather two varieties of the same species, of which the spatial distribution depends on temperature and particularly on the existence of a winter season suitable for vernalization. A change in temperature level can then make it more advantageous to switch between winter and spring varieties, than trying to maintain the original growing season as an adaptation option. However, selecting a static growing season as a uniform adaptation measure again facilitates better interpretation of the results. Still, uncertainties are linked to the differences in interpreting the modeling protocol. The simulations conducted by CARAIB did not parametrize cultivar traits to reproduce the harmonization target for crop maturity (Elliott et al., 2015) but do keep their growing seasons constant under warming in the adaptation setup. Other models did follow the harmonization protocol, but growing seasons are not always closely reproduced (see Figure S2). This contributes to the uncertainty in the modeled response to adaptation.

## 5. Conclusions

Without agronomic adaptation measures, future warming as projected under climate change will negatively affect global crop production in absence of adaptation measures. Despite possibly compensating or amplifying effects from simultaneously changing precipitation and atmospheric $CO_2$ concentrations, it is important to understand temperature-driven plant physiological processes, in order to identify adaptation options to warming-induced yield reductions. By using a GGCM ensemble, we find that adaptation via new cultivars that would maintain current crop growing periods under warming is a viable option with substantial potential to fully compensate warming-induced yield reductions, especially in the temperate and continental climate zones. Even though growing period adaptation also shows positive effects in the tropics but hardly any in arid regions, these effects are insufficient to fully compensate warming-induced yield reduction even at low levels of warming. Tropical regions are also not very responsive to introducing irrigated production systems so that maintaining current crop productivity under warming is particularly challenging in the tropics. Here we have used the largest available data set of model simulations at global scale to present the most comprehensive approach for simulating temperature impacts on crop yields. That said, scarcity of global-scale management input data renders simulations at this scale inherently uncertain. Yet we find good agreement on the globally aggregated impacts and effects of adaptation across the GGCMs that implicitly represents a broader set of management systems by differing in the parametrization of management-related features. Future research will have to explore the potential for adaptation and intensification in temperate and continental climate zones to contribute to future food security and will have to identify ways how the double burden of strong climate change impacts and low adaptation potential in the tropical and arid climate zones can be alleviated.

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