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Large potential for crop production adaptation depends on available future varieties

Florian Zabel[1] | Christoph Müller[2] | Joshua Elliott[3] | Sara Minoli[2] | Jonas Jägermeyr[2,3,4] | Julia M. Schneider[1] | James A. Franke[5,6] | Elisabeth Moyer[5,6] | Marie Dury[7] | Louis Francois[7] | Christian Folberth[8] | Wenfeng Liu[9] | Thomas A.M. Pugh[10,11] | Stefan Olin[12] | Sam S. Rabin[13] | Wolfram Mauser[1] | Tobias Hank[1] | Alex C. Ruane[4] | Senthold Asseng[14]

[1]Department of Geography, Ludwig-Maximilians-Universität München (LMU), Munich, Germany

[2]Climate Resilience, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

[3]Center for Climate Systems Research, Columbia University, New York, NY, USA

[4]NASA Goddard Institute for Space Studies, New York, NY, USA

[5]Department of the Geophysical Sciences, University of Chicago, Chicago, IL, USA

[6]Center for Robust Decision-making on Climate and Energy Policy (RDCEP), University of Chicago, Chicago, IL, USA

[7]Université de Liège, Liège, Belgium

[8]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[9]Center for Agricultural Water Research in China, College of Water Resources and Civil Engineering, China Agricultural University, Beijing, China

[10]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

[11]Birmingham Institute of Forest Research, University of Birmingham, Birmingham, UK

[12]Lund University, Lund, Sweden

[13]Institute of Meteorology and Climate Research – Atmospheric Environmental Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

[14]School of Life Sciences, Technical University of Munich (TUM), München, Germany

Correspondence
Florian Zabel, Department of Geography, Ludwig-Maximilians-Universität München (LMU), Munich, Germany.
Email: f.zabel@lmu.de

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Abstract

Climate change affects global agricultural production and threatens food security. Faster phenological development of crops due to climate warming is one of the main drivers for potential future yield reductions. To counter the effect of faster maturity, adapted varieties would require more heat units to regain the previous growing period length. In this study, we investigate the effects of variety adaptation on global caloric production under four different future climate change scenarios for maize, rice, soybean, and wheat. Thereby, we empirically identify areas that could require new varieties and areas where variety adaptation could be achieved by shifting existing varieties into new regions. The study uses an ensemble of seven global gridded crop models and five CMIP6 climate models. We found that 39% (SSP5-8.5) of global cropland could require new crop varieties to avoid yield loss from climate change by the end of the century. At low levels of warming (SSP1-2.6), 85% of currently cultivated land can draw from existing varieties to shift within an agro-ecological zone for adaptation. The assumptions on available varieties for adaptation have major impacts on the effectiveness of variety adaptation, which could more than half in SSP5-8.5. The results highlight that region-specific breeding efforts are required to allow for a successful adaptation to climate change.

KEYWORDS

AgMIP, breeding, climate change, climate scenarios, CMIP6, crop traits, cultivar adaptation, food security, GGCMI, variety adaptation

1 | INTRODUCTION

Climate change is expected to reduce agricultural productivity and increase risks of crop failures without adaptation (Challinor et al., 2014; Liu et al., 2016; Rosenzweig et al., 2014; Zhao et al., 2017). The agricultural sector is facing the challenge of increasing production to meet rising demands and adapting to climate change to ensure food security (Ceccarelli et al., 2010; Howden et al., 2007; Lobell et al., 2008; Nelson et al., 2009).

Rising temperatures are the main driver of projected negative climate change impacts on yields (Asseng et al., 2015, 2019; Degife et al., 2021; Porter et al., 2014; Zhao et al., 2017). A simulation study with wheat has shown that the shortening of the growing period (time from sowing to maturity) with increasing temperatures reduces light interception, biomass accumulation and grain set and consequently grain yield (Asseng et al., 2015). Crop varieties are differently sensitive to temperatures and require specific accumulated heat units for growth. To counter the effect of faster maturity, Asseng et al. (2015) suggest that varieties adapted to increased temperatures require more heat units to delay maturity and extend grain filling. In case of wheat, this would result in shifting the grain filling period to the warmer part of the year, which would get even warmer with climate change, requiring an additional improvement in heat tolerance. Breeding lines with delayed maturity and improved heat tolerance do exist in current breeding programs and some regional modern varieties and have been shown to yield higher under increased temperatures in field experiments (Asseng et al., 2019).

If suitable varieties for adaptation already exist, variety shift might be a possible adaptation option within an acro-ecological zone (Butler & Huybers, 2013; Morales-Castilla et al., 2020; Sloat et al., 2020). It is currently not known which regions could potentially draw from the spectrum of existing varieties for adaptation and which regions require new varieties to be developed in breeding programs. To focus future breeding programs, it is therefore important to identify regions where traits of existing varieties are unsuitable for adaptation under future climate conditions.

Among different adaptation measures in agriculture, variety adaptation has been identified as one of the most effective (Challinor et al., 2014). However, it still remains an open question how benefits of variety adaptation globally vary across crops, regions, and projected climate change scenarios (Abid et al., 2019; Bedeke et al., 2019; Minoli, Müller, et al., 2019; Moore & Lobell, 2014). Existing adaptation studies often use incomparable settings, and thus are not well suited to draw global conclusions on the overall adaptation potentials toward climate change. Here, we present results from a comprehensive global scale multi-model framework as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP; Deryng et al., 2016; Müller et al., 2017; Rosenzweig et al., 2013, 2014; Ruane et al., 2017) to consistently investigate global and regional potentials of applying adapted crop varieties in response to climate change. We focus on major staple crops (maize, rice, soybean, spring wheat, and winter wheat) that currently produce nearly two-thirds of global agricultural calories (FAOSTAT, 2020; Ray et al., 2015). Crop yields have been estimated for four different climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), each driven with bias-corrected climate model data from five CMIP6 climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) using a crop yield emulator (Franke, Müller, Elliott, Ruane, Jägermeyr, Snyder, et al., 2020). The crop yield emulator has been trained with outputs from a model sensitivity analysis that has been conducted with seven well-established process-based global gridded crop models (CARAIB, GEPIC, LPJ-GUESS, LPJmL, pDSSAT, PEPIC, PROMET; Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020; Müller et al., 2017).

This study aims at (i) investigating spatial patterns of variety adaptation effectiveness, (ii) quantifying the impacts of variety adaptation on global caloric production, and (iii) identifying regions that can either adapt through shifting existing varieties or require new varieties through breeding programs.

2 | MATERIALS AND METHODS

2.1 | Sensitivity Analysis

In a multi-model sensitivity analysis (Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020), crop yields are computed for 1440 combinations along the CTWN-A (**C**arbon dioxide, **T**emperature, **W**ater, **N**itrogen, **A**daptation) dimensions for 31 years (1980–2010). The crop yield simulation consists of seven global gridded crop models (Table S1), of the Global Gridded Crop Model Intercomparison

(GGCMI) within AgMIP (Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020; Müller et al., 2017). Each model follows a harmonized protocol (Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020), defining the use of same data on harvested areas, climate forcing, growing periods, and fertilizer application, prescribed based on observations. The sensitivity analysis uses AgMERRA (Ruane et al., 2015) historical climate forcing (=baseline). The PROMET model uses ERA-Interim (Berrisford et al., 2011) reanalysis data, due to its sub-daily temporal resolution. The sensitivity analysis consists of five temperature offsets (T: +1 to +6 K, 5 K skipped), eight precipitation factors (W: −50% to +30%, −40% skipped), and four atmospheric CO_2 concentration levels (360, 510, 660, 810 ppm) that are applied on the baseline climate input for each time step. All results in this study refer to potential yields, assuming high nitrogen (N) application rates of 200 kg N ha^{-1} a^{-1}. All results refer to current land-use distribution for rainfed and irrigated crop-specific areas (Portmann et al., 2010). Irrigated areas are assumed to maintain soil moisture at field capacity and to have no limitations on water availability for irrigation.

All simulations are conducted with and without variety adaptation. Thereby, modelling teams have to ensure that (i) the simulated crop-specific phenology over historical periods over 31 years matches the statistical growing period for each location without fixing the harvest date and (ii) that the growing period under the warming scenario maintains the baseline growing period (without warming) for the variety adaptation scenario in average over 31 years for each location. Thereby, the process-based crop models consider interactions between multiple physiological processes, such as longer periods of light interception occurring water and temperature stress during the extended growing period and their impacts on yields. As a result, yields of adapted varieties in the overall balance can be lower than yields of currently used varieties, which is classified as "maladaptation" (Minoli, Müller, et al., 2019; Rickards & Howden, 2012). In this case, we assume that variety adaptation is unlikely to be implemented and use the yields of non-adapted varieties instead.

Participating crop models have been evaluated and simulated yields have been compared with statistics for historical periods in previous studies (Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020; Jägermeyr et al., 2020; Müller et al., 2017). Model characteristics and protocol implementation including how new variety parameters are adjusted to impose the new temperature requirements are described in Minoli, Müller, et al. (2019).

2.2 | Yield emulator

The results of the multi-model sensitivity analysis are used to statistically derive spatially explicit yield responses for different climate scenarios by fitting individual regression models for each crop, model, and 0.5 degree pixel to the regressors of the CTWN-A analysis (Franke, Müller, Elliott, Ruane, Jägermeyr, Snyder, et al., 2020). Climate scenarios are described by their SSP-RCP combination (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and are applied for five different CMIP6 climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL), as also described by Müller et al. (2021). A third-order polynomial function is applied to provide climatological mean yield responses for SSP-specific changes in CO_2, temperature, and precipitation for each climate and crop model. Changes in temperature and precipitation are capped to the boundaries of the CTWN sensitivity analysis (+6 K, −50%), which affects only few pixels with little or no cultivated area in higher latitudes. Thus, yield changes for different SSPs are attributed to changes in temperature, precipitation, and CO_2, but ignore possible SSP-specific changes in the composition of diffuse and direct radiation, for example, due to changed cloud cover. However, the large-scale gross significance of this relationship still remains unresolved (Pongratz et al., 2012) and the effects are not yet captured by the crop models. Possible impacts of CO_2 increase and high nitrogen supply on yield quality are not considered in this study but have the potential to reduce the nutritional value of crops (Asseng et al., 2019).

2.3 | Identification of regions that require new varieties

In this study, we present a first global empirical approach to identify regions that can either adapt through shifting existing varieties or require new varieties by breeding. To counter the effect of faster maturity under warming, adapted varieties require higher heat units (Asseng et al., 2019). To our knowledge, an inventory of globally existing crop traits including heat units does not exist. Our approach is based on the assumption that the crop-specific range of heat units, expressed by growing degree days (GDDs), across global harvested areas (Portmann et al., 2010) under the reference climate (1980–2010) represents the full spectrum of GDDs of existing varieties under current environmental conditions (Pugh et al., 2016; Figure S1). This assumption implies that farmers today use varieties best suited for local conditions and that crops are not grown where no suitable variety exist. This is supported by Parent et al. (2018), who show for historical data over Europe that farmers autonomously choose adapted varieties with optimal crop cycle durations if they are available for their agro-ecological region. Based on the daily climate model data for the different considered climate scenarios, we compute how many GDDs would be required for different future climate scenarios to regain the reference growing period for each location and crop (Figure S2). We compare GDDs required for the same growing period under future climate (GDD_{fut}, 2070–2100) with GDDs from the reference period (GDD_{ref}, 1980–2010) to assess, if an adapted variety exists within the current global distribution of GDD_{ref} of the considered crop (Figure S1), disregarding in this first step all regional specifics of these varieties that may actually limit their transferability to other regions. Based on reference growing periods (Elliott et al., 2015), we calculate GDDs annually for

31 years from sowing (planting for rice, respectively) until harvest for each crop according to an approach by McMaster and Wilhelm (McMaster & Wilhelm, 1997; Zhou & Wang, 2018), where GDD is the cumulative daily thermal time (DTT) over the growing period (F1).

$$\text{GDD} = \sum \text{DTT} \tag{F1}$$

DTT (F2) is calculated as:

$$\text{DTT} = \begin{cases} 0, \ T_{\text{avg}} < T_b \\ T_{\text{avg}} - T_b, \ T_b < T_{\text{avg}} < T_u \\ T_u - T_b, \ T_{\text{avg}} > T_u \end{cases} \tag{F2}$$

where T_{avg} is the daily average near surface (2 m) air temperature, T_b is the base temperature, and T_u is the upper threshold temperature. We assume T_b =8, 5, 8, 0, 0°C for maize, rice, soybean, spring wheat, and winter wheat, respectively (Licker et al., 2010), and T_u of 40°C for all crops. GDD_{ref} and GDD_{fut} are averaged over 31 years to exclude the effect of extreme events in individual years with possible crop failures, for example, due to heat waves and associated droughts. We assume that the distribution of GDD_{ref} represents the genetic variability of existing crop varieties that are currently cultivated. Varieties adapted to future climate at a certain location could already exist today at a different location on the globe. Similar to other approaches (Fitzpatrick & Dunn, 2019; Mahony et al., 2017; Pugh et al., 2016), we choose different percentiles as thresholds to assess the similarity between GDD_{fut} and GDD_{ref} and to remove outliers due to uncertainties in the statistical data. If GDD_{fut} is below one standard deviation (approximately 68th percentile), two standard deviations (approximately 95th percentile), three standard deviations (approximately 99.7th percentile), the maximum range (100th percentile), or beyond the maximum of the distribution of GDD_{ref}, we assume a low, moderate, elevated, high, and serious risk, respectively, that an adapted variety might not be available from the pool of currently existing varieties (Figure S1). We acknowledge that the ability to use varieties from different regions may be constrained by a multitude of processes other than GDD requirements and just use the different GDD distributions as a proxy to generate different risk classes in order to illustrate that the assumed varieties may not be available at all or only if considerable efforts are taken to create these.

The five considered crops are widely spread around the globe and cultivated in different climate zones, questioning the spatial transferability of varieties, which can additionally be limited due to sensitivities to abiotic factors other than GDDs, for example, photoperiod or pedo-climatic stresses, such as soil nutrients, structure, depth or available water, and humidity (Abdulai et al., 2012; Beck et al., 2018; Cober & Morrison, 2010; Song et al., 2019). In order to illustratively represent such additional constraints, variety transferability is restricted to the same Koeppen–Geiger region (Tier 1, five classes), which shares common vegetation characteristics and implicitly accounts for day length, as well as sensitivities to temperature and moisture regimes (Beck et al., 2018; Revilla et al., 2016), even though they may not be representative for all crop-specific aspects that need to be considered. We calculate the Koeppen–Geiger regions for past and future climate conditions according to an approach by Beck et al. (2018) for each GCM and SSP combination (Figure S3). Since climate zones move according to the SSP, the approach allows for using varieties from different current climate zones at a certain location, if the climate zone has changed over time (Supplementary Note 1). The climate zone stratification more coarsely adopts the concept of the mega-environments, defined as the largest subunits of a crop's growing or target environment within which a particular variety is used, that has been developed by CIMMYT to target germplasm development (Hartkamp, 2001). The direct application of the CIMMYT mega-environments was not possible, since they are not available for different climate scenarios nor all global regions and crops.

To analyze how hypothetical availability of adapted varieties affects global production, the yields of the hypothetical varieties used in the crop models are masked with the risk classes. Global caloric production is computed separately for each risk class, assuming yield levels of non-adapted varieties and thus shortened growing seasons in all grid cells with higher classes (Figure S1).

3 | RESULTS

We found that global caloric production declines by 2% (median) when continuously using current varieties under SSP5-8.5 for the average of 31 years (2070–2100) compared to the baseline (1980–2010) (Figure 1). Assuming successful breeding of all required future adapted varieties, targeted breeding for variety adaptation could potentially outweigh climate change induced losses and increase production for SSP5-8.5 by 17%, resulting in a total difference of 19 percentage points. The use of hypothetical adapted varieties (=potential variety adaptation) results in the highest production for SSP3-7.0 (+18%), which exceeds that in SSP2-4.5 (+14%) due to stimulating CO_2 effects that outweigh other negative effects of climate change, when assuming no or only minor nitrogen limitations for crop growth (Deryng et al., 2016). Crop production under potential variety adaptation is relatively stable between the considered SSPs and increases baseline production between 12% and 18%. Considering only variety adaptation through shifting varieties from other regions, results in smaller areas at which variety adaptation can be applied at higher levels of warming. As a result, the beneficial effects of adaptation on global caloric production are substantially reduced by about one quarter (i.e., variety adaptation leads to only 9% instead of 12% increases in global calorie production) in SSP1-2.6, and by more than half (i.e., only 7% instead of 17% increase in global calorie production) for SSP5-8.5 (Figure 1). Nevertheless, even with today's varieties, global caloric production can significantly be increased, but not as much as if additional new varieties were developed through breeding programs. The lower the

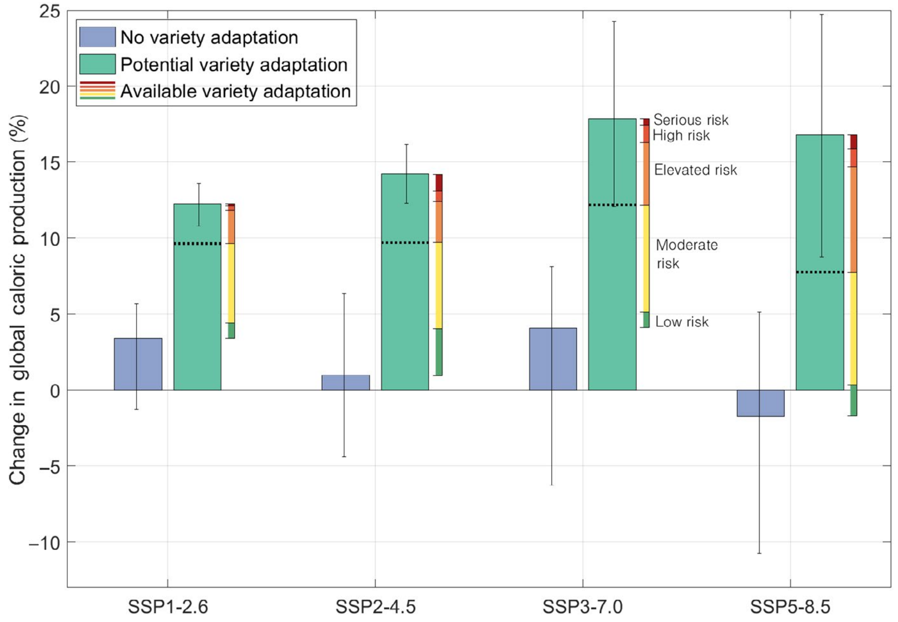

FIGURE 1 Average 2070–2100 changes in global staple crop production under different SSPs and different assumptions on future available crop varieties. Changes refer to the baseline period 1980–2010. Total global caloric production changes (maize, wheat, rice, and soybean) are shown as median across the crop and climate model ensemble for SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 without adaptation using current varieties (blue) and potential variety adaptation assuming hypothetical adapted varieties (green). The area in between no variety adaptation and potential variety adaptation depends on the assumptions on available adapted varieties. The narrow bar indicates by how much the potential decreases when assuming no available varieties in the corresponding risk class (low risk, moderate risk, elevated risk, high risk, and serious risk). The dashed lines highlight the reduction of the potential when assuming no variety adaptation on areas with elevated, high, and serious risk for unavailable adapted varieties for each scenario. For these areas, yields are simulated under local changing climate conditions with current varieties instead of adapted varieties. The whiskers indicate one standard deviation of the crop and climate model ensemble

warming, the larger the proportional effect of shifting existing varieties on potential global caloric production.

3.1 | Potential effectiveness

However, not all regions benefit from variety adaptation in the same way. Our simulations show that variety adaptation under SSP5-8.5 can be highly effective (ratio between adapted and non-adapted production) in most parts of Europe, China, and Russia (Figure 2). On the other hand, several regions show no or relatively low adaptation potentials through selecting varieties that preserve the growing season length under warming, such as Turkey, north-eastern Brazil, Texas, Kenya, Thailand, eastern India, parts of Australia, Spain, and Northern Africa (Figure 2). In these regions, we found that crop yields do not benefit from an extended growing period, due to occurring stresses. This could either be a result of water stress in arid regions, and/or acute temperature stress during the reproductive growth stage in tropical regions, which would have been avoided in a shortened growing season.

While the effectiveness of variety adaptation is highest for SSP5-8.5, it decreases with less intensive climate change (Figure 2). Model uncertainties increase with more intensive climate change and are highest in marginal and remote mountainous areas, where cultivated area and productivity potentials are usually low (Figure 2). Model discrepancies can often be attributed to the fact that these regions are susceptible to crop failures to which models are not equally sensitive.

3.2 | Sensitivity analysis

The results obtained for certain temperature and precipitation offsets at constant CO_2 level of 360 ppm (Figure 3) show that global caloric production in non-adapted systems generally declines under increasing temperatures by 4.9% per K warming and by approximately 5% per 10% decrease in precipitation. Variety adaptation in general dampens this reduction to 2.0% per K warming and thus potentially more than halves the percentage production loss. A temperature increase by, for example, 4 K and a precipitation reduction of 10% would reduce global caloric production by 25.5%, while adaptation would dampen the reduction to 11.7% compared to the baseline (Figure 3).

The results show that the use of adapted varieties could maintain current global caloric production up to approximately 2 K of growing season warming without increasing water demand (Figure 3). The compensation of losses due to higher temperatures, however, would require more water resources at constant CO_2 concentration. A growing season warming of 3.5 K would require 30% more water to regain current global caloric production.

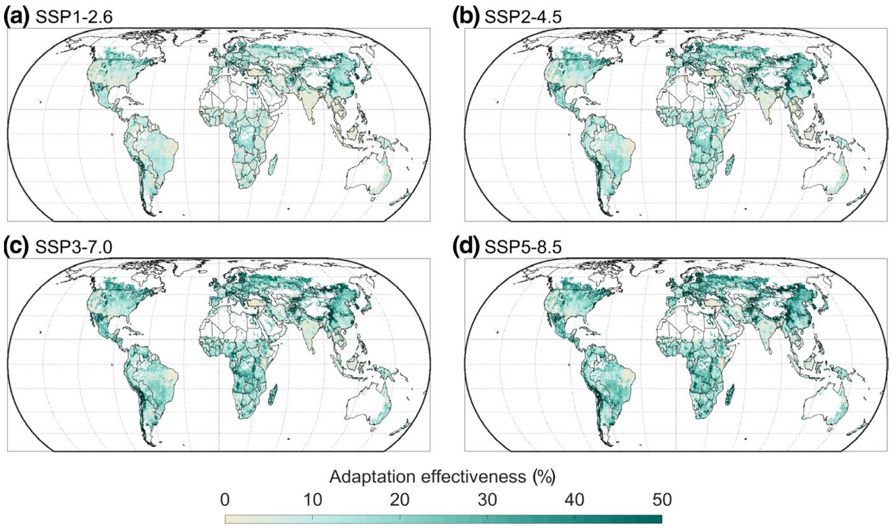

FIGURE 2 Average 2070–2100 variety adaptation effectiveness of staple crop production for different SSPs. Adaptation effectiveness shows the crop model ensemble median percentage difference between adapted and non-adapted cumulative caloric production of maize, wheat, rice, and soybean under SSP1-2.6 (a), SSP2-4.5 (b), SSP3-7.0 (c), and SSP5-8.5 (d). Yields of adapted varieties that were lower than yields of current varieties (maladaptation) are set to yields of current varieties. Grid cells (0.5°) without harvested area are displayed in white color and hatched areas illustrate regions with relatively high model uncertainty (interquartile range (IQR) of all crop models > ±25%)

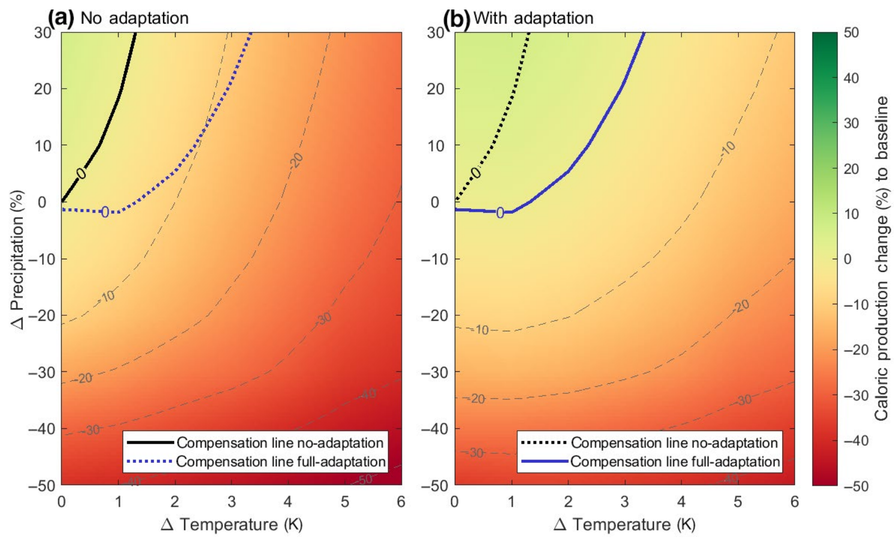

FIGURE 3 Response surfaces of global staple crop production to local temperature and precipitation changes. Impacts on global staple crop caloric production (summed for maize, wheat, rice, and soybean) are shown for local grid cell-level shifts in air temperature (x-axis; ΔT, [K]) and precipitation (y-axis; ΔW, [%]) relative to the 1980–2010 baseline (T0, W0). Data presented are the crop model ensemble median (a) without and (b) with variety adaptation. Isolines show specific levels of production change across temperature–precipitation space; the solid 0% isolines are the "compensation lines" below and right of which crop yield is reduced. For better comparability, the compensation lines for a) and b) are shown in both plots, but are dashed in the respective other plot. Atmospheric CO_2 concentration is held constant at 360 ppm. Results refer to combined production on current irrigated and rainfed harvested areas

The region above the compensation line with adaptation (Figure 3b) represents a full compensation or overcompensation of losses, which we define as full adaptation following Lobell (2014), while data below the compensation line indicate reduced production compared to the baseline. The option space of adaptation for compensation, describing the space between the compensation lines in Figure 3b, shows by how much variety adaptation potentially affects the sensitivity of global agricultural caloric production to changes in temperature and precipitation. Similar to the isolines along different levels of production change, the slope of the compensation line without adaptation is steeper than the full adaptation compensation line for the same temperature. Accordingly, the option space for compensation increases with adaptation (Figure 3), indicating that variety adaptation becomes more potent at higher temperatures.

While the option space of adaptation is relatively small in tropical and arid regions, due to temperature and water constraints, respectively, it is larger in temperate and cold regions (Figures S4–S7). Our simulations at higher constant CO_2 concentrations (510, 660, 810 ppm) indicate that higher temperatures can be compensated with less use of water. Globally, the effectiveness of variety adaptation is ensured also under higher CO_2 concentrations, but at a higher level of production (Figure S8).

3.3 | Identification of regions that require new varieties

Based on the current distribution of crops, we calculate the range of existing GDDs and thus estimate whether a required adapted variety under future temperature conditions can be chosen among the existing crop varieties. If varieties with GDD requirements need to be assumed in the simulations in order to maintain the original growing season length are not in use elsewhere, the area that is suitable for variety adaptation is reduced. For these regions, the development of new varieties with GDD requirements outside the currently available range across varieties would be required.

For different crops, regions are affected differently (Figure 4; Figures S9–S12), resulting from the interplay of different planting and harvest dates, levels of temperature and temperature increase, and different regional pools from which adapted varieties can be selected. For maize, 39% of current global harvested areas show elevated, high, or serious risk that new varieties would be required until 2100 for SSP5-8.5 (Figure 4). Globally important production regions are affected for SSP5-8.5, such as the U.S. Corn Belt, South Africa, India, parts of Mexico, Brazil, and Argentina. Even for the low warming scenario in SSP1-2.6, 20.7% of global harvested maize areas show elevated and high risk for the need of new varieties, mainly covering parts of the U.S. Corn Belt, the Chaco region in Argentina, parts of North-Eastern Brazil, and regions in Ethiopia, Kenya, and Egypt.

In total over all crops, the global elevated, high, and serious risk areas increase with warming climate, while the medium- and low-risk areas decrease (Figure 5). Accordingly, 39% of global cropland areas are exposed to elevated, high, or serious risk for non-existing adapted varieties under SSP5-8.5 (16% in SSP1-2.6, 23% in SSP2-4.5, and 30% in SSP3-7.0) (Figure 5). High- and serious-risk areas comprise 3% (SSP1-2.6), 6% (SSP2-4.5), 9% (SSP3-7.0), and 12% (SSP5-8.5) of global harvested area. Considering model uncertainties, between 35% and 56% of total global cropland areas are beyond

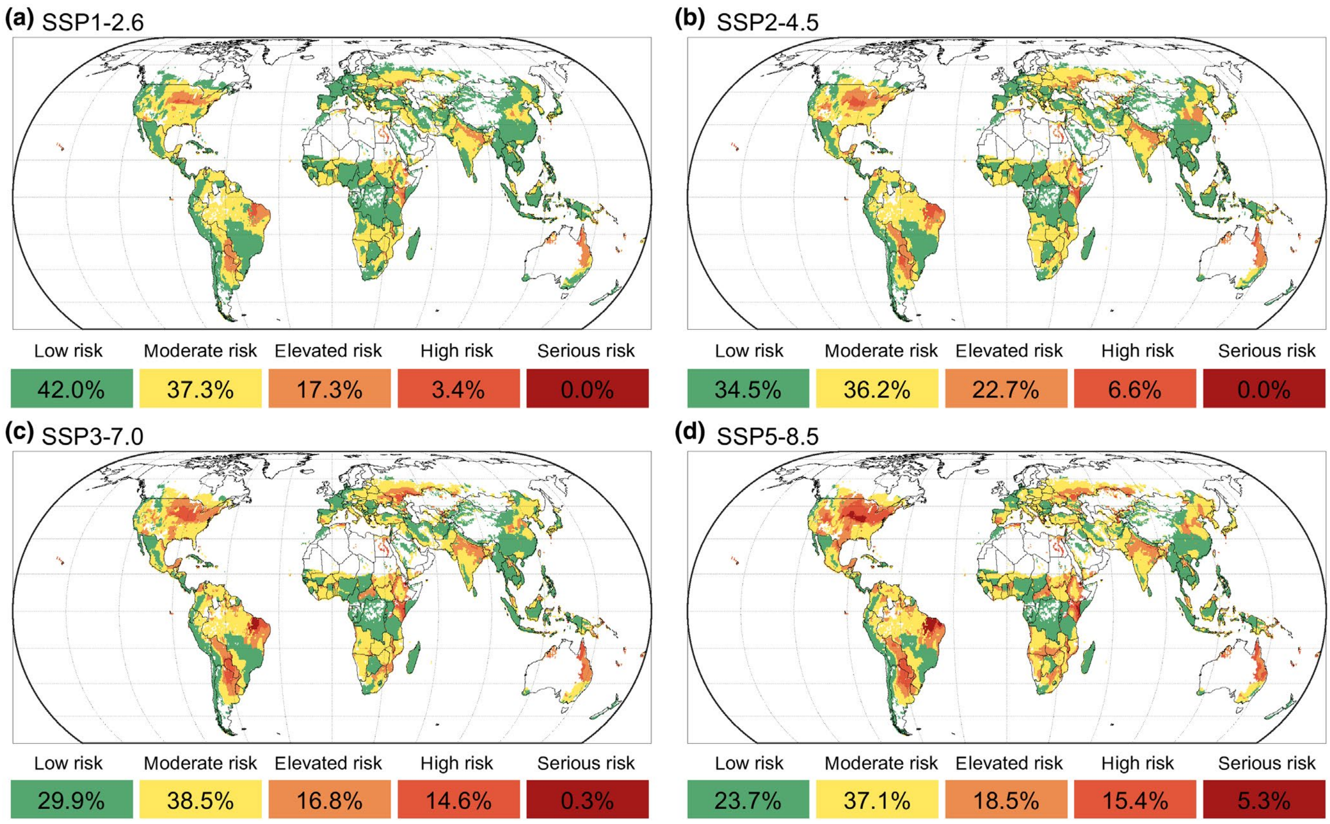

FIGURE 4 Average risk to the requirement for developing new varieties for maize. The categories indicate the risk to the requirement for developing new maize varieties under 2070–2100 climate conditions for SSP1-2.6 (a), SSP2-4.5 (b), SSP3-7.0 (c), and SSP5-8.5 (d). Maps are shown as pixel-specific model median over five climate models where green areas represent a "low risk", yellow areas a "moderate risk", light orange areas an "elevated risk", dark orange areas a "high risk," and red areas a "serious risk." For "serious risk" areas, the required future GDDs lie beyond the range of the distribution of GDDs of currently existing varieties. The percentage of the total harvested area is shown for each risk category. Grid cells (0.5°) without harvested area are displayed in white color

elevated risk under SSP5-8.5 (Figure S14). While 39% of global caloric production is produced on low-risk areas in SSP1-2.6 (Figure S13), production on low-risk areas under SSP5-8.5 decreases to 22% in SSP5-8.5 and takes place on 25% of global harvested area.

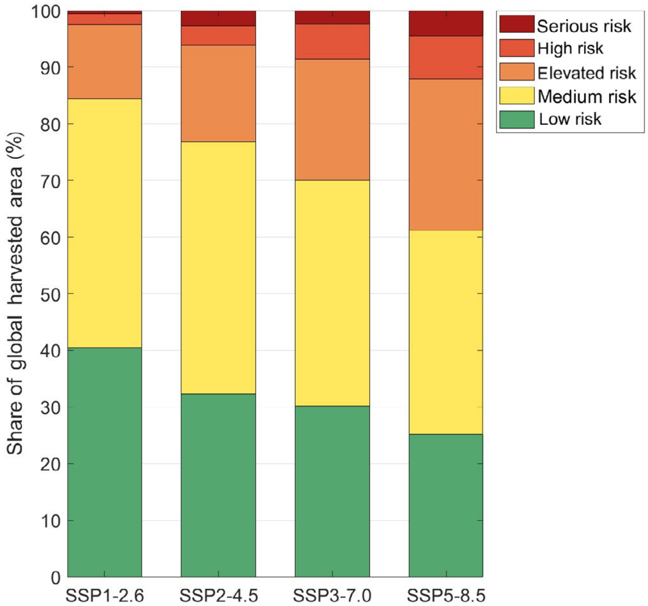

FIGURE 5 Share of areas with different risks for non-existing adapted varieties on global cropland. The bars show the model median over five climate models (summed for the harvested area of maize, wheat, rice, and soybean) for low, medium, elevated, high, and serious risk, respectively. The scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) refer to 2070–2100. Harvested areas are kept constant for all scenarios

Focusing on crop-specific changes for elevated, high, and serious risk areas, varieties with GDD requirements as would be needed by the hypothetical adapted maize varieties do not yet exist for 35% of crop-specific total harvested area (Figure S14). In terms of harvested area requiring new varieties, rice is least affected (21% for SSP5-8.5), while soybean shows the largest constraints (63% for SSP5-8.5), which can be attributed to the fact that existing soybean varieties show the smallest range of GDDs across the considered crops (Figure S15). Additionally, the globally harvested area of soybean is the smallest across the considered crops (Portmann et al., 2010), and the most productive growing regions (in the USA, China, and South America) are more likely to be affected by the unavailability of adapted varieties (Figure S10). For rice, the most important production regions in India and China can still make use of existing varieties for adaptation in the future. Considering only areas with high and serious risk for non-existing adapted varieties again shows highest reductions for soybean (30%) and least reductions for rice (1%) (Figure S16).

3.4 | Limited effectiveness

Assuming that variety adaptation might only be possible on areas with low and moderate risk for non-existing adapted varieties reduces the effectiveness of variety adaptation (Figure 1). Figure 6 shows the distribution of global effectiveness of adaptation for each of the considered crops, both constraining variety adaptation to areas with existing adapted varieties and assuming all required adapted varieties are available. For maize, the median global effectiveness of adaptation changes from potentially more than 19% to

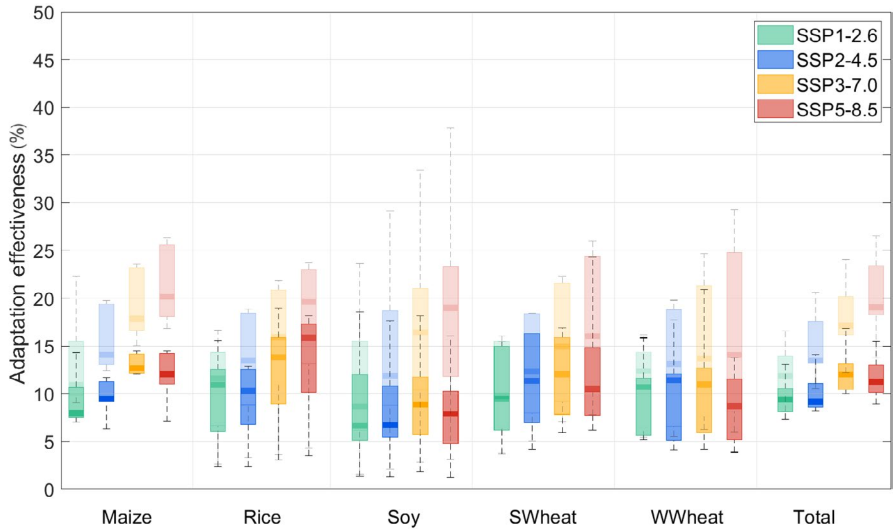

FIGURE 6 Adaptation effectiveness for different staple crops and different SSPs (2070–2100). Adaptation effectiveness shows the percentage difference between adapted to non-adapted caloric production of maize, rice, soybean, spring wheat, winter wheat, and their cumulative total effectiveness on the combined current irrigated and rainfed harvested areas for SSP1-2.6 (green), SSP2-4.5 (blue), SSP3-7.0 (yellow), and SSP5-8.5 (red). Boxplots show the ensemble range across seven crop models and five climate models. Lighter boxes illustrate the potential adaptation effectiveness, while darker boxes constrain variety adaptation to areas with low and moderate risk for non-existing adapted varieties

11% in SSP5-8.5 (Figure 6). The lowest effectiveness of variety adaptation for hypothetical varieties was found for wheat, while for soybean, the potential loss through adaptation due to non-existing adapted varieties is the largest (Figure 6). The model variance is increasing with higher SSP, with an average of 79% that results from different crop models, while 21% of the variance results from different climate models (Figure S17).

4 | DISCUSSION

Our results confirm the average yield losses of 4.9% per K warming and 5% per 10% decrease in precipitation as reviewed by Challinor et al. (2014) and show that variety adaptation can contribute to an increase in global caloric production for all investigated scenarios. For SSP5-8.5, variety adaptation could globally compensate and outweigh long-term climate change induced losses. Thereby, variety adaptation minimizes negative effects of temperature increase at global scale while crop growth benefits at the same time from elevated atmospheric CO_2 concentrations. The results suggest that mitigation toward SSP1-2.6 could be beneficial for global crop productivity (Figure 1). In global average, the results show that current global production can be assured up to 2 K of growing season warming with variety adaptation at constant atmospheric CO_2 concentration. Temperature increases of more than 2 K would require additional measures, such as, for example, the application of additional water for adapted varieties to compensate production losses (Figure 3).

In our experimental setup, we adopt an approach tested by Asseng et al. (2015) for wheat as the main cereal crops, and assume that adapted varieties require higher heat units for delayed maturity to regain the previous growing period that would be shortened without an adaptation in varieties. We classify regions in classes of likelihood to be able to choose adapted varieties among already existing varieties, based on today's distribution of GDDs. Although we consider possible constraints for shifting varieties into other regions, the approach may not reflect all crop-specific traits that would be required to transfer existing varieties to new regions under climate change. However, it helps illustrating how strongly the potential in growing season adaptation may depend on the need for developing new adapted varieties. The results suggest that existing crop varieties cover a broad spectrum of GDD requirements that are needed in the future. For low levels of warming such as in SSP1-2.6, 85% of global cropland areas can be supplied with adapted varieties from the pool of currently existing varieties. On the other hand, 39% of global cropland areas could require new varieties for SSP5-8.5. For these areas, regional information on long-term required GDDs can be provided to allow for targeted long-term breeding programs (Boote et al., 1996; Challinor et al., 2016).

Studies have shown that the overall process of breeding, delivery, and adoption of new varieties can take up to 30 years (Challinor et al., 2016), which could additionally restrict the availability of new varieties over time. However, new approaches and technologies, such as CRISPR-Cas9, speed breeding, or participatory plant breeding, could accelerate the development of adapted varieties in the future (Fedoroff et al., 2010; Garcia-Molina & Leister, 2020; Long et al., 2015; Tester & Langridge, 2010). Our results show that even important production regions could be at high risk that new varieties may not be available because their required GDD requirements are at the edge or outside the range of GDD requirements observed in varieties grown globally today. The development of locally adapted varieties to warming climatic conditions is particularly important for regions where agriculture is an important socioeconomic factor to avoid implications for local economy, employment, society, and culture.

The effectiveness for variety adaptation is generally lower in tropical and arid regions, where developing countries tend to have fewer adaptive capacities and rapidly increasing food demands. Different pathways of seed development and delivery (Challinor et al., 2016) could improve the provisioning of adapted and affordable seeds for developing countries and are also important measures to close yield gaps. The strong regional differences in the effectiveness of variety adaptation that show up in our results, in addition to different abilities and capacities for adaptation, could have major implications for future land-use changes, which are tightly coupled to trade flows and agricultural markets (Delzeit et al., 2018; Ewert et al., 2015; Robinson et al., 2018). Since market forces will likely intensify agricultural production in areas with suitable varieties and more conducive agricultural conditions (Nelson et al., 2014), the global importance of breadbaskets could increase.

This study focuses on long-term production changes that may obscure more acute extreme climate events. Studies also suggest increasing inter-annual yield variability (Challinor et al., 2014) that could reduce beneficial effects of variety adaptation, since adapted varieties might not be suitable or beneficial in extreme seasons, for example, due to heat waves or drought events.

Future variety adaptation assessments should consider ranges of adaptation rather than exploring the impacts of full adaptation versus no adaptation. In addition to variety adaptation, other adaptation measures, such as changing sowing dates (Waha et al., 2012), exploiting the potential of longer growing periods in regions where growing periods are currently limited by cold temperatures, or shifting to different crops could be beneficial and should be investigated jointly in further studies. The modelling exercise used here does not consider shifts in sowing dates as this was not part of the experimental protocol of the underlying dataset (Franke, Müller, Elliott, Ruane, Jägermeyr, Balkovic, et al., 2020). Shifting both sowing and harvest dates into cooler periods could contribute to adaptation in regions with sufficient temperature amplitude and help exploit the pool of current varieties for adaptation (Minoli et al., 2019; Waha et al., 2012). However, water availability and other factors like crop rotation constraints and risk of early frost events might prevent such an adaptation, but could be explored in future studies.

Switching to different crops as an adaptation measure could also be investigated, but will require considerations of regional consumer preferences and supply chain adaptations. Altering land-use patterns with warming climate could move farmland into more suitable but currently uncultivated areas, although potentially at the expense of natural ecosystems and biodiversity (Mbow et al., 2019; Zabel et al., 2014, 2019). In contrast, variety adaptation offers an opportunity to increase resilience without requiring land-use change or shifting agricultural regions into previously unused areas (Morales-Castilla et al., 2020), thus preventing negative impacts on biodiversity.

Region-specific breeding efforts are needed to allow for successful adaptation. The identified hot spot regions for crop breeding highlight the limits and challenges of variety adaptation. They could be considered as input to economic models to make SSP- and region-specific assumptions on variety adaptation and its limitations. By bridging the gap between genotyping, phenotyping, and the parameters used in crop models (Chenu et al., 2017; Marshall-Colón & Kliebenstein, 2019; Marshall-Colon et al., 2017; Peng et al., 2020), farmers could benefit from digital platforms to select best suited varieties.

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AUTHOR CONTRIBUTIONS

F.Z., C.M., J.E., A.C.R. designed the study. F.Z. performed the data analysis and wrote the initial paper draft; F.Z., C.M., S.M., J.J., J.M.S., W.M., T.H., and A.C.R. conceptualize the methodology of the study. F.Z., C.M., J.E., M.D., C.F., L.F., W.L., T.A.M.P., S.O., W.M., and T.H. performed the crop model simulations. C.M. provided GGCMI phase II crop emulator yields. All authors contributed to the interpretation of the data and the revision of the manuscript.

DATA AVAILABILITY STATEMENT

GGCMI phase II simulation data, separated by crop and model, are made available for download at a central open-access repository (https://zenodo.org/communities/agmip/).

ORCID

Florian Zabel https://orcid.org/0000-0002-2923-4412
Christoph Müller https://orcid.org/0000-0002-9491-3550
Sara Minoli https://orcid.org/0000-0001-7920-3107
Jonas Jägermeyr https://orcid.org/0000-0002-8368-0018
Julia M. Schneider https://orcid.org/0000-0001-9588-3157
James A. Franke https://orcid.org/0000-0001-8598-750X
Christian Folberth https://orcid.org/0000-0002-6738-5238
Wenfeng Liu https://orcid.org/0000-0002-8699-3677
Thomas A.M. Pugh https://orcid.org/0000-0002-6242-7371
Stefan Olin https://orcid.org/0000-0002-8621-3300
Sam S. Rabin https://orcid.org/0000-0003-4095-1129
Wolfram Mauser https://orcid.org/0000-0002-2963-8759
Tobias Hank https://orcid.org/0000-0001-7491-0291
Alex C. Ruane https://orcid.org/0000-0002-5582-9217
Senthold Asseng https://orcid.org/0000-0002-7583-3811

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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