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LETTER

Current and future adaptation potential of heat-tolerant maize in Cameroon: a combined attribution and adaptation study

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Abstract

Sub-Saharan Africa is projected to be exposed to substantial climate change hazards, especially in its agricultural sector, so adaptation will be necessary to safeguard crop yields. Tropical and subtropical maize production regions approach critical temperature thresholds in the growing season already in today's climate, and climate change might already be contributing to this. In this study we analyse the impact of anthropogenic climate change on maize yields and the potential for adaptation in Cameroon. We innovate by introducing a counterfactual climate as baseline to a definition for adaptation potential proposed in the literature to assess the relative benefit heat-tolerant crop varieties have already under current and under projected climate change. Spatially detailed simulations of maize yields are performed using the process-based crop model APSIM with W5E5 reanalysis data and bias-corrected and downscaled climate model data from CMIP6/ISIMIP3b for counterfactual, historical and projected future climate scenarios SSP1-2.6 and SSP3-7.0. It is found that unadapted maize yields experience significant losses under all climate change scenarios, with mean losses of 0.3 t ha^{-1} for the current period compared to the counterfactual climate without anthropogenic climate forcings and that yields are significantly higher for the heat-tolerant varieties across all scenarios simulated. Yield impacts of heat tolerance are highest under projected climate change, making it effective climate change adaptation. This result is robust to the exact value of parameterised heat tolerance. Breeding heat-tolerant varieties as parameterised in this study can be an effective adaptation but is still not enough to mitigate simulated losses under a high-emissions scenario.

1. Introduction

Climate change is projected to adversely affect agricultural production throughout the world, threatening the required productivity gains to achieve food security for a growing world population (Cairns *et al* 2013, Zhao *et al* 2017, Jägermeyr *et al* 2021). Sub-Saharan Africa (SSA) possesses substantial exposure to climate shocks in its agricultural sector (Müller *et al* 2014, Epule 2021, Nelson *et al* 2022) with already observed climate change impacts on agricultural productivity (Iizumi *et al* 2018, Sultan *et al* 2019, Ortiz-Bobea *et al* 2021). Cameroon specifically is a climate-vulnerable country dependent on cereals for its food security, of which maize is the dominant crop (Manu *et al* 2014). Temperatures in tropical maize growing regions during the growing season (GS) frequently approach crop-limiting thresholds (Yengoh *et al* 2010, Jägermeyr *et al* 2021), making maize farming highly sensitive to climate extremes (Epule 2021) such as heat waves, which are likely to increase under future climate change (Gourdji *et al* 2013, Zhang *et al* 2018, IPCC 2023).

Several studies indicate a growing biophysical limitation to maize production in tropical rainfed environments, namely due to an increase of drought and heat stress (Cairns *et al* 2013, Cairns and Prasanna 2018, Prasanna *et al* 2021). As conditions causing heat stress are expected to become much more likely under climate change, in particular for the high-emissions scenarios (Lobell *et al* 2011b, Wang *et al* 2020, Kummu *et al* 2021), developing heat-tolerant maize varieties may be paramount. Their potential can be assessed prior to investments in field trials and varietal development using process-based crop models such as the Agricultural Production Systems Simulator (APSIM; Holzworth *et al* 2014; extensively validated for maize and often used for climate change impact studies for maize and other crops in SSA; see Bassu *et al* 2014, Falconnier *et al* 2020, Rötter *et al* 2018).

Improvements in crop tolerance to climatic stresses cannot be equated with measures that compensate for yield loss under future climate change. Stresses from drought and heat already are a common stress in most maize cropping systems under present climate (Gourdji *et al* 2013, Schauberger *et al* 2017). This means that higher heat tolerance might lead already to benefits in yield regardless of future climate change. Maintaining a strict definition of climate change adaptation as an activity reducing climate *change* impacts, clearly separating it from climate change-independent benefits of agricultural development, i.e. intensification (Lobell 2014), can inform decision making in climate policy and financing.

Attribution science, however, makes it clear that climate change is happening now (Eyring *et al* 2021, Seneviratne *et al* 2021, Otto 2023), and is already having impacts (Ortiz-Bobea *et al* 2021, O'Neill *et al* 2022). A rigorous definition of climate change adaptation should thus include present climate change. We therefore innovate on Lobell (2014)'s approach by introducing a baseline that represents a counterfactual climate that might have occurred without increasing greenhouse gas concentrations and changes in other human-induced climate forcings since 1850. This allows to assess adaptation potential under *both* current and projected climate change. As populations in both West Africa and Cameroon are growing and strongly rely on subsistence agriculture, timely adaptation to both current and future climate change has large potential benefits for food security in a region that is home to more than 450 million people, of which more than 50 million are considered food insecure (IPC 2024).

While multiple impact modelling studies have already incorporated drought tolerance, heat tolerance, and other yield-enhancing traits into synthetic crop varieties in order to quantify the potential of varietal improvement under future climate change (Singh *et al* 2014, Tesfaye *et al* 2017, Zhang and Zhao 2017, Beah *et al* 2021), none have used the rigorous adaptation definition presented above that accounts for the influence of climate change on current climate. Furthermore, studies on heat tolerance in maize for West Africa and Cameroon specifically have rarely been done (for an exception, see Parkes *et al* 2018) or deal with other crops (Guan *et al* 2018) and do not assess yield sensitivity to the degree of heat tolerance increase. The presented study fills these gaps by modelling the effect of three degrees of crop-varietal heat-tolerance in maize and their potential as climate change adaptation under current and future climate change using counterfactual, factual, and projected future climate scenarios.

2. Data & methods

2.1. Study area

Cameroon is a tropical country in central-western SSA with a population of 27 million, the majority of which lives in rural areas and works in the agricultural sector (Epule 2021). The climate in Cameroon can be divided into two major zones based on the oscillations of the Intertropical Convergence Zone: a tropical-wet Guinean climate with short dry seasons in the south, mountainous west, and coastal parts with maritime influence as well as a sub-tropical zone with a longer, distinct dry season encompassing the rest (Tingem *et al* 2008, Mboka *et al* 2021). These areas can be divided into five specific agro-ecological zones (AEZs, figure 1, Yengoh *et al* 2010). A detailed description of the zones is given in the supplemental information (S1).

2.2. Crop yield modelling

2.2.1. Crop system model: APSIM

APSIM is a process-based model that simulates crop growth in a daily time step forced by temperature, radiation, soil moisture, and nutrient supply. Crop species, weather, soil, and management variables are provided to the model to cover site-specific conditions. APSIM includes management routines representing agricultural practices in tropical rainfed environments, such as intercropping, sowing based on rainfall, and complete residue removal at harvest.

APSIM accounts for both water and temperature stresses during crop growth. Water deficits directly limit photosynthesis as well as leaf-expansion and can slow phenology. Temperature stress mainly affects crop growth indirectly due to raising the atmospheric evaporative demand, limiting transpiration and subsequently radiation use efficiency. The maize module includes a temperature-dependent grain set-limiting factor which is of particular interest to the simulation experiment conducted in this study. It is calculated as an accumulated weighted average using thermal time under heat stress during flowering as the weighting multiplied by a temperature-dependent stress value, progressively reducing grain set and thus potential grain number and creating a sink limitation (P. de Voil, personal communication, 12 December 2022).

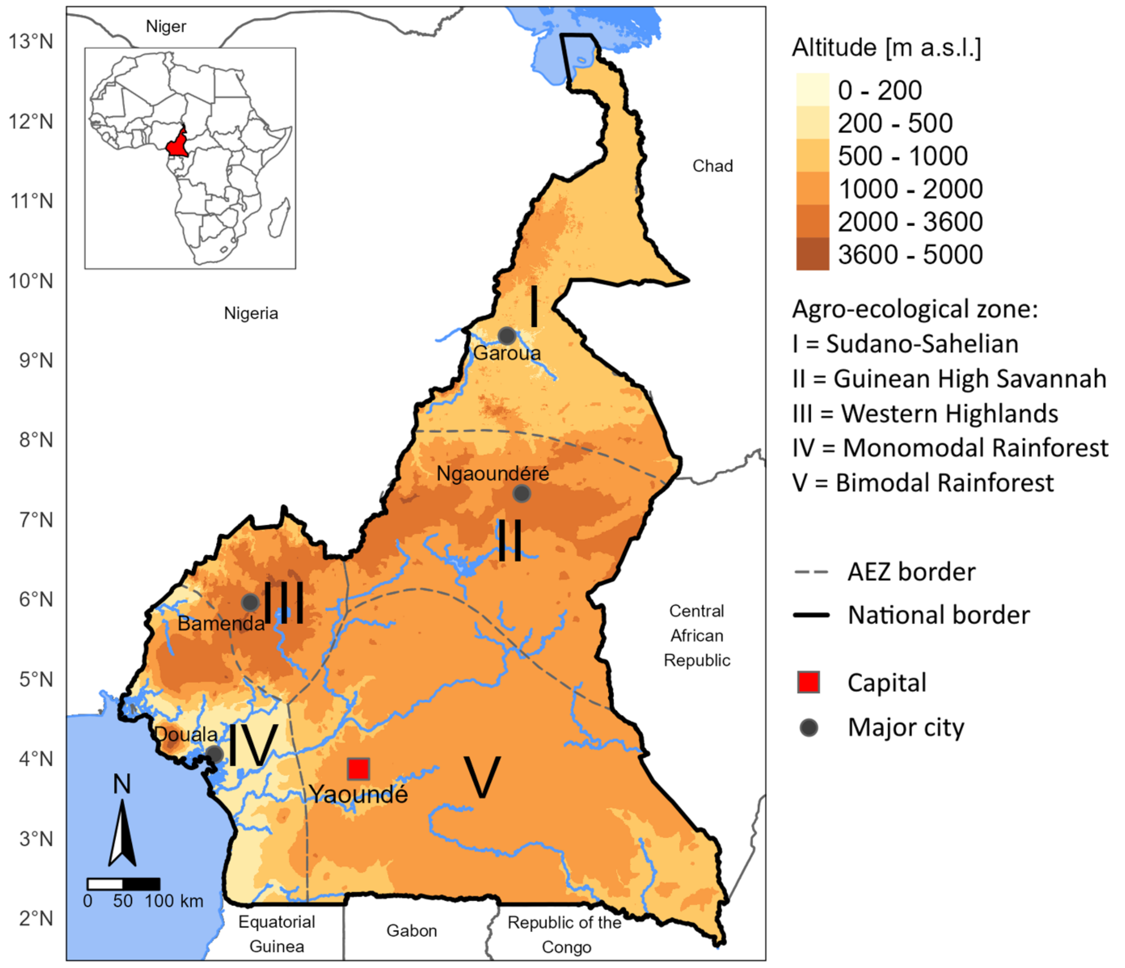

Figure 1. Map of Cameroon and neighbouring countries with altitudes and agro-ecological zones. Locations of selected major rivers (length >100 km), the capital, and selected major cities (population >200 000) are further shown. Inset map shows the location of Cameroon on the African continent with Cameroon highlighted in red.

2.2.2. Model input data

2.2.2.1. Climate

Climate data for the impact assessment simulations were taken from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) phase 3 data. The W5E5 v2.0 reanalysis product (Lange *et al* 2021), part of ISIMIP3a (Frieler *et al* 2024) was used as the observationally derived dataset. Moreover, the ISIMIP3b climate input datasets (Lange and Büchner 2021, 2022) that are bias-adjusted to the W5E5 data and statistically downscaled were used which consist of 10 global climate models (GCMs) taken from the Climate Model Intercomparison Project Phase 6 (CMIP6; Eyring *et al* 2016). All climate input data had 0.5° (roughly 50 km^2 at the equator) and daily spatial and temporal resolution.

The climate change scenarios employed were based on the shared socioeconomic pathways (SSP) used in CMIP6-ScenarioMIP (O'Neill *et al* 2016, Riahi *et al* 2017). Two contrasting scenarios and RCPs were considered: SSP1-2.6, which implies significant shifts in global cooperation of economies towards mitigation, and SSP3-7.0, which represents a continuation of past trends. The counterfactual climate data are sourced from the ISIMIP3b climate input datasets as well and comprise 6 GCMs/simulations (see table A in S3 for details). The counterfactual climates approximate climate without anthropogenic forcings (Gillet *et al* 2016, as part of CMIP6-DAMIP), i.e. a hypothetical scenario where human-induced emissions of greenhouse gases, aerosols, and other short-lived climate forcers as well as land-use changes have not influenced the climate system.

2.2.2.2. Soil, cultivar & management

We parametrised soil profiles for each grid cell individually except for soil inorganic N. Soil profiles were obtained from the International Soil Reference and Information Centre SoilGrids 2.0 dataset (Poggio *et al* 2021, Miguez 2022). Layer-specific data on soil inorganic N in tropical soils is scarce and no data exists for the whole of Cameroon (Silatsa and Yemefack 2017). As APSIM requires soil inorganic N for modelling crop growth, data from literature (Shepherd *et al* 2000, Tully *et al* 2016, Suzuki *et al* 2017) using study sites with comparable climatic characteristics to Cameroon's AEZs were chosen, taking previous agricultural use into account (see table B in S3 for details and S5 for a discussion on uncertainties).

The baseline or unadapted maize cultivar used in all simulation runs was Hybrid 511, a cultivar already calibrated in APSIM using field-scale trial data. Hybrid 511 is a Kenyan medium-maturing hybrid with a growth period averaging 120 d suited for mid to high altitudes (KALRO 2023). It is representative of maize cultivars grown in tropical rainfed environments and similar to the medium maturity CMS 8704 variety, Cameroon's most widespread maize cultivar (Mafouasson 2020, IFATI and MINEFOP 2022). Following methodologies to model heat tolerance by Tesfaye *et al* (2017) and Zhang and Zhao (2017), the threshold temperatures above which grain number is reduced were shifted by +1 °C for the hypothetical heat-tolerant cultivar. To assess the sensitivity of the resulting yield impacts of heat tolerance, alternative threshold temperature shifts of +0.5 °C and +1.5 °C were tested as well.

Management of the maize crop in APSIM was calibrated such that it represents growing practices typical for Cameroon and kept static across all grid cells except for sowing date. The sowing date varied with AEZ according to the agricultural calendar of Cameroon's National Observatory on Climate Change (ONACC 2021). Maize was rainfed and received no fertilizer. Sowing criteria were set as a minimum of 20 mm of rainfall over the course of five days in order to represent the onset of the rainy season, which is typically when farmers start planting in Cameroon. Maize was sown twice per year in AEZ V as two maize-GSs are enabled in this zone by its bimodal rainfall pattern.

2.2.3. Simulation setup and model evaluation

APSIM simulations were set up in APSIM Classic 7.10 using a grid-based approach on national scale for Cameroon. As agricultural activity is present in almost all of Cameroon (REDD-PAC 2015), and existing crop mask products do not agree on the extent and location of maize production in Cameroon, spatial masking of agricultural land area was not performed. Model evaluation was based on simulations for the observational climate reanalysis input dataset for the period of 1984–2014. A spin-up period to equilibrate soil moisture contents was set to five years before each simulation time period. This setup resulted in a total of 1 361 050 simulation years across all factors.

The model was evaluated by comparing the model-simulated yields with observed yields for Cameroon obtained from the global dataset of historical yield (GDHY; Iizumi 2019) and reported FAOSTAT national yields (FAOSTAT 2024). GDHY uses satellite-derived crop-specific vegetation indices and FAO-reported country yield statistics to create grid-level yields. Only yields from the major maize GS were considered. The model was evaluated by using goodness of fit, i.e. the coefficient of determination R^2, mean absolute error, root mean square error, percent bias (pBias), and Willmott's index of agreement d (Willmott 1982) for 20 year yield means of the reference period 1995–2015.

2.3. Adaptation potential definition

Adaptation impacts were calculated as given in figure 2 following Lobell (2014) as the absolute yield differences between the unadapted and the adapted cultivar. To calculate the true potential for adaptation, we take the absolute difference between adaptation impacts under the counterfactual climate and under current or future projected climate change. All differences are calculated from 20 year mean yields for the four time periods 1995–2015, 2020–2040, 2040–2060 and 2080–2100. Positive values of the adaptation potential indicate a greater yield advantage from the cultivar change under climate change than under no-climate change conditions (figure 2(a)), indicating true climate change adaptation.

3. Results

3.1. Current and projected climate change impacts on maize yields

The APSIM maize model is able to reproduce observed yields satisfactorily, giving a Willmott's $d > 0.8$ and low pBias of 2.9, though individual grid cells are not simulated well (see figure (E) in S4). Means of factual yields match the national mean of observational yield data at 2.3 t ha^{-1}.

Yields in Cameroon have already been negatively impacted by climate change (figure 3), as counterfactual yields are significantly higher ($p < 0.001$, see table C in S3) than factual yields, with the strongest impact visible in AEZs I and IV at −25% and −13%, respectively (see table D in S3 for details). Both current and projected future climate change show a general increase in GS mean temperature (figure (A) in S2) and the number of hot days (figure (C) in S2) during the GS, with a more mixed picture for total precipitation and the number of dry days (figures (B) and (D) in S2), with changes for most zones and GS climate variables increasing in magnitude with climate change scenario and time. The simulated yield impacts reflect this climate signal. Apart from individual grid cells, yield impacts under projected climate change constitute losses, with all AEZs seeing further decreases in yields in all periods and climate change scenarios, with the highest losses towards the end of the century. National average yield losses range from 16% to 25% under SSP1-2.6 in the periods 2020–2040 and 2080–2100, respectively, and from 14% to 69% under SSP3-7.0 for the same periods. The

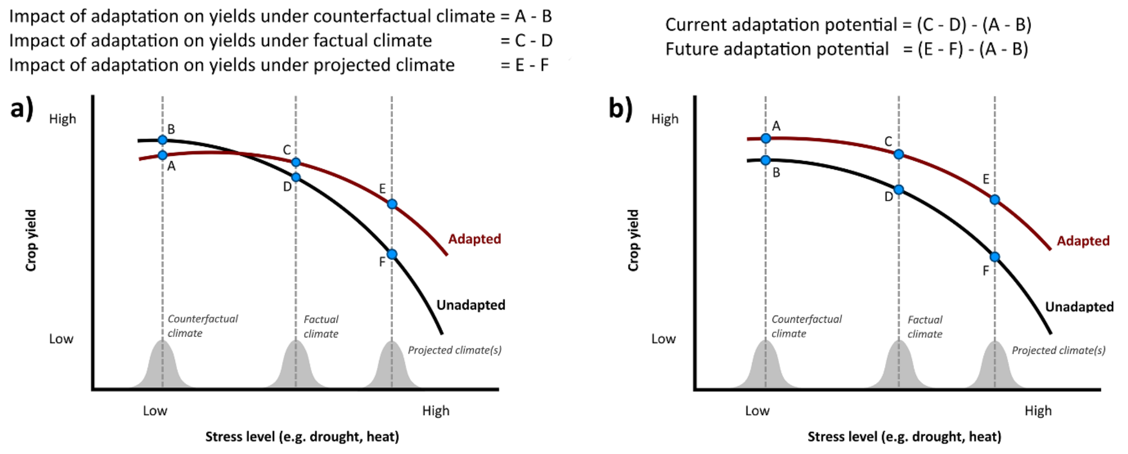

Figure 2. Adaptation impact on crop yields and adaptation potential adapted from Lobell (2014) and extended by the authors for (a) a scenario where adaptation potential is maximised, and (b) a scenario where adaptation potential is negligible.

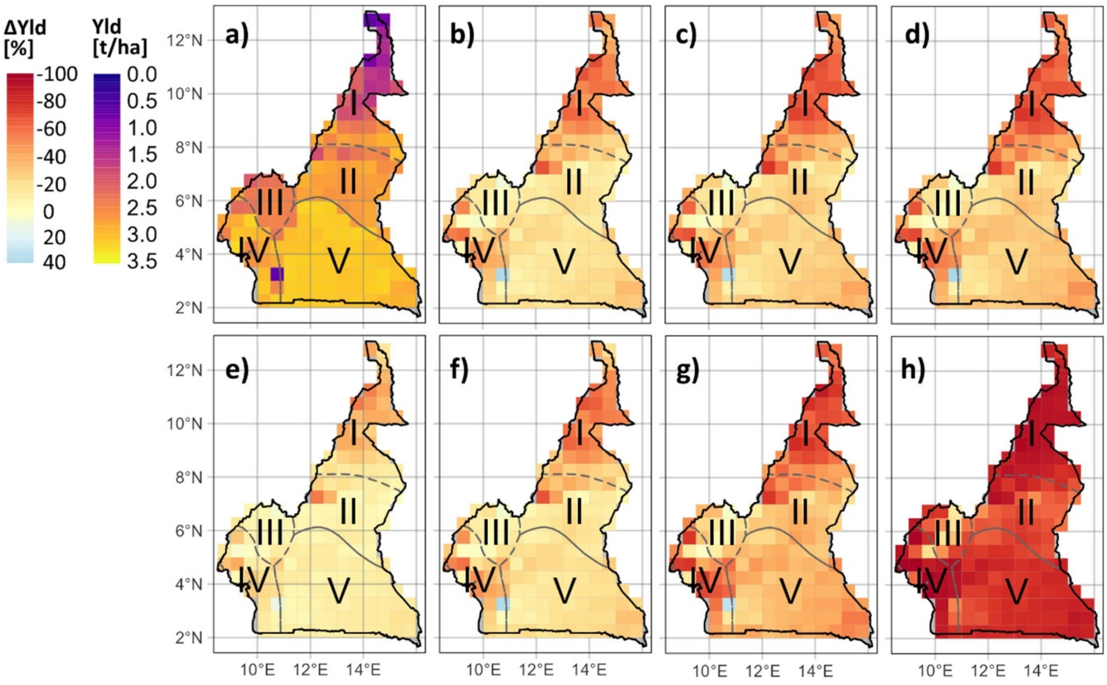

Figure 3. (a) Counterfactual maize yield (Yld) averaged over 1995–2015 and relative changes compared to this baseline for (b)–(d) SSP1-2.6 averaged over 2020–2040, 2040–2060 and 2080–2100, (e) factual simulations averaged over 1995–2015 and (f)–(h) SSP3-7.0 averaged over 2020–2040, 2040–2060 and 2080–2100.

highest losses are simulated in the hottest AEZ, AEZ I: Compared to the counterfactual scenario, yields are already 25% lower, with losses almost doubling by 2030 under both climate change scenarios, reaching 57% and 87% by 2090 under SSP1-2.6 and SSP3-7.0, respectively.

3.2. Heat-tolerance adaptation: impact on yield and adaptation potential

Visualising the relationship between maize yield and the number of hot days in the GS as a proxy for climate change stress (as described in figure 2) gives insight to the different yield responses of heat-tolerant cultivars (figure 4). Yields of the heat-tolerant cultivars are significantly higher ($p < 0.01$) than those of the baseline cultivar in all scenarios, time periods and AEZs. Mean yield impacts of adaptation, i.e. the difference between baseline and heat-tolerant yields, are lowest under the counterfactual climate but still significant ($p < 0.01$), ranging from 0.05 [0.03; 0.06][1] t ha^{-1} in AEZ III to 0.38 [0.24; 0.58] t ha^{-1} in AEZ I for the heat tolerance increase by 1 °C [0.5 °C; 1.5 °C], respectively. The pattern of hotter AEZs benefitting

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[1] Numbers in brackets denote values for the [+0.5 °C; +1.5 °C] cultivars, while unbracketed numbers refer to values for the +1 °C cultivar.

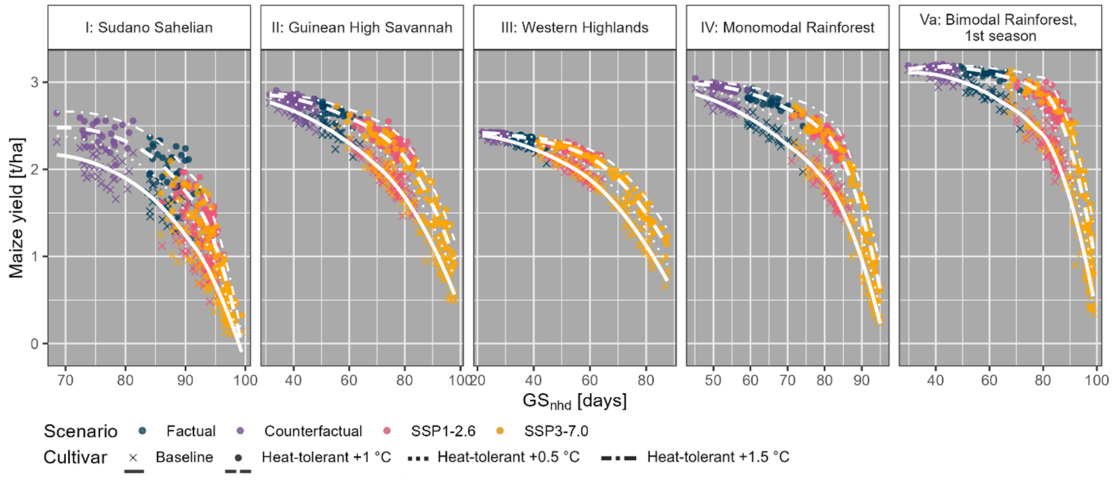

Figure 4. Maize yields averaged over each AEZ as a function of AEZ-mean growing season number of hot days (GS_{nhd}) by cultivar adaptation. Data points are individual years. Colours highlight different scenario data subsets. Point shape denotes baseline and +1 °C cultivars. Fitted lines are LOESS fits of all cultivars (for visualisation only).

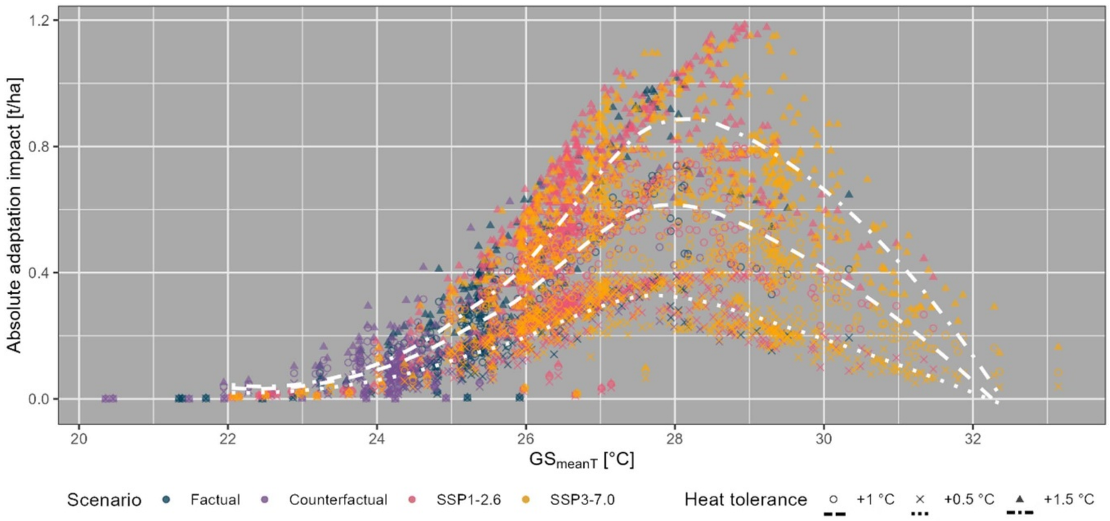

Figure 5. Mean yield impact of heat tolerance (t ha^{-1}) as a function of growing season-mean temperature (GS_{meanT} in °C) by climate scenario (colour) and cultivar for individual grid cells (data points). Fitted lines are LOESS fits (for visualisation only).

more from heat-tolerance adaptation does not hold under projected climate change: Under SSP3-7.0, it is the hottest AEZ I that sees the lowest yield impact in the late period of 2080–2100. Yield gains from heat tolerance compared to the yields of the baseline cultivar in the corresponding scenario increase generally with the degree of heat tolerance and climate change, with a national average yield impact of 0.31 [0.18; 0.41] t ha^{-1} under current climate change compared to 0.18 [0.11; 0.24] t ha^{-1} for the counterfactual scenario. National average yield gains under projected climate change reach a maximum of 0.49 [0.26; 0.68] t ha^{-1} in 2090 under SSP1-2.6, while they decrease under SSP3-7.0 after 2050 (see figures (F)–(H) in S4). The yield impact curve of heat tolerance seems to be linked to a non-linear response to GS mean temperature: The highest yield impact is realised under GS mean temperatures of ~28 °C and increases with the degree of heat tolerance (figure 5).

Looking at the adaptation potential of heat-tolerance under current and projected climate change, the following patterns emerge: Adaptation potential is generally positive under both current and projected climate change except in the extreme north of Cameroon; and adaptation potential is higher under projected climate change than under current climate change (figure 6). National average adaptation potentials range from 0.13 [0.07; 0.16] t ha^{-1} under current climate change and peak at 0.34 [0.17; 0.48] t ha^{-1} under SSP3-7.0 by 2050. Adaptation potential decreases slightly under SSP3-7.0 after the midterm period 2040–2060 for all heat-tolerant cultivars except the +1.5 °C cultivar, making yields in the late 2080–2100 period the most sensitive to the

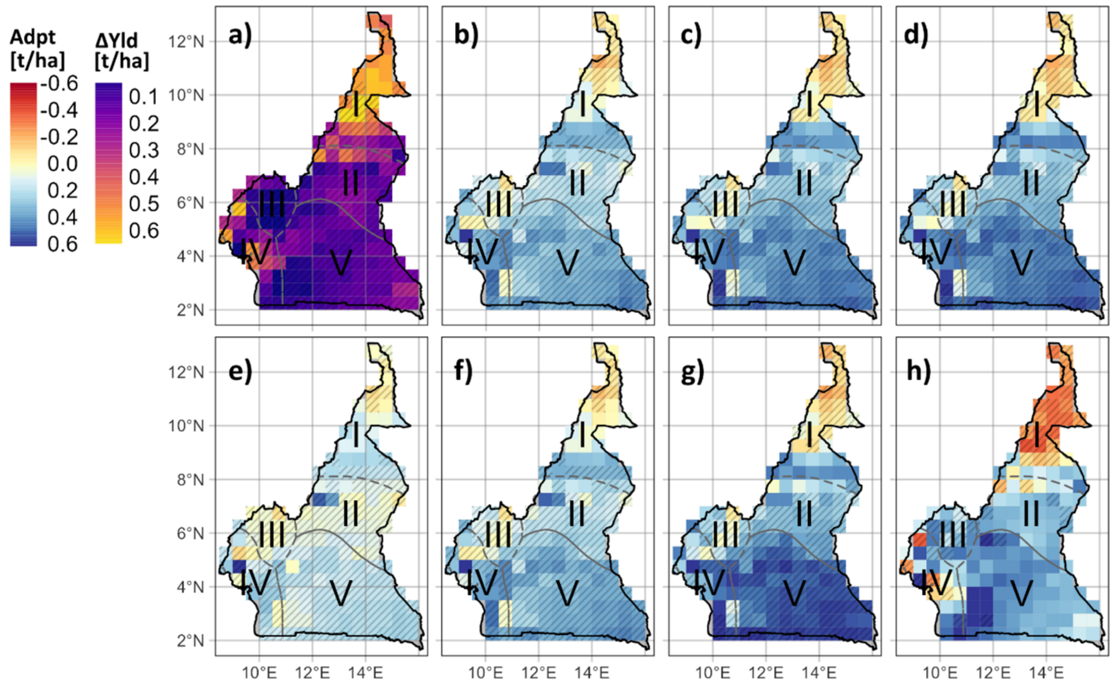

Figure 6. (a) Baseline yield impact of heat tolerance under the counterfactual climate (ΔYld) averaged over 1995–2015. Adaptation potential (Adpt) of heat tolerance for (b)–(d) SSP1-2.6 averaged over 2020–2040, 2040–2060 and 2080–2100, (e) the factual simulations averaged over 1995–2015, and (f)–(h) SSP3-7.0 averaged over 2020–2040, 2040–2060 and 2080–2100. Hatching indicates less than 50% mean difference between the values derived for the +1 °C heat-tolerant cultivar and the +0.5 °C/+1.5 °C cultivars.

degree of heat tolerance (figure 6). Values of absolute and relative mean yield impacts of heat tolerance and its adaptation potential are given in tables E and F in S3.

4. Discussion & conclusion

This study used APSIM for spatially resolved modelling of maize yields in Cameroon under climate-model derived data for counterfactual, current, and future climate for a baseline cultivar representing current practice and three hypothetical heat-tolerant cultivars, a switch to which is discussed as a scalable agricultural adaptation measure to climate change. We find that climate change has significantly decreased maize yields and will continue to do so, making effective adaptation paramount. Heat tolerance significantly increases yields under all scenarios, and adaptation potential is positive for both low- and high-emission scenarios. The novelty of this paper is to extend the adaptation impact framework from Lobell (2014) to show that current climate already includes attributable anthropogenic climate change and that heat-tolerant varieties already have a positive adaptation potential. This means that yield gains under current (factual) climate also constitute climate change adaptation. Furthermore, the adaptation potential of heat tolerance increases under future climate change, which is in line with results from Guan *et al* (2018) and Singh *et al* (2014). Furthermore, yield impacts are proportional but robust to the degree of parametrised heat tolerance.

A positive adaptation potential was found for current and projected climate change, though adaptation impacts varied across time, AEZs, and climate change scenario. The adaptation potential was negligible in AEZ I for all climate change scenarios, implying that heat tolerance as parametrised in this study constitutes more of an adaptation to counterfactual conditions in this AEZ rather than to current or future climate change. GS maximum temperatures in AEZ I in the counterfactual baseline already eclipse 34 °C, and yield declines for maize are expected for temperatures above 30 °C (Lobell *et al* 2011a), in line with the premise of maize yield's temperature sensitivity and the regional production system's operation close to critical thresholds. Climate change impacts and consequently adaptation potentials can of course be mediated by a multitude of other factors, such as a shortening of phenological periods, CO_2-fertilisation, and water stress (Rötter *et al* 2018, Minoli *et al* 2019, Falconnier *et al* 2020). However, our crop model forced with multivariate climate data which represents also other stresses, identified indeed heat stress and correspondingly, heat tolerance, as the major factor in mediating yield impacts in Cameroon under climate change (for a more detailed examination of the confounding factors, see S5). This shows the relevance of focusing in this study on adaptation to heat.

The high adaptation potentials in AEZ II, IV and V under future climate change peak in the period 2040–2060 for SSP3-7.0 and in the period 2080–2100 for SSP1-2.6 which suggests a high suitability of the modelled heat tolerances for mitigating impacts of low to medium amounts of warming. Nevertheless, the low or even negative adaptation potentials in AEZ I and under end-of-century warming for SSP3-7.0 showcase limits of the degree heat tolerance parameterised in this study. As adaptation impacts increased with the increase of threshold temperatures, higher heat tolerances may extend these limits further. Yet, it is unclear if modelled heat tolerance of this magnitude can be achieved using real-world breeding efforts, as genetic diversity of heat tolerance in maize remains largely unknown (Tiwari and Yadav 2019, Dong *et al* 2021) and yields may become increasingly water- and nutrient-limited instead. Furthermore, this study uses synthetic cultivars whose only differing trait is their heat tolerance, enabling isolation of its yield impact—real-world cultivars may come with different traits altogether due to the heat tolerance trait's polygenic nature. Studies on heat tolerance in maize in other regions show a common trend in heat tolerance being able to mitigate modelled yield losses under projected climate change at least partially (Tesfaye *et al* 2017, Zhang and Zhao 2017, Guan *et al* 2018), sometimes even completely (Tachie-Obeng *et al* 2013). This is reproduced and extended by the presented results, though comparisons with other studies are complicated due to the employment of different climate change scenarios, time periods and parameterisation of heat tolerance. Nevertheless, any degree of heat tolerance was found to be beneficial for yields. The simulated yield impacts and climate change adaptation potential of heat tolerance in this study should thus be seen as an impetus for refocusing breeding and research efforts on heat tolerance, especially as varietal development can take up to 30 years (Challinor *et al* 2016).

Projected future yield losses found here are higher than those from previous studies. Other estimates range generally between 10% and 30% by 2090 for maize yield in SSA under high emissions scenarios or equivalent climate conditions ($\geqslant$4 °C of warming) and no adaptation (Tingem and Rivington 2009, Waha *et al* 2013b, Challinor *et al* 2014, Liman and Maina 2018, Falconnier *et al* 2020, Jägermeyr *et al* 2021, Carr *et al* 2022). Our values for the Cameroon-average end-of-century mean yield losses under SSP3-7.0 amount to more than double of this. This underlines the significance of including direct heat stress effects on heat-sensitive crops such as maize as climate change impacts may otherwise be severely underestimated. Our inclusion of a counterfactual baseline further shows that yields losses under climate change are already significant today, not only in the future. Parkes *et al* (2018), who use a different model with explicit heat stress parametrisation, also find high maize yield losses of 38% for 4 °C of warming and no adaptation. Furthermore, modelled yields of the adapted varieties are still lower than their baselines under SSP3-7.0, which underscores the role of mitigation in reducing climate change impacts.

Despite these advances, we note some caveats. Although our crop model evaluated with a high index of agreement d >0.8 comparable to those in similar studies (Tachie-Obeng *et al* 2013, Chemura *et al* 2021, Heinicke *et al* 2022), uncertainties in the magnitude of the yield response to heat remain, as evidenced by the sensitivity of yields to the degree of parameterised heat tolerance. Historical exposure to critical temperatures for maize has been low in its global production regions (Gourdji *et al* 2013), hence there are few observed heat events to draw data from. Moreover, model uncertainty under extreme temperatures remains high (Roberts *et al* 2017, Heinicke *et al* 2022). Crop models have also not been validated under the extreme conditions expected at the end of the century for high emissions scenarios (Jin *et al* 2016, Rötter *et al* 2018), caveating the extreme yield declines under SSP3-7.0 in 2090 found here. This is a common issue as the parameterisation of heat stress effects through empirical relationships may not hold outside current ranges of climatic variability (Schewe *et al* 2019), calling for further crop model evaluation and development (Rötter *et al* 2018, Minoli *et al* 2019, Falconnier *et al* 2020, Couëdel *et al* 2023). Using a crop model ensemble would not overcome this issue but might increase confidence in modelled yields otherwise; to reach performance comparable to site-based crop model calibrations however requires an ensemble of at least eight calibrated crop models (Falconnier *et al* 2020), which was out of scope for this study. The homogeneity of simulated end-of-century yield losses is noteworthy as other studies find much more spatially heterogeneous climate change impacts on cereal yields in Ethiopia or Burkina Faso also using gridded national-scale approaches (Chemura *et al* 2021, Arumugam *et al* 2023).

Laux *et al* (2010) found a high dependence of maize yields on planting date in Cameroon under climate change with yield-maximising dates differing up to two months from current dates, suggesting pronounced seasonality in maize's heat exposure. Shifts in sowing date are indeed often mentioned as possible adaptation strategies for heat stress (Tesfaye *et al* 2017, Waqas *et al* 2021). The adaptation impact of heat tolerance as modelled here might thus be maximised if the GS timing is concomitantly adapted to climate change. Eventual widespread adoption of new heat-tolerant cultivars also depends on local availability and effectiveness of governmental and non-governmental extension services communicating their benefit, their suitability to local contexts and environments, including cultivar parameters unrelated to yield such as taste and texture, on farmer education level and on access to inputs (Kafle 2010, Acevedo *et al* 2020, Murken *et al* 2024). Given the critical role of maize as a staple crop in Cameroon and many other regions, effective adaptation to climate change through the adoption of heat-tolerant cultivars could thus significantly enhance food security and resilience for smallholder farmers. Even with such adaptation, however, negative climate change impacts in this respect are to be expected, as we find that absolute yields decreased under SSP3-7.0 even for the best-adapted cultivar despite highest adaptation benefit. Informed agricultural adaptation as contributed to by this study will hence be paramount, whereas any definition of 'adaptation' needs to consider an updated framework such as the one suggested here that acknowledges that climate change is already having impacts today.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.48662/daks-57 (Jansen 2024).

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Conflict of interest

The authors declare no competing interests.

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