Increased temperature stress reduces future yields despite intensification of irrigation

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Keypoints:

- Increased temperature stress strongly reduces future crop yields.
- Lowered plant productivity due to heat stress markedly reduces plant water demand.
- Intensified irrigation to increase future crop yields is not a viable climate change adaptation measure.

Abstract

Climate change and variability threatens the sustainability of future food productions, especially in semi-arid regions where water resources are limited, and irrigated agriculture is widespread. Increasing temperatures will exacerbate evaporative losses and increase plant water needs. Consequently, higher irrigation intensities would be a logical measure to mitigate climate change impacts in these regions. Using an ensemble of well-parameterized crop model simulations, we show that this mitigation measure is oversimplified and that besides water resources availability, strong temperature increases play a crucial role in crop developments and resulting plant water needs. Our analysis encompasses agricultural areas of the Lower Chenab Canal System in Pakistan (15 000 km^2), which is part of the Indus River irrigation system, the largest irrigation system in the world; and covers economically important crop growing areas (e.g., of cotton, rice and maize crops). Climate models project an above average increase in temperature over the study region, and the agro-hydrological and biophysical crops models respond with a strong decline of up to -24% (±12%) in future crop productions. Our modeling results further suggest that evaporative and irrigation demands do not align with increasing future temperature trends. The resulting decline in crop productions is consistent among model projections despite an intensification of irrigation measures and the positive effect of future CO_2 enrichments. Overall, our study emphasizes the role of elevated temperature stress, its effects on agricultural production as well as water demand, and its implications for climate change adaption strategies to mitigate adverse impacts in an intensively irrigated region.

Keywords: Climate change, agricultural yield decline, SWAT, APSIM, temperature stress

1. Introduction

In recent years, climate change and its impact on the environment have become one of the main concerns worldwide. Especially, its effect on agricultural systems has become a major problem, considering the alarming global developments regarding water and food security (Hanjra and Qureshi, 2010; Schewe et al., 2014). The latest special report of the UN Intergovernmental Panel on Climate Change (IPCC 2019) predicts, with high confidence, that future changes in climatic conditions will exacerbate existing water and food shortages for billions of people. One of the main reasons considered responsible for the expected food shortage is the inability to meet future agricultural water demands (Fader et al., 2016). Globally, irrigation volumes have more than doubled since the 1960s (IPCC 2019) and are likely to increase further due to climate change in regions with already limited water supply (Wada et al., 2013; Wang et al., 2016).

In semi-arid and developing regions like Pakistan, agriculture is the most important economic sector, employing nearly half of the population (Qureshi, 2011). A large part of agricultural workers are small scale farmers, highly dependent on maintaining their productivity levels and becoming increasingly vulnerable to climate change impacts and potential losses of income (Oxfam, 2009). The projected increase in water scarcity, due to climate change along with the increasing demand of the fast-growing population, poses a severe threat to the national food supply and to the productivity of economically important cash crops such cotton, maize and rice (Khan et al., 2016; Qureshi, 2011; Schewe et al., 2014).

Especially the Indus Basin in Pakistan's Punjab province is a hot spot for the impact of climate change on water availability and agricultural productivity, as it constitutes one of the world's largest closed irrigation areas (Mekonnen and Hoekstra, 2011). Currently irrigation water in the region accounts for over 90% of the total water demand (Fischer et al., 2007). Significant climate induced changes in the upstream glacio-hydrology – the major water source for the Indus Basin - are threatening future water availability in the basin (Immerzeel et al., 2010); along with the rising temperatures that are generally projected to increase faster than on global average in the region (Saeed and Athar, 2018).

Under such conditions, water related adaptation strategies, such as increased irrigation amounts, and enhanced irrigation efficiency are possible solutions to cope with these challenges. The benefits of such adaptation measures have been studied for agricultural systems experiencing similar climate change pressures and have been suggested as possible actions (Elliott et al., 2014; Fader et al., 2016; Molden et al., 2010). Yet, sensitivities of crops to changes in temperature can be higher than those due to water availability changes (Lobell and Burke, 2008). Temperature induced stress on crop growth and productivity could counteract the potential of optimized water management for increased productivity (Lobell et al., 2015; Zaveri and Lobell, 2019). It is therefore imperative to understand the role of temperature stress on crop growth and resulting plant water demand, in connection to water (availability) stress. Furthermore, improved knowledge about possible impacts of temperature and water stress as well as their interlinkages on future crop growth will help defining adequate adaptation strategies. In terms of adequate water availability for crop growths, especially in semi-arid regions, previous studies highlight that there is still very limited understanding of the potentials and limits of irrigation related climate change adaptation (Tack et al., 2017; Taraz, 2018); and that more research is needed to disentangle the effects of temperature and water stress related climate change impacts on agricultural yields (Carter *et al* 2016).

This study elaborates on how temperature stress controls agricultural productivity and plant water requirements in an intensively irrigated agricultural system in Pakistan's Punjab province. It suggests that the intuitive assumption, that increasing temperatures will inevitably lead to higher transpiration and thus to increasing irrigation demands, might not be a universal principle. This is shown by the application of two models from two different scientific disciplines. In order to tackle diversity in crop model parameterization, we consider the hydrological SWAT model (Arnold et al., 2012) and the biophysical-crop modelling framework APSIM (Holzworth et al., 2014) to analyze climate change impacts on yield and water demand. Numerous modeling studies regarding negative climate change impacts on yields and the potential of irrigation to mitigate these impacts exist. These studies, however, have been conducted using either hydrological models or crop models (Elliott et al., 2014). The combination of both model types is expected to allow a more detailed understanding of strengths and weaknesses of either model and thus, might result in a more reliable assessments of changes in future yield and water demand dynamics. Both models are used in an ensemble framework to analyse the climate change impacts on resulting crop growth over the study area. To this end, we use 9 climate model realizations; bias-corrected and downscaled to force both crop models under moderate (Representative Concentration Pathways (RCP) 4.5) and high-end (RCP 8.5) future carbon emission scenarios. We design a careful modelling experiment to analyse the impacts of increased temperature stress on future crop yields in connection to potential water stress. Through these analyses, we aim to provide a better understanding on the interlinkages between temperature and water stress and to detect dominant drivers of declining (future) agricultural productivity - which could then aid in defining effective adaptation measures.

2. Methods and Materials

2.1 Study Area

The study area is part of the Lower Chenab Canal System Area (LCC) in Pakistan, which comprises about 15 000 km^2 of agricultural land on the floodplains between the Rivers Chenab and Ravi (Fig. 1A and 1B). The LCC region is part of the Indus Basin Irrigation System (IBIS), the world largest irrigation system, feeding more than 200 million people (Immerzeel et al., 2010). The area is characterized by small-scale and highly fragmented agricultural cropping patterns. During dry winter season (Rabi) the dominating crop type is winter wheat while during the wetter and hot summer (Kharif) the crop pattern diversifies and mainly cotton, maize, rice and fodder are grown on small scale farm plots. Annual potential evaporation (1800 mm/a) is more than three times larger than annual precipitation (500 mm/a), resulting in a strong demand for additional irrigation. Knowing about potential negative impacts on agricultural productivity and defining possible adaptation strategies is therefore of paramount importance for water and food security in this region.

In this study we focus on analyzing the impacts of future climate change on summer crops, namely cotton, maize and rice, grown between May and October. The impact is evaluated based on changes in crop yield and relevant hydrologic and biophysical variables including evapotranspiration, irrigation demand, leaf-area growth, and biomass production (Fig. 2A). Due to high summer temperatures in our study region (mean daily Temperature > 30 °C), evaporative loss is highest during this time and changes in irrigation needs have a particularly strong impact on basin wide water demand. The selected crops represent high value crops with a wide distribution in the study area (Fig. 1A) and changes in yield will have significant economic impacts.

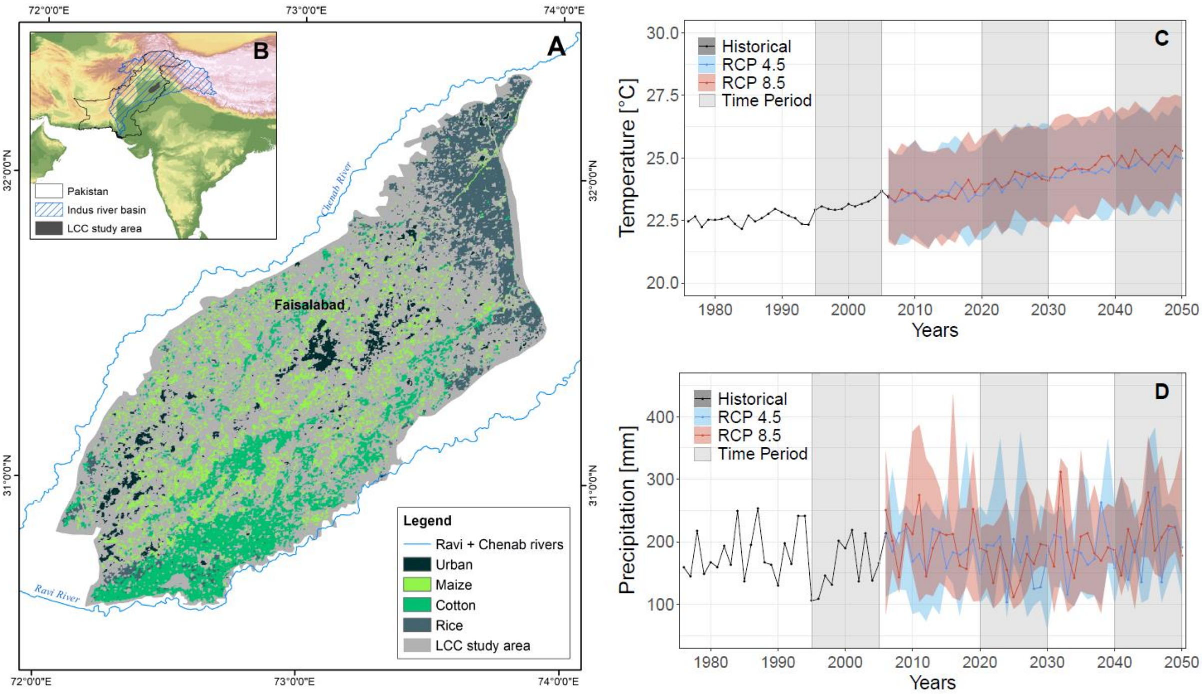

Figure 1: LCC study area and spatial distribution of cotton, maize and rice growing regions (A, Land-use data from Awan et al., 2016). Lower Chenab Canal (LCC) study area, Pakistan, and the Indus River Basin (B). Mean annual temperature (C) and precipitation trends (D) of historical data (black line) and future climate projection of 9 CORDEX models (red and blue line – ensemble mean; colored uncertainty band span between 25^{th} and 75^{th} percentiles). Shaded grey areas (C and D) show the historical period (1996-2005) and future time periods of 2021-2030 and 2041-2050, examined in this study.

2.2 Models: SWAT and APSIM

The hydrological model SWAT (Soil & Water Assessment Tool) simulates the quantity and quality of water flow within catchments, incorporates detailed management strategies (e.g. irrigation schedule, planting schedule) and basic plant physiognomic stages, e.g. root development, leaf area development, biomass change (Arnold et al., 2012; Gassman et al., 2014). The main underlying principle for the simulation of water fluxes is the water balance equation (Neitsch et al., 2009). By accounting for spatially distributed environmental changes, it simulates their effects on individual water balance components. Its strengths are therefore the closing of the hydrological cycle and the detection of spatially distributed changes in water availability and demand. Impacts of changing atmospheric CO_2 concentrations are accounted for in the estimation of potential evapotranspiration, affecting (i.e., reducing) plant water demand as well as in the estimation of plant radiation use efficiency, affecting (i.e., enhancing) the biomass production. To ensure correct and spatially differentiated parameterization, the model is calibrated following an automated and spatially distributed calibration approach (Becker et al. 2019). In this study the model is run on a daily timescale, with daily climate input data. Yield levels are taken at the end of each growing period.

The Agricultural Production System Simulator (APSIM; Holzworth et al., 2014) is a biophysical crop modelling framework which simulates agricultural crop dynamics with respect to varying climatic and environmental conditions. It has been used extensively to assess climate change impacts on agricultural productivity (e.g. Deihimfard et al., 2018; Liu et al., 2013; Williams et al., 2015). Model performance and applications are studied in depths within the scope of the Agricultural Modelling Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2014), in which the APSIM model was applied in the same study region of southern Punjab to assess climate change impact on crop production. Focus and strength of the APSIM framework is the plant-specific simulation of biophysical dynamics with respect to changes in the environment. Due to its modular approach, with individual sub-models for each crop type, it can account for plant specific reactions to climate change. For example, with individual models for cotton, rice, and maize it accounts for plant type specific carbon assimilation processes (C3 vs. C4-plants) and hence, differentiates between plant type reactions to increased atmospheric CO_2 levels. The APSIM model parameterization for the study area was established (calibrated) following the guidelines given for the APSIM classic model (APSIM model documentation, 2021) for three crop specific modules for cotton, maize and rice. Like the SWAT model the APSIM model is run on a daily time scale, with daily climate input data. Yield estimates are taken at the time of harvest at the end of the growing season.

To allow comparison between the SWAT and the APSIM models, we adopted the soil and management parameter configurations from the calibrated SWAT model. Soil parameters were furthermore verified through laboratory analysis of soil samples collected during a field campaign in the study region (Schulz et al., 2021 and Supplementary Section 2.3). We also conducted a sensitivity analysis to analyze the effect of varying soil parameters on the APSIM simulated crop yields that further allowed to constrain appropriate parameters for the APSIM soil module. Details of the employed parameters and underlying estimation procedure for both crop models are described in the Supplementary Information S2 and Tables S1-S3.

Finally we compared and contrasted the modeled crop yields with observed data provided by the Agricultural Statistics of Pakistan, published by the Ministry of National Food Security & Research (MNFSR, 2021) (Fig. 2B). Yield data for cotton, rice, and maize from the province of Punjab was taken for the years 2009-2013 and compared to simulated yield levels by SWAT and APSIM for the same period (mean of all years is shown in Fig. 2B). Details of the model validation can be found in the Supplementary Information S2.5.

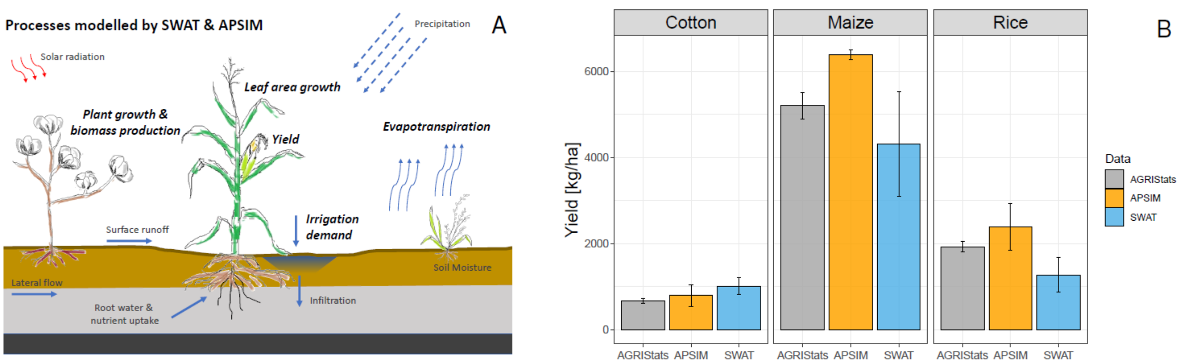

Figure 2: (A) Schematics of the main processes simulated by SWAT and APSIM models and analyzed in this study (bold italic). (B) Evaluation results of simulated yield simulations compared to observations; with the latter based on the AGRIStats = Agricultural Statistics of Pakistan. Bar heights show the mean of the years 2009-2013 and uncertainty bars show +/- one standard deviation.

2.3 Climate data sets

Daily Climate Forecast System Reanalysis data (CFSR; Saha *et al* 2010) are taken as historical reference climate data for a baseline period (1996-2005). The used data set encompasses temperature, precipitation, relative humidity, solar radiation and wind speed. To ensure the accuracy of the baseline data set, the CFSR data is bias-corrected using climate records of three available local climate stations (Supplementary Section 1.1).

Climate projection datasets are taken from the Coordinated Regional Downscaling Experiment (CORDEX), which provides a suite of regional climate projections based on the Global Climate Models of the Coupled Model Intercomparison Project, Phase 5 (CMIP5; Taylor *et al* 2012). We consider medium (RCP 4.5) and high (RCP 8.5) greenhouse gas emission scenarios from the IPCC - Fifth Assessment Record (AR5); and analyze the impacts in the near future (short; until 2030) and the mid future (medium; until 2050). The short-term time frame is selected to show the potential changes expected to occur in the coming next decade, and to show the necessity for immediate actions. The medium-term scenario is chosen to show the consequences of climate change at a time scale still relevant for today's population. Due to the capabilities of management and plants to adapt to changes in climate as well as long-term reactions of farming community to adapt to new environmental conditions, we do not include a long-term impact assessment. For the short- and medium-term scenarios, we assume that factors such as plant genetics and management strategies remain constant and at a current level.

The projections of future CO_2 concentration are based on van Vuuren et al. (2011) and are assumed to be 420 ppm and 450ppm CO_2 for RCP 4.5 and RCP 8.5, respectively during the time period 2021-2030; and 470 and 520 ppm CO_2 for RCP 8.5 are projected for the time period 2041-2050.

3. Results and Discussions

3.1 Future climate trends in the LCC study area

The climate models project a strong increase in temperature over the study region, under the high-emission scenario RCP 8.5 as well as under the moderate emission scenario RCP 4.5 (Fig. 1C). For the summer season (May-October), the ensemble means predict an increase of 1.0 °C (±0.4°C) for RCP 4.5 and 1.0 °C (±0.3°C) for RCP 8.5 until 2030, compared to the historical period of 1996-2005. A warming of 1.6 °C (±0.5°C) and 1.8 °C (±0.5°C) is projected for RCP 4.5 and 8.5, respectively, until 2050 (Fig. 3A). Strong increases in temperature under both scenarios points towards higher pressure on agricultural production resulting from increased temperature stress on crop growth, especially during summer months (Fig. 3B). A high agreement between the climate model ensemble members regarding consistent increase in future temperature indicates that the future summer season warming in the LCC area can be projected with high confidence (Fig. 1C; Fig. 3A and 3B).

Precipitation projections, on the other hand, are highly uncertain and there is no clear trend in annual or monthly precipitation amounts (Fig. 1D, Fig. 3C and 3D). Future water availability in terms of precipitation projections over the study area is therefore difficult to predict. In this study, we assume that due to the constant irrigation activities in the LCC irrigation system, agricultural water availability is always assured, and plant water demand is met. Thus, impacts of changes in precipitation on our model results are small and water stress is kept low.

Scenarios that future water availability either by water abstractions from the river Chenab or from ground water resources can no longer meet irrigation demands are not analyzed in this study, as we purely focus on the effect of climate change impacts of agricultural productivity given enough water.

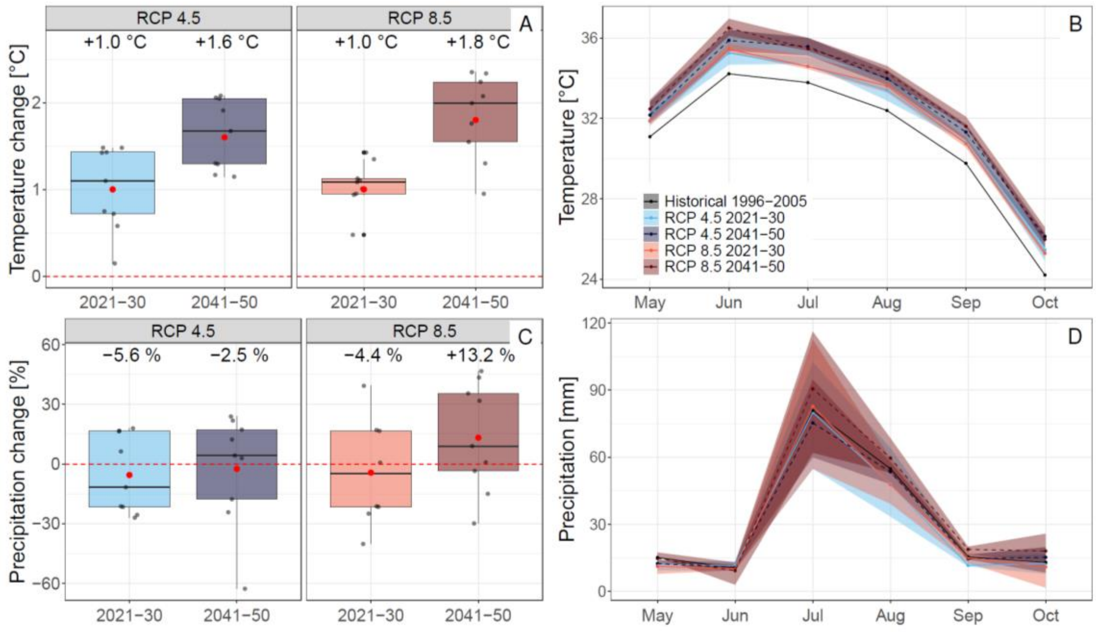

Figure 3: Projected temperature and precipitation change during Kharif (summer) months, for selected time periods 2021-2030 and 2041-2050, with respect to historical data (1996-2005). Absolute seasonal temperature change (A) and absolute monthly temperature changes (B). Relative seasonal precipitation changes (C) and absolute monthly precipitation changes (D). Red dots and the displayed percentages show ensemble mean changes. Grey dots represent single ensemble members. Right panels show model ensemble uncertainty bands of 25th and 75th percentiles.

3.2 Declining yield levels under climate change

Both models show that climate change will lead to a substantial reduction of future yield levels in the study area. Under current CO_2 concentrations, mean yield levels are projected to decrease by up to -24% (±12%) under the high emission and mid-century scenario (Fig. 4A, light grey bar, RCP 8.5 2041-50). Despite their differences in predicted magnitudes of yield declines (SWAT: -32% (±12%) and APSIM: -16% (±2%)), the models agree in their trends (sign) and show increasing yield losses with increasing temperatures for all crop types (Fig. 4B-4D). Considering that water demand is assumed to be met, these results underline that the increasing temperature stress alone will have a strong negative effect on crop growth, which is in-line with findings of previous studies (Deryng et al., 2014; Saddique et al., 2020; Siebert and Ewert, 2014; Zhao et al., 2017).

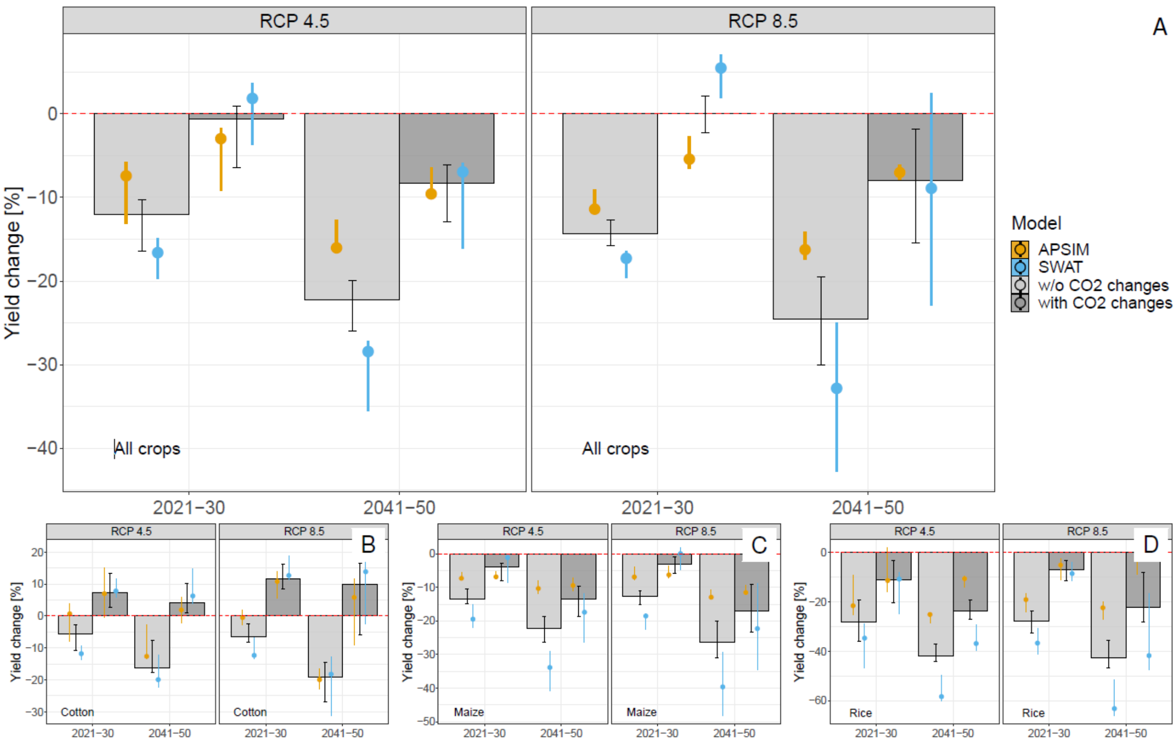

Figure 4: Projected changes in future crop yield under the RCP 4.5 and RCP 8.5 scenario, neglecting (light grey bars) and considering (dark grey bars) the impact of CO_2 changes. Results are shown for all crops combined (A) as well as separately for cotton (B), maize (C) and rice (D). Filled bars show the model ensemble median and black error bars show the respective 25^{th} and 75^{th} percentiles of the model ensemble (SWAT and APSIM with nine climate models). Separate results for SWAT and APSIM models are shown as colored dots (median) and error lines (25^{th} and 75^{th} percentiles for the model ensemble of nine climate models).

Accounting for increasing CO_2-concentrations (Fig. 4, dark grey bars) dampens the negative impact of the temperature increase on yields, revealing the significant positive effect of higher CO_2 levels on agricultural productivity due higher photosynthesis rates, also known as CO_2-fertilization. For the short-term scenario (2021-2030), increasing CO_2-concentrations prevent the strong decline in simulated crop yields. This is generally in-agreement with previous studies showing this strong positive effect of increasing CO_2 concentrations on plant growth and its ability to counteract plant growth limiting effects (Parry et al., 2004). Yet, the effectiveness of CO_2-fertilization is still a large source of uncertainty (Elliott et al., 2014; McGrath and Lobell, 2013). In the context of our study, uncertainty arises through the differences in representing CO_2-impacts on plant physiology by SWAT and APSIM. The hydrological SWAT model does not account for plant type specific impacts of CO_2 (e.g. different reactions of C3-plant and C4-plant) and might overestimates the positive effects of CO_2

(Wu et al., 2012). The APSIM crop models, on the other hand, consider plant specific impacts, e.g. the maize-model (Fig. 4C) correctly assumes maize-insensitivity to changing CO_2 effects (maize = C4-plant). In the case of cotton, which shows a lower yield reduction than rice and maize, the enhanced productivity under rising CO_2 levels even leads to an increasing yield (Fig. 4B). The sensitivities of rice and SWAT-maize yield to CO_2-concentrations are comparable, but their yield reductions due to temperature stress are too severe for increasing CO_2 emissions to compensate (Fig. 4D).

Overall, APSIM results show declining yields even for the short-term future, indicating that elevated CO_2 concentrations are not able to compensate for reduced yield due to higher temperature stress. Under further rising temperatures (2041-2050), both models project decline in crop yields (-8% (±9%), RCP 4.5 and -7% (±12%), RCP 8.5); and disclose that even with further elevated CO_2-concentrations and unlimited water availability climate change induced yield declines cannot be prevented. All estimated crop productivities show that yields are expected to benefit less from increasing CO_2 levels, as temperatures continue to rise (Fig. 4B).

Previous studies have indicated that increasing CO_2 improves water use efficiency by reducing plant transpiration which facilitates plant growth during dry/drought conditions (Wullschleger et al., 2002; Yoo et al., 2009). At the same time, it has been also reported that reduced plant transpiration leads to increased temperature stress, due to a reduced evaporative cooling effect (Siebert et al., 2014; Vanuytrecht et al., 2012). Both these effects are not covered presently by either of the models. As the strong increase in future temperature is projected under both RCPs and together with abundance of water due to irrigation, the positive effect of CO_2 on yield levels is most likely overestimated by both crop models. Recently, Wang et al., 2020 noted the positive effects of CO_2 tend to be overestimated by crop models based on their analysis of a global reduction in CO_2 fertilization effect on vegetation photosynthesis, which most models do not account for.

3.3 Future irrigation and evaporative demand

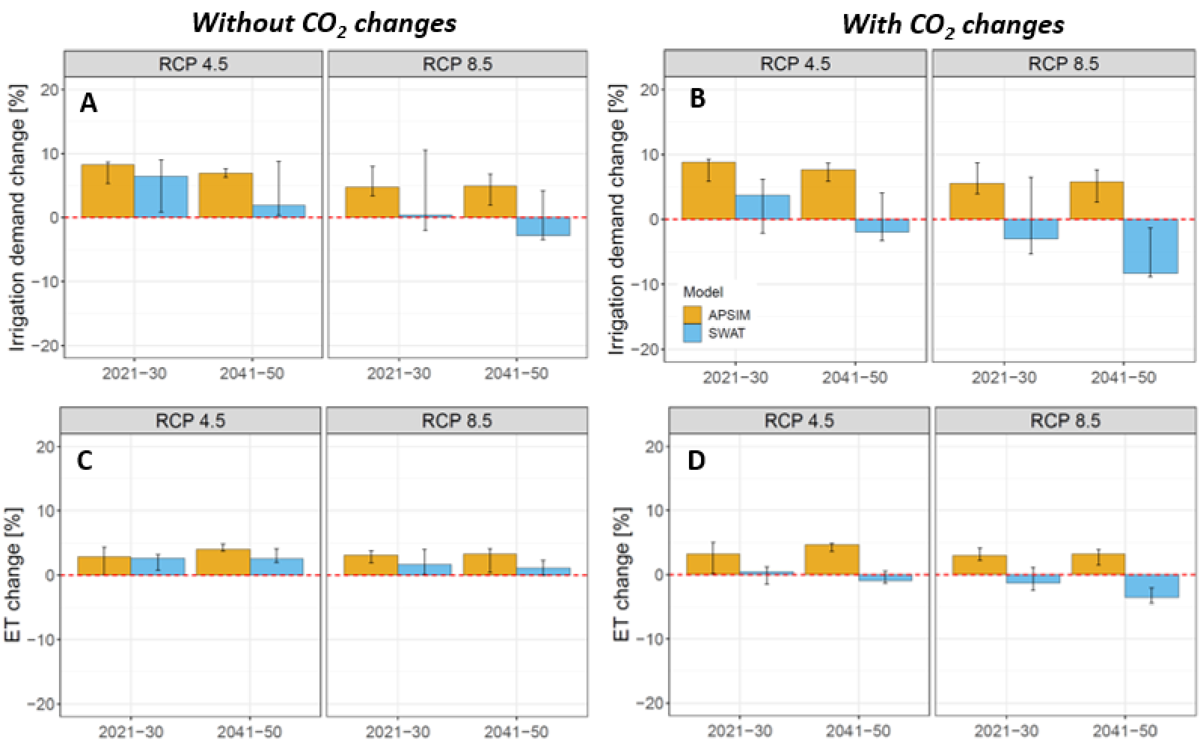

Figure 5: Projections of future irrigation demand (A and B) and future ET rates (C and D). Changes under the baseline CO_2-scenario (A and C) and with increased CO_2-levels (B and D).

In the following, we discuss the reasons behind the estimated yield declines based on changes in irrigation demand, evapotranspiration, leaf area index and biomass productivity. Results presented here are averaged over the selected summer crops cotton, maize and rice. Crop specific results are presented in the supplementary material (Supplementary Figures S4-S5).

Considering the significant temperature increase one would expect a strong increasing signal in plant water demand (Döll, 2002; Wada et al., 2013). Examining irrigation and evaporative demands in the study area, however, reveals that trends in future water demand do not align with projected temperature trends. Increasing water demands are surprisingly moderate and do not increase by more than 5% (average of both models; Fig. 5C). Against the expectation of a strong increase in irrigation needs under rising temperatures, both crop models show that average irrigation demands increase less under higher temperatures. Under both emission scenarios, a maximum increase is predicted for the moderate scenario (RCP 4.5, 2021-2030) while a minimum increase is predicted for the high-end emission scenario (RCP 8.5, 2041-2050). Figure 5 displays the results for APSIM and SWAT separately to reveal important differences in their simulation results. SWAT projects the lowest increase in water demand for the RCP 8.5 and mid-term future scenario (1±8%). Under elevated CO_2 concentrations (Fig. 5B), water demand even further reduces (-4±7%), which generally agrees with the effect of reduced plant water demand due to reduced stomatal conductance (Kimball et al., 2002).

The APSIM model simulated irrigation demand appears insensitive to CO_2 changes, as irrigation demands remain constant regardless of changes in CO_2 levels (Fig. 5A vs. 5B). Yet, the significant increase in LAI (leaf area index) under elevated CO_2 levels (see below, Fig. 6B) and the negligible change in irrigation demand illustrates that the APSIM model likewise account for the positive CO_2 effects on water demand and show decreasing irrigation demands relative to leaf area growth.

The reason for the surprisingly low increase in irrigation demand can be explained by the low increase in actual evapotranspiration (Fig. 5C and 5D), which prevents irrigation demands to significantly increase. Despite the strong temperature rise, increases in ET are projected by both crop models to stay on average below 3% (±4%), and do not increase with higher temperatures, even under the assumption of unchanged CO_2 emissions.

Noting that water supply is guaranteed in both crop models, the low ET rates under rising temperatures cannot be related to water shortages and should be explained by ET controlling plant parameters, such as LAI and biomass production (as discussed below in the following section). The limited changes in water demand also reveal that even if more water for intensified irrigation activity would be available, it would not help to reduce yield losses.

3.4 Future plant growth and agricultural productivity

The SWAT model estimates LAI development based on the influence of the predominant environmental stress factor (Neitsch et al., 2009), i.e. heat stress in this study. This results in a significant reduction in LAI by up to -27% (±6%) under the high-emission scenario (RCP 8.5, 2041-2050). The decreasing LAI trend clearly follows the increasing temperature trend, with highest LAI reductions under the RCP8.5 scenario (Fig. 5A) and confirms the LAI sensitivity towards temperature.

In combination with the reduction of stomatal conductance, a significant decline in LAIs therefore seems to be one of the main reasons for the overall low ET rates simulated by the SWAT model under high temperatures (Fig. 5C). LAI calculations in SWAT do not account for CO_2 effects (Fig. 6A vs 6B), which leads to strong LAI decreases even under higher CO_2 concentrations (Fig. 6B) and to decreasing ET rates (Fig. 5D).

APSIM on the other hand, which does not account for a specific heat stress factor in parts of its LAI calculations, shows a clear LAI insensitivity to temperature (Fig. 6A and 6B). Yet, APSIM-LAI predictions show a notable sensitivity to CO_2-concentrations and increasing leaf growth under rising CO_2 levels. APSIM based simulated LAIs are projected to increase by up to 15% (±10%) under the high emission scenario, which explains why APSIM-ET rates do not decrease despite ET reducing CO_2-effects (Fig. 5D). Similar effects were described recently by Singh et al., 2020, revealing a strong increase in LAI due to CO_2 increases which can offset higher water use efficiency.

As the leaf area growth and temperature increase jointly control the evaporative demands and ultimately irrigation water needs, the differences in LAI projections underline the importance of model sensitivity with respect to temperature stress. These differences in the underlying model parameterizations between both models leads to two different conclusions. On the one hand, the SWAT model projects a decline in future plant growth, which is strong enough to reduce ET and irrigation demand -- this leads to the conclusion that irrigation intensification cannot help to mitigate future yield losses. APSIM on the other hand, forecast increasing leaf area growth and indicates that due to its (even if only moderately) rising irrigation demands, intensified irrigation is necessary to not further strengthen the predicted yield losses.

The apparent inconsistency in decreasing LAI and at the same time increasing biomass in SWAT under elevated CO_2 concentrations (Fig. 6B and 6D) can be explained by the sensitivity of biomass production in SWAT to changes in CO_2. In SWAT, the biomass production is dependent on radiation use efficiency and available light for photosynthesis (see Supplementary Material S.2.1.1). While the availability of light is dependent on LAI development, radiation use efficiency is positively affected by changes in CO_2-concentrations (Neitsch et al., 2009). Increasing CO_2 concentrations thus enhance biomass production. In this study, this biomass enhancing effect is stronger than the negative effect due to decreasing LAI (SWAT results Fig. 6D, RCP 4.5). Yet, for RCP 8.5 and a further temperature increase, this effect is dominated by a further reduction in LAI, leading to a reduction in biomass even under further elevated CO_2 concentrations (Fig. 6D).

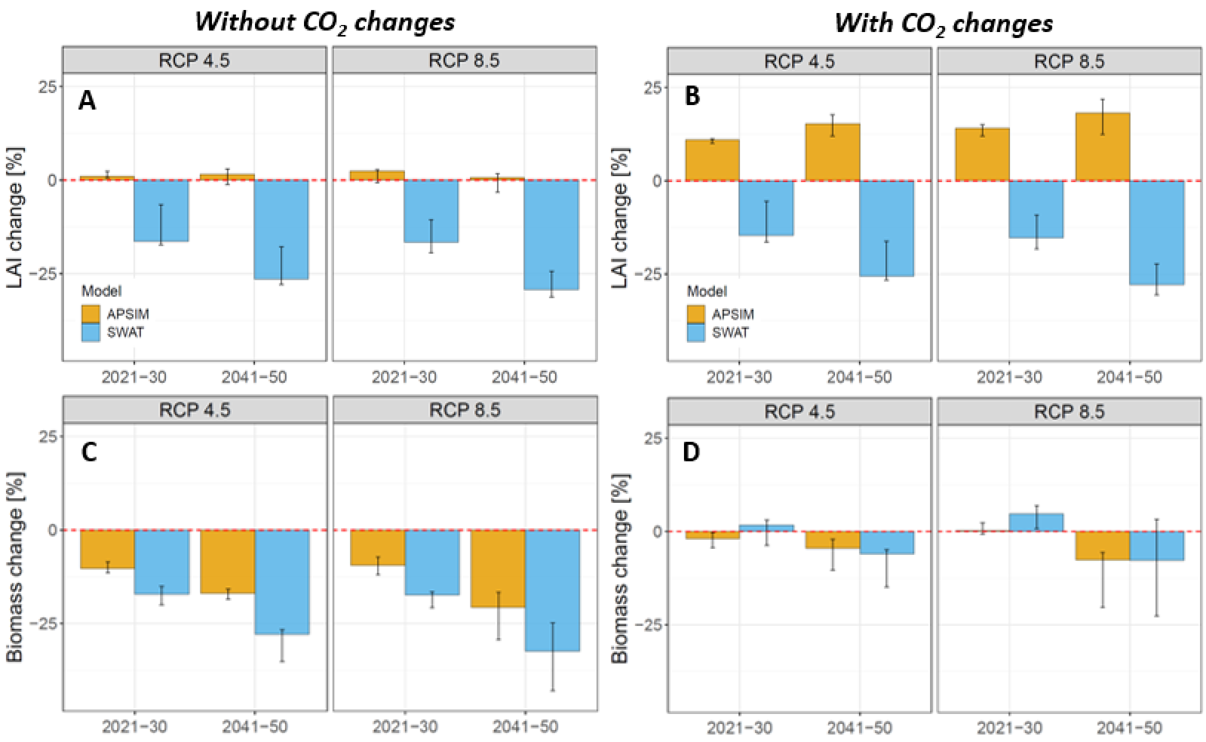

Figure 6: Projections of future LAI changes (A and B) and future biomass changes (C and D). Changes under the baseline CO_2-scenario (A and C) and with increased atmospheric CO_2-levels (B and D).

Despite their differences in LAI estimation procedures, both models show that even if the increased future water demand is fulfilled, a substantial reduction in plant biomass (and thereafter yields) due to increasing temperatures is projected in future (Fig. 6C). To this end, both models show a good agreement in their predicting trends. Rising CO_2 levels might compensate negative temperature effects in the near future but already for the mid-century scenario (2041-2050), biomass is projected to decline despite further elevated CO_2 levels (Fig 6D).

The reason for the discrepancy between increasing LAI predictions and decreasing biomass estimates by APSIM, can be found in the way APSIM accounts for biomass partitioning processes. As a biophysical crop model, the APSIM model accounts for carbon assimilation in different plant parts (i.e. leaves, stem, fruit). Leaf area can therefore remain constant or even increase while the overall biomass decreases (APSIM model documentation, 2021).

Recalling that both models assure a sufficient supply of irrigation water to meet changing water demands, our results reveal that temperature stress alone is responsible for the simulated yield declines in this study. We therefore conclude that increased water use has a strong limit in mitigating future yield losses. Intensification of irrigation might be able to mitigate yield declines in the near future, when positive CO_2 effects balance the harmful temperature effects and irrigation demands are still increasing (Fig. 5B). For the mid-century scenario however, when positive CO_2 effects are no longer sufficient and irrigation demand decrease, irrigation intensification will not be able to mitigate the projected yield losses.

It should be mentioned that our deductions are based on the average trends estimated for maize, cotton, and rice crops. Plant specific reactions should be considered, when impacts on individual crop types are the focus. The effects of climate change on each crop type showed that even though crop reactions differ, they agree in their overall responses to temperature stress and sensitivity to CO_2 (see Supplementary Section S3 for details). The exception to this general trend is the maize crop simulated by the APSIM model due its particular physiologies as a C4-plant (Supplementary Section S3).

4. Conclusions

The main finding of our study is that under the expected climate change scenarios a substantial reduction in summer crop yields is likely to occur in the study region, even though enough irrigation water is assumed to be available. It could be shown that plant development is dominantly controlled by temperature stress and that therefore the negative climate change impact on agricultural productivity cannot be mitigated by an intensification of irrigation.

Assuming a constantly satisfied plant water demand, our results indicate that in the intensively irrigated agricultural system we looked at, the limit of additional water as adaptation measure could be reached in the near future. The dominant future factor, likely causing a substantial yield decline, seems to be plant heat stress. Under these circumstances, temperature related adaptation strategies such as the selection of more heat resistant crops, or changes in crop planting schedules to avoid high temperature stress seem more suitable than water related adaptation measures.

The results contradict previous studies, which suggest that increased irrigation amounts can help to reduce crop heat sensitivity in such a way that it partially or even entirely offsets temperature induced yield reduction (Shaw et al., 2014; Tack et al., 2017; Zaveri and Lobell, 2019). However, these studies also argue that yield gains from intensified irrigation have already slowed down in recent years and that the application of more water has its limits as a potential adaptation strategy to prevent harmful effects of rising temperatures.

Finally, by using two crop models from two different scientific disciplines, this study showed that while both models agree in their overall yield simulations, their predictions of future water demand and the capability of irrigation to counteract the dominating temperature stress can vary significantly. Hence, when using models as decision support systems for future water resources planning, it needs a careful examination of their respective model structures and especially their sensitivities with respect to temperature stress in order to draw the reliable conclusion about future irrigation demands.

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Data Availability Statement

The data produced in this study can be accessed through the following data repository: **https://doi.org/10.5281/zenodo.4603703**

References

APSIM, Crop Module Documentation. https://www.apsim.info/documentation/model-documentation/ (last accessed: 2021-14-03)

Arnold, J.G., D. N. Moriasi, P. W. Gassman, K. C. Abbaspour, M. J. White, R. Srinivasan, C. Santhi, R. D. Harmel, A. van Griensven, M. W. Van Liew, N. Kannan, M. K. Jha, 2012. SWAT: Model Use, Calibration, and Validation. Transactions of the ASABE 55, 1491–1508. https://doi.org/10.13031/2013.42256

Awan, U.K., Liaqat, U.W., Choi, M., Ismaeel, A., 2016. A SWAT modeling approach to assess the impact of climate change on consumptive water use in Lower Chenab Canal area of Indus basin. Hydrology Research 47, 1025–1037. https://doi.org/10.2166/nh.2016.102

Becker, R., Koppa, A., Schulz, S., Usman, M., aus der Beek, T., Schüth, C., 2019. Spatially distributed model calibration of a highly managed hydrological system using remote sensing-derived ET data. Journal of Hydrology 577, 123944. https://doi.org/10.1016/j.jhydrol.2019.123944

Carter, E.K., Melkonian, J., Riha, S.J., Shaw, S.B., 2016. Separating heat stress from moisture stress: analyzing yield response to high temperature in irrigated maize. Environmental Research Letters 11, 094012. https://doi.org/10.1088/1748-9326/11/9/094012

CORDEX, n.d. Coordinated Regional Climate Downscaling Experiment [WWW Document]. URL https://cordex.org/ (accessed 4.15.20).

Deihimfard, R., Eyni-Nargeseh, H., Mokhtassi-Bidgoli, A., 2018. Effect of Future Climate Change on Wheat Yield and Water Use Efficiency Under Semi-arid Conditions as

Predicted by APSIM-Wheat Model. Int. J. Plant Prod. 12, 115–125. https://doi.org/10.1007/s42106-018-0012-4

Deryng, D., Conway, D., Ramankutty, N., Price, J., Warren, R., 2014. Global crop yield response to extreme heat stress under multiple climate change futures. Environmental Research Letters 9, 034011. https://doi.org/10.1088/1748-9326/9/3/034011

Döll, P., 2002. Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective. Climatic Change 54, 269–293. https://doi.org/10.1023/A:1016124032231

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences 111, 3239–3244. https://doi.org/10.1073/pnas.1222474110

Fader, M., Shi, S., von Bloh, W., Bondeau, A., Cramer, W., 2016. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrology and Earth System Sciences 20, 953–973. https://doi.org/10.5194/hess-20-953-2016

Fischer, G., Tubiello, F.N., van Velthuizen, H., Wiberg, D.A., 2007. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. Technological Forecasting and Social Change 74, 1083–1107. https://doi.org/10.1016/j.techfore.2006.05.021

Gassman, P.W., Sadeghi, A.M., Srinivasan, R., 2014. Applications of the SWAT Model Special Section: Overview and Insights. Journal of Environmental Quality 8.

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software 62, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate Change Will Affect the Asian Water Towers. Science 328, 1382–1385. https://doi.org/10.1126/science.1183188

IPCC, 2019, Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., n.d. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Khan, M.A., Khan, J.A., Ali, Z., Ahmad, I., Ahmad, M.N., 2016. The challenge of climate change and policy response in Pakistan. Environ Earth Sci 75, 412. https://doi.org/10.1007/s12665-015-5127-7

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free air CO2 enrichment. Advances in Agronomy 77, 293–361.

Liu, L., Zhu, Y., Tang, L., Cao, W., Wang, E., 2013. Impacts of climate changes, soil nutrients, variety types and management practices on rice yield in East China: A case study in the Taihu region. Field Crops Research 149, 40–48. https://doi.org/10.1016/j.fcr.2013.04.022

Lobell, D.B., Burke, M.B., 2008. Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environmental Research Letters 3, 034007. https://doi.org/10.1088/1748-9326/3/3/034007

McGrath, J.M., Lobell, D.B., 2013. Regional disparities in the CO2 fertilization effect and implications for crop yields. Environ. Res. Lett. 8, 014054. https://doi.org/10.1088/1748-9326/8/1/014054

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. https://doi.org/10.5194/hess-15-1577-2011

MNFSR, Pakistan Ministry of National Food Security & Research, http://www.mnfsr.gov.pk/pubDetails.aspx (last accessed: 2021-03-14)

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management 97, 528–535. https://doi.org/10.1016/j.agwat.2009.03.023

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2009. Soil and Water Assessment Tool. Theoretical Documentation. Version 2009.

Oxfam, 2009. Climate change, poverty and environmental crisis in the disaster prone areas of Pakistan.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14, 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008

Qureshi, A.S., 2011. Water Management in the Indus Basin in Pakistan: Challenges and Opportunities. Mountain Research and Development 31, 252–260. https://doi.org/10.1659/MRD-JOURNAL-D-11-00019.1

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci USA 111, 3268–3273. https://doi.org/10.1073/pnas.1222463110

Saddique, Q., Khan, M.I., Habib ur Rahman, M., Jiatun, X., Waseem, M., Gaiser, T., Mohsin Waqas, M., Ahmad, I., Chong, L., Cai, H., 2020. Effects of Elevated Air Temperature and CO2 on Maize Production and Water Use Efficiency under Future Climate Change Scenarios in Shaanxi Province, China. Atmosphere 11, 843. https://doi.org/10.3390/atmos11080843

Saeed, F., Athar, H., 2018. Assessment of simulated and projected climate change in Pakistan using IPCC AR4-based AOGCMs. Theoretical and Applied Climatology 134, 967–980. https://doi.org/10.1007/s00704-017-2320-5

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, Jiande, Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, Jun, Hou, Y.-T., Chuang, H., Juang, H.-M.H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R.W., Rutledge, G.,

Goldberg, M., 2010. The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91, 1015–1058. https://doi.org/10.1175/2010BAMS3001.1
Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P., 2014. Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences 111, 3245–3250. https://doi.org/10.1073/pnas.1222460110
Schulz, S., Becker, R., Richard-Cerda, J.C., Usman, M., Beek, T., Merz, R., Schüth, C., 2021. Estimating water balance components in irrigated agriculture using a combined approach of soil moisture and energy balance monitoring, and numerical modeling. Hydrological Processes. https://doi.org/10.1002/hyp.14077
Shaw, S.B., Mehta, D., Riha, S.J., 2014. Using simple data experiments to explore the influence of non-temperature controls on maize yields in the mid-West and Great Plains. Climatic Change 122, 747–755. https://doi.org/10.1007/s10584-014-1062-y
Siebert, S., Ewert, F., 2014. Future crop production threatened by extreme heat. Environmental Research Letters 9, 041001. https://doi.org/10.1088/1748-9326/9/4/041001
Siebert, S., Ewert, F., Eyshi Rezaei, E., Kage, H., Graß, R., 2014. Impact of heat stress on crop yield—on the importance of considering canopy temperature. Environmental Research Letters 9, 044012. https://doi.org/10.1088/1748-9326/9/4/044012
Singh, A., Kumar, S., Akula, S., Lawrence, D.M., Lombardozzi, D.L., 2020. Plant Growth Nullifies the Effect of Increased Water-Use Efficiency on Streamflow Under Elevated CO2 in the Southeastern United States. Geophysical Research Letters 10.
Tack, J., Barkley, A., Hendricks, N., 2017. Irrigation offsets wheat yield reductions from warming temperatures. Environmental Research Letters 12, 114027. https://doi.org/10.1088/1748-9326/aa8d27
Taraz, V., 2018. Can farmers adapt to higher temperatures? Evidence from India. World Development 112, 205–219. https://doi.org/10.1016/j.worlddev.2018.08.006
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1
van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Climatic Change 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z
Vanuytrecht, E., Raes, D., Willems, P., Geerts, S., 2012. Quantifying field-scale effects of elevated carbon dioxide concentration on crops. Climate Research 54, 35–47. https://doi.org/10.3354/cr01096
Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F.T., Stacke, T., Tessler, Z., Schewe, J., 2013. Multimodel projections and uncertainties of irrigation water demand under climate change: Irrigation demand under climate change. Geophysical Research Letters 40, 4626–4632. https://doi.org/10.1002/grl.50686
Wang, X., Zhang, J., Shahid, S., Guan, E., Wu, Y., Gao, J., He, R., 2016. Adaptation to climate change impacts on water demand. Mitigation and Adaptation Strategies for Global Change 21, 81–99. https://doi.org/10.1007/s11027-014-9571-6
Williams, A., White, N., Mushtaq, S., Cockfield, G., Power, B., Kouadio, L., 2015. Quantifying the response of cotton production in eastern Australia to climate change. Climatic Change 129, 183–196. https://doi.org/10.1007/s10584-014-1305-y

Wu, Y., Liu, S., Abdul-Aziz, O.I., 2012. Hydrological effects of the increased CO2 and climate change in the Upper Mississippi River Basin using a modified SWAT. Climatic Change 110, 977–1003. https://doi.org/10.1007/s10584-011-0087-8
Wullschleger, S.D., Tschaplinski, T.J., Norby, R.J., 2002. Plant water relations at elevated CO_2 - implications for water-limited environments: Interactions between elevated CO_2 and drought. Plant, Cell & Environment 25, 319–331. https://doi.org/10.1046/j.1365-3040.2002.00796.x
Yoo, C.Y., Pence, H.E., Hasegawa, P.M., Mickelbart, M.V., 2009. Regulation of Transpiration to Improve Crop Water Use. Critical Reviews in Plant Sciences 28, 410–431. https://doi.org/10.1080/07352680903173175
Zaveri, E., Lobell, D., 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. Nature Communications 10. https://doi.org/10.1038/s41467-019-12183-9
Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z., Asseng, S., 2017. Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci USA 114, 9326–9331. https://doi.org/10.1073/pnas.1701762114