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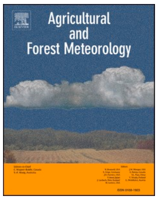

Limits to management adaptation for the Indus' irrigated agriculture

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ABSTRACT

Future irrigated agriculture will be strongly affected by climate change and agricultural management. However, the extent that agricultural management adaptation can counterbalance negative climate-change impacts and achieve sustainable agricultural production remains poorly quantified. Such quantification is especially important for the Indus basin, as irrigated agriculture is essential for its food security and will be highly affected by increasing temperatures and changing water availability. Our study quantified these effects for several climate-change mitigation scenarios and agricultural management-adaptation strategies using the state-of-the-art VIC-WOFOST hydrology–crop model. Our results show that by the 2030s, management adaptation through improved nutrient availability and constrained irrigation will be sufficient to achieve sustainable and increased agricultural production. However, by the 2080s agricultural productivity will strongly depend on worldwide climate-change mitigation efforts. Especially under limited climate-change mitigation, management adaptation will be insufficient to compensate the severe production losses due to heat stress. Our study clearly indicates the limits to management adaptation in the Indus basin, and only further adaptation or strong worldwide climate-change mitigation will secure the Indus' food productivity.

1. Introduction

Irrigated agriculture is essential for worldwide food security. By supplementing rainfall deficits with other water resources, irrigation enables agriculture in arid regions and dry periods that would otherwise not support crop cultivation. Moreover, agricultural intensification and yield-gap closure through, among others, irrigation expansion is likely needed to maintain sufficient food production for a growing and developing population (Foley et al., 2011; Godfray et al., 2010; Mueller et al., 2012).

However, irrigated agriculture is threatened by climate-change and its two fold impacts on crop growth and water availability. Temperature increases under climate change will reduce crop productivity and cropland suitability, especially in lower latitudes, as crop development and stress is strongly linked to growing season temperatures (Ortiz et al., 2008; Pugh et al., 2016; Tan et al., 2021). In addition, changing precipitation, evaporation and snow melt patterns under climate change will affect the timing and distribution of surface and groundwater availability (Haddeland et al., 2014; Immerzeel et al., 2010). Contrary to these negative climate impacts, elevated atmospheric carbon dioxide concentrations ([CO_2]) will positively affect irrigated agriculture through increased crop productivity and water-use efficiency (especially for C_3 crops) (Ainsworth and Long, 2021; Toreti et al., 2020).

These climate-change impacts on irrigated agriculture is especially important for the Indus basin. Agriculture in the Indus basin supports the livelihoods of more than half of its 240 million inhabitants and is a key component of the local government's food self-sufficiency strategy (GOI, 2015; GOP, 2018, 2020). To enable agriculture in the arid Indus basin, croplands are extensively irrigated with water from the mountainous upper Indus region in combination with large scale groundwater extractions, redistributed through the world's largest contiguous irrigation system (FAO, 2011). However, agricultural productivity is well below its potential and barely able to sustain the food requirements of the rapidly developing population (Ahmad and Farooq, 2010; Khan et al., 2021; Shapouri et al., 2010). Moreover, excessive water withdrawals threaten the long-term viability of irrigated agriculture. Groundwater depletion and associated salinity problems are prevalent (Qureshi, 2018; Qureshi et al., 2010; Sidhu et al., 2021; Watto and Mugera, 2016) and water withdrawals and reservoir construction are endangering the integrity of the riverine ecosystem (de Graaf et al.,

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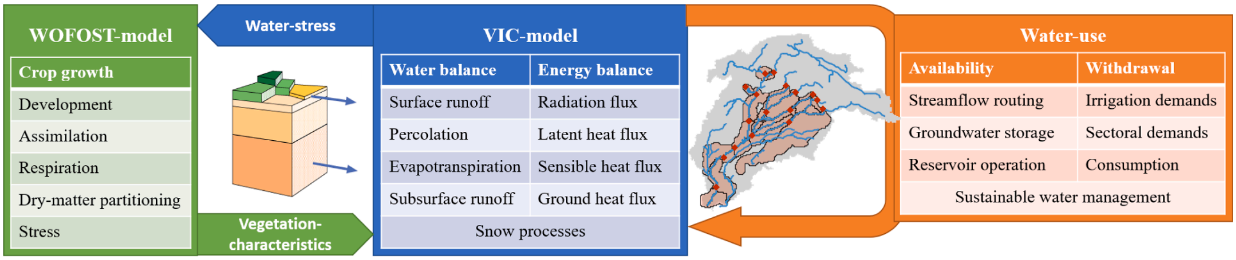


Fig. 1. Conceptualization of the VIC-WOFOST model implementation. The VIC hydrological simulates the water and energy balance for various land-cover tiles and the WOFOST crop model simulates crop growth for wheat and rice land-cover tiles. Water use is based on the simulated water availability and withdrawal. For croplands in an irrigation scheme (orange regions on map), irrigation can be withdrawn from the irrigation scheme inlet (orange points on map). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

2019; Irfan et al., 2019; Salik et al., 2016).

To achieve sufficient and sustainable agricultural productivity in the Indus basin, the possibilities and limitation of management adaptation under climate change need to be addressed. While the impact of climate-change on crop heat stress (Ali et al., 2017; Arshad et al., 2017) and water availability (Dahri et al., 2021; Wijngaard et al., 2017) in the Indus basin is well studied, their combined impact on irrigated agriculture is often poorly understood and quantified. Moreover, the possibilities and limitations of agricultural management adaptation to increase productivity and constrain excessive water withdrawals is hardly ever considered, while recognizing these limitations is essential to determine the need for more drastic interventions and plan for those appropriately.

Our study therefore quantifies the effects of agricultural management adaptation in the Indus basin under various climate-change mitigation scenarios. To this end, the effects of projected climate change and elevated [CO_2] on the productivity of primary food crops, wheat and rice (Section 3.1), and the availability of and demand for water (Section 3.2) are quantified. Subsequently, the extent to which agricultural management adaptation can enhance agricultural productivity and achieve sustainable water use is explored (Section 3.3). Lastly, the implications of these results for the Indus basin food security are examined (Section 4).

We use the state-of-the-art process-based hydrology–crop model VIC-WOFOST (Droppers et al., 2021) to estimate crop growth, water availability and their two-sided interactions (Section 2). Three climate-change mitigation scenarios were included (Lange, 2019): high mitigation (+2 °C by 2100), medium-low mitigation (+4 °C by 2100) and low mitigation (+5 °C by 2100). Furthermore, three periods are assessed: the 1980s (1970–2000), the 2030s (2020–2050) and the 2080s (2070–2100), representing the historical, mid-century and end-of-the-century periods, respectively. Considered management-adaptation options are: (1) reduced crop nutrient limitations (i.e. improved soil and fertilizer management) to increase crop productivity and (2) constrained irrigation withdrawals to avoid unsustainable water use (i.e. avoiding non-renewable water withdrawals and protecting riverine ecosystems). The model is specifically setup for the Indus basin, and thoroughly calibrated and validated for the elevated [CO_2] effects on crop growth and for the Indus' agriculture and hydrology (Appendix A and Supplementary Information S1, S2 and S3).

2. Methods

2.1. Model description

VIC-WOFOST (Droppers et al., 2021) is a two-way coupling between the variable infiltration capacity (VIC) hydrological model (Droppers et al., 2020; Hamman et al., 2018; Liang et al., 1994) and the world food studies (WOFOST) crop model (de Wit et al., 2019; 2020; Supit et al., 1994) (Fig. 1). In the coupled model framework, the VIC hydrological model is used to estimate water availability while the WOFOST crop model is used to estimate crop growth. The hydrological model simulates the gridded (5-arcminute resolution) spatially distributed water and energy balance for various land-cover tiles (e.g. forests, grasslands, rainfed agriculture, irrigated agriculture and bare soil). Evapotranpsiration and latent heat fluxes are governed by the Penman-Monteith equation (Shuttleworth, 1993), where energy and water balance components meet. Each land-cover tile is simulated separately, meaning there is no interaction between the water and energy balance of each tile. The crop model simulates crop growth for each wheat and rice land-cover tile over the growing season. The crop model subsequently informs the hydrological model regarding changes in vegetation characteristics (e.g. LAI, rooting depth and height), thereby affecting water and energy fluxes. Further information on the model setup is given in Supplementary Information S1.

2.2. Water use

Water demands originate from several sectors: irrigation, domestic, industrial (i.e. manufacturing and thermoelectric energy) and livestock. Irrigation water demands are determined by model simulation (Droppers et al., 2020). For wheat, and other crops except rice, irrigation is required when crop water stress would occur (see Section 2.3). Irrigation demands are subsequently set to fill the soil moisture up to field capacity. For paddy rice, irrigation is required when the upper soil layer becomes dry. Irrigation demands are subsequently set to fill the upper soil layer. Domestic, industrial and livestock water demands are given as an input to the model, and are estimated based on reported values for Pakistan and estimates of population growth (see Supplementary Information S1). These sectors combined constitute only between 6% and 17% of the total water demands.

Simulated surface and subsurface runoff is routed along flow paths to simulate river streamflow (Lohmann et al., 1996; Watt and Chow, 1985) (Fig. 1). River streamflow is further modified by reservoir storage and release, which operates according to the reservoir's main purpose (Hanasaki et al., 2006). For example, reservoirs with an irrigation purpose will increase river streamflow when needed for irrigation. Water demands are subsequently withdrawn from local (i.e. within grid) river streamflow. For irrigation areas that are part of a centralized irrigation scheme, water can additionally be withdrawn from remote river streamflow at the irrigation scheme inlet (Biemans et al., 2019). If rivers streamflow is insufficient to supply these water demands, water is withdrawn from a local (i.e. within grid) unconfined groundwater aquifer. Groundwater aquifer withdrawals are unrestricted. However, if the aquifer storage has been reduced, subsurface runoff will be redirected to recharge the aquifer, instead of contributing to river discharge.

Only part of the withdrawn water resources actually evaporates, referred to as 'consumed', while the rest is returned to the water system. These return flows play an important role in the Indus basin irrigation efficiency, as the contribute significantly to groundwater recharge (Laghari et al., 2012). Irrigation efficiency is separated into conveyance and application efficiency. Conveyance efficiency refers to percolation losses during transport from inlet to field and is set to 0.6 (Hussain et al., 2011). Application efficiency refers to evaporation and percolation losses during field irrigation, which is assumed to occur via surface application (Hussain et al., 2011). As such irrigation is applied continuously to the upper soil layer and may subsequently increase evaporation and percolation. Percolation from both conveyance and application are eventually returned to the groundwater aquifer or, if there is no aquifer deficit, to the river streamflow. These return flows are again available for withdrawal. Therefore, the overall irrigation efficiency changes based on the spatial extent of the analysis. For example, our simulations indicate the consumption efficiency for an individual field (irrigation water transpiration per withdrawal) is only 0.29, while the consumption efficiency for the whole region (irrigation water transpiration per evapotranspiration) is 0.63.

2.3. Crop growth

Crop growth results from carbon assimilation and nutrient uptake during the growing season. Crop growing seasons follow reported planting and harvesting dates (Portmann et al., 2010), including one wheat and two rice seasons, and crop phenology (i.e. the temperature requirements for crop development) is adjusted accordingly.

Growth is affected by several stress factors that reduce productivity and yield. The most important stress factors in our study are heat, water and nutrient stress. Heat stress occurs when daily air temperatures exceed suitable crop growing temperatures. Suitable growing temperatures were based on detailed field experiments (Boons-Prins et al., 1993), and are further adjusted in our study to match regional wheat varieties (GOP, 2015) (rice suitable growing temperatures were deemed sufficient (Hussain et al., 2019)). Water stress occurs when soil moisture drops below the critical moisture point (Keulen and Wolf, 1986; van Diepen et al., 1988) and restricts water uptake. In order to avoid water stress, irrigation may be used to increase the soil moisture content, as described in Section 2.2. Lastly, nutrient stress occurs when nutrient supply is insufficient to meet nutrient demands, and crop nutrient concentrations drop below their critical nutrient concentration (Shibu et al., 2010).

Nutrient supply is determined by soil mineralization and fertilizer application. Mineralization rates were estimated based on the soil pH, soil carbon content and air temperature (Batjes, 2016; Sattari et al., 2014). Organic and inorganic fertilizer application rates between 1850 and 2015 were derived from various studies (Hurtt et al., 2020; Mueller et al., 2012; Zhang et al., 2017). Mineralization rates and fertilizer efficiencies were scaled to match observed yields under minimal fertilizer application and observed yield trends respectively (see Appendix A). Only nitrogen fertilization data was available and accounted for in our study.

Several crop responses to elevated [CO_2] were simulated: increased maximum carbon assimilation rates, increased light-use efficiency and increased stomatal resistance. Increased maximum assimilation and light-use efficiency increases the potential crop productivity while increased stomatal resistance decreases crop water demands. Increases in maximum assimilation rates and light-use efficiency were based on values from WOFOST (Wolf et al., 2012). However, increases in maximum assimilation rates were reduced compared to the default values because they overestimated field conditions (Long et al., 2006; Wolf et al., 2010), as confirmed by our validation (see Appendix A and Supplementary Information S2). Stomatal resistance increases were based on a meta-analysis of a multitude of free air concentration enrichment (FACE) experiments (Ainsworth and Rogers, 2007), and were applied appropriately to each land-cover tile. Stomatal resistance hyperbolically increases with increases in [CO_2] (i.e. strong increase at the start that levels-off at higher [CO_2]) (Li et al., 2019).

2.4. Agricultural management-adaptation strategies

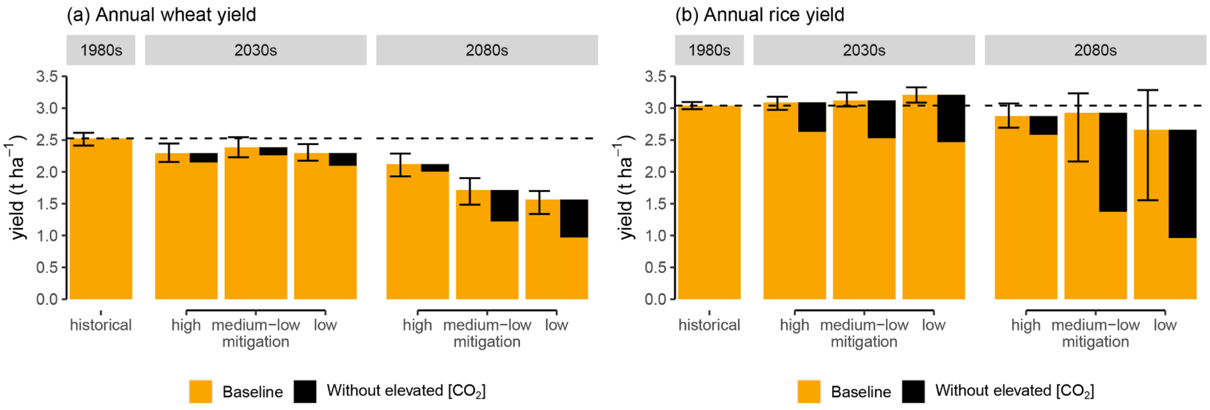
Apart from contemporary agricultural management practices, referred to as the ‘baseline’, two agricultural management-adaptation strategies were explored: production-focused and sustainability-focused management. Production-focused management aims to maximize crop productivity by closing crop yield gaps (i.e. the gap between the potential and actual yield) resulting from water and nutrient limitations. This is done by improving nutrient supply (e.g. through increased fertilizer application or improved soil management) compared to the baseline, and by allowing irrigation withdrawals from surface and groundwater resources.

Contrastingly, sustainability-focused management aims for sustainable water management by avoiding non-renewable groundwater withdrawals and protecting stream flow requirements for riverine ecosystems. Following the variable monthly flow method (Pastor et al., 2014), 60%, 45% and 30% of the historical naturalized river stream flow is allocated for river ecosystems during low, medium and high flows respectively. Note that these allocations are also accounted for during reservoir operation (Droppers et al., 2020). In addition, groundwater withdrawals cannot exceed long-term groundwater recharge. Temporary storage deficits were allowed, to account for interannual variation in groundwater withdrawal and recharge. As a result, irrigation withdrawals for agriculture are constrained compared to the baseline. However, within these irrigation constraints, sustainable crop production increases are still possible through improved nutrient supply.

2.5. Climate-change mitigation scenarios

Climate inputs are derived from the inter sectoral impact model intercomparison project phase 3b (ISIMIP3b), which includes three of the newest United Nations intergovernmental panel on climate change (IPCC) mitigation scenarios: high mitigation (radiative forcing of 2.6 W m^{-2}), medium-low mitigation (radiative forcing of 7.0 W m^{-2}), and low mitigation (radiative forcing of 8.5 W m^{-2}). These scenarios result in average temperature increases of 2 °C, 4 °C and 5 °°C by 2100 in the Indus basin for each mitigation scenario respectively. Meteorological inputs (daily precipitation, air temperature, surface pressure, wind speed, long and shortwave radiation and vapor pressure) at 30-minute resolution are based on five models from the coupled model intercomparison project phase 6 (Eyring et al., 2016) (CMIP6) climate models: GFDL-ESM4 (Dunne et al., 2020), IPSL-CM6A-LR (Boucher et al., 2020), MPI-ESM1-2-HR (Müller et al., 2018), MRI-ESM2-0 (Yukimoto et al., 2019) and UKESM1-0-LL (Sellar et al., 2020). These models were selected in ISIMIP3b based on their performance during the historical period, and represent the CMIP6 ensemble spread in climate sensitivity. For ISIMIP3b, these inputs were bias-adjusted and statistically downscaled (Lange, 2019) based on the water and global change (WATCH) forcing data methodology applied to ERA5 data (WFDE5) (Cucchi et al., 2020).

However, bias-adjustments often provide poor results in the upper Indus, as meteorological observations, especially at greater altitudes, are lacking and suffer from gauge under-catch corrections (Dahri et al., 2018; Immerzeel et al., 2015). Therefore, the upper Indus was further corrected based on meteorological inputs, at 15-minute resolution, from the European centre for medium-range weather forecasts reanalysis 5th data (ERA5) (ECMWF, 2021), which compares favorably to other dataset in the upper Indus region (Dahri et al., 2018). Monthly correction factors (one for each month of the year) were calculated for each model, such that the multi-year monthly average temperature, total precipitation and average short and longwave radiation would match ERA5 in the overlap period (1979–2015). These monthly correction factors were subsequently applied for all years (historical and future). Simulations were run for three periods: the 1980s (1970–2000), the 2030s (2020–2050) and the 2080s (2070–2100).


(a) Annual wheat yield

(b) Annual rice yield

(c) Annual wheat yield difference
between the 1980s and 2080s

(d) Annual rice yield difference
between the 1980s and 2080s

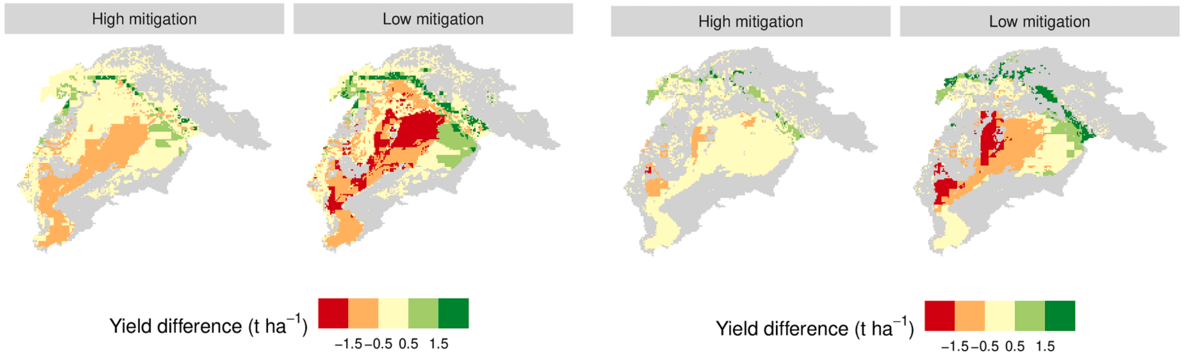


Fig. 2. Simulated baseline (i.e. no management adaptation) annual median (a) wheat and (b) rice yield, and spatially distributed annual median (c) wheat and (d) rice yield differences between the 1980s (historical) and 2080s. Black bars indicate the annual median yield difference (bar height) between simulations with and without elevated [CO_2]. Error bars denote interannual and intermodel variability (1st to 3rd quartile).

3. Results

3.1. Climate-change mitigation and crop productivity

Climate and [CO_2] changes have a diverging impact on the Indus' crop production. Elevated [CO_2] will increase crop carbon assimilation and final yields. On the other hand, higher temperatures contribute to increased crop heat stress and decrease final yields. Both these processes become stronger under lower climate-change mitigation due to a higher increase in [CO_2] and temperature.

For wheat, with optimal growing temperatures between 15 °C and 30 °C (GOP, 2015), heat stress dominates. Wheat production is estimated to decrease by 16% and 38% by the 2080s under high and low mitigation scenarios respectively (Fig. 2a). For rice, with optimal growing temperatures between 25 °C and 35 °C (Hussain et al., 2019), heat stress is likely to be less important. Rice production is estimated to decrease 5% and 12% by the 2080s under high and low mitigation scenarios respectively (Fig. 2b). However, these results are highly uncertain due to the large spread in climate-model sensitivities. Under some climate models with a lower climate sensitivity (GFDL-ESM4 and MPI-ESM1-2-HR) temperature increases are lower and rice production is actually expected to increase (Fig. 2b).

Note that a turning point for wheat and rice yields exists. During the 2030s productivity remains relatively similar to the historical production because the positive impacts of elevated [CO_2] compensates for the negative impacts of higher temperatures. However, towards the 2080s temperature increases clearly offsets the elevated [CO_2] benefits. Climate-change impacts are unevenly distributed across the Indus basin (Fig. 2c and d). In the north-eastern region yields tend to increase, while decreases are prevalent in the south-western region. These geographic differences can largely be attributed to elevation (i.e. temperatures in the higher northern regions actually become more suitable under climate change), growing seasons (i.e. eastern Indus wheat harvest occur earlier, thereby avoiding temperature increases), and spatial distribution of temperature increases (i.e. western Indus temperatures increase relatively further). Furthermore, the effects of elevated [CO_2] are smaller for wheat than rice, with a 2080s average increase of 12% and 22% for wheat and rice respectively (average of all mitigation scenarios). These effects are smaller because heat stress and nutrient limitations are larger for wheat than rice, thus decreasing the effectiveness of the elevated [CO_2] on wheat carbon assimilation.

3.2. Climate-change mitigation and water availability

As the Indus' agriculture is mostly irrigated, precipitation changes will not directly affect crop production. Rather, changes in precipitation and [CO_2] will affect water availability and irrigation water demands.

Increases in renewable surface water availability (i.e. the pristine river streamflow) are expected for all mitigation scenarios, mostly due to projected precipitation increases (Fig. 3a). Water availability increases between 11% and 25% by the 2080s for high and low mitigation scenarios respectively. Relative water availability increases are largest during the dry season of October to February, while absolute increases are largest during the early wet season of March to May (Fig. 3c). Note that these results indicate a shift to an earlier start of the wet season.

At the same time, irrigation demands are expected to continuously and substantially reduce towards the 2080s, mostly due to the crop [CO_2] response (Fig. 3b). This response is largest under low mitigation scenarios, with demand reductions of 28%. Moreover, decrease in groundwater irrigation demands of up to 58% are expected under low mitigation scenarios (Fig. 3d). These reductions are larger than the total reductions as, besides the crop [CO_2] response, they also account for the

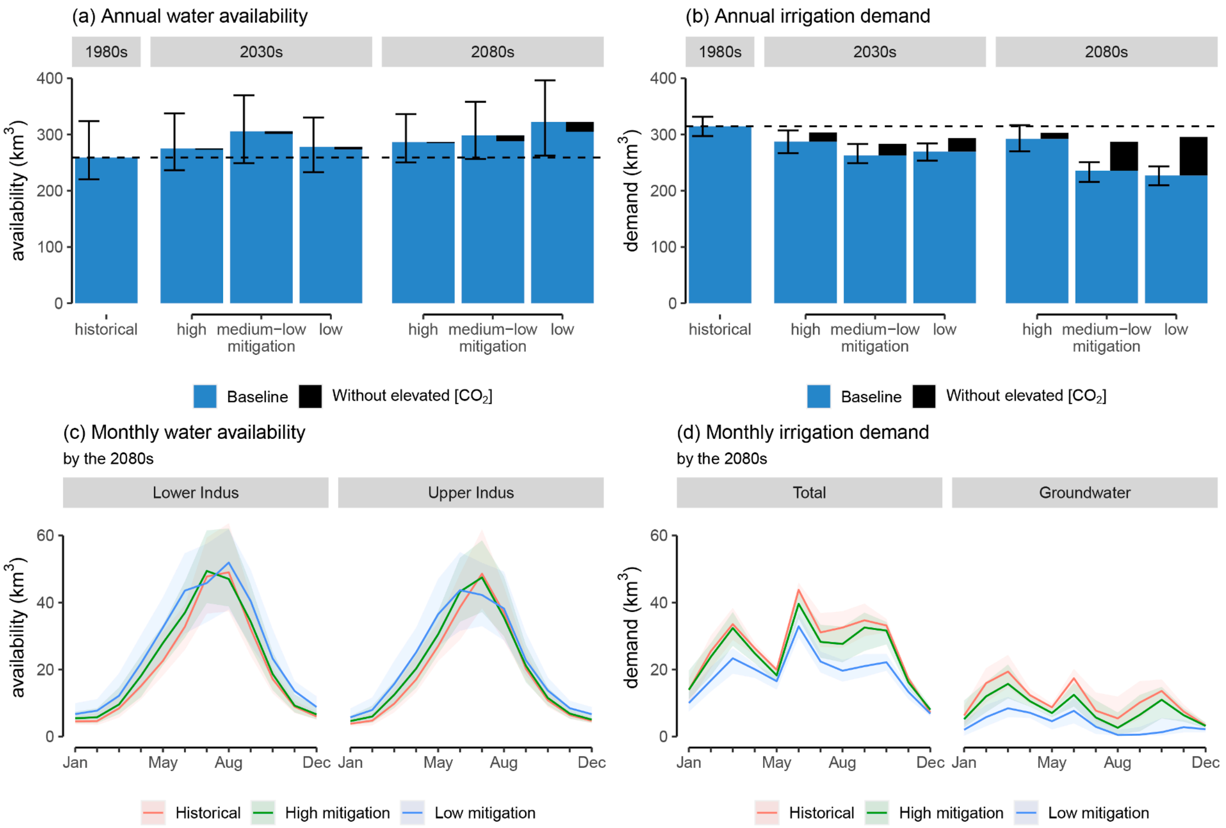


Fig. 3. Simulated baseline (i.e. no management adaptation) annual median (a) water availability and (b) irrigation demand, and temporally distributed 2080s annual median (c) water availability by location and (d) irrigation demand by source. Water availability is estimated based on pristine river streamflow without water withdrawals and reservoir operation. Black bars indicate the annual median availability and withdrawal difference (bar height) between simulations with and without elevated [CO$_2$]. Error bars and shaded areas denote interannual and intermodel variability (1st to 3rd quartile).

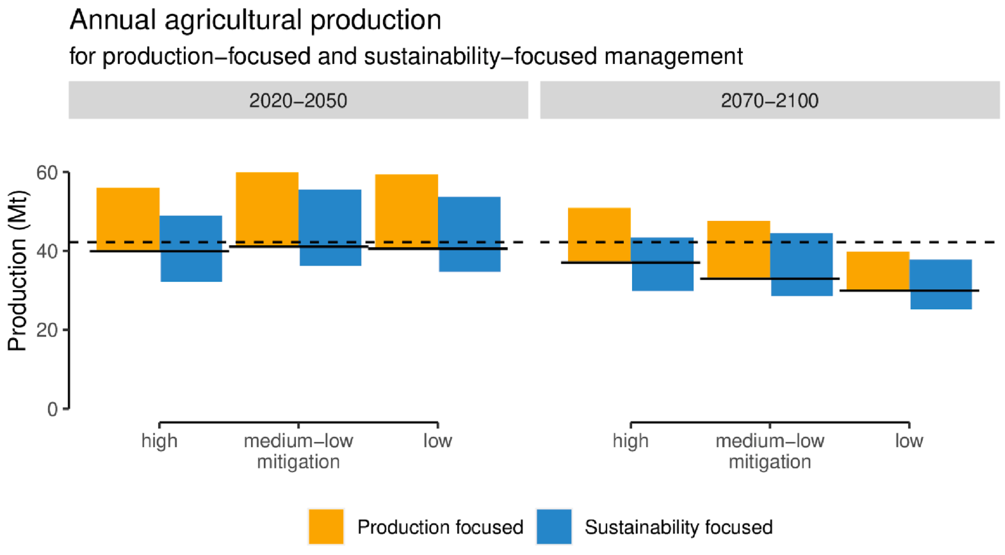


Fig. 4. Simulated possibilities and limitations of management adaptation, in annual median agricultural production, for (yellow) production focused and (blue) sustainability focused management. The solid lines indicate baseline production without management adaptation, while bar heights indicates the production range under management adaptation. Production focused management starts at the baseline and ends at the maximum production possible under improved nutrient supply. Sustainability focus management start below the baseline, due to irrigation constraints, and end at the maximum production possible under both improved nutrient supply and irrigation constraints. The dashed line indicates the historical production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increase in available river streamflow.

3.3. Management adaptation

Management decisions are a major factor determining future crop production. Under production-focused management, agricultural production increases between 10 Mt (2080s low mitigation) and 19 Mt (2030s low mitigation) are possible compared to the baseline (Fig. 4). Especially during the 2030s, production increases between 38% and 45% of the historical (1980s) production are possible. Larger crop production increases are expected for wheat as compared to rice, as wheat has a higher nutrient deficit than rice.

However, the high irrigation withdrawals that accompany production-focused management would be hard to maintain due to continuing groundwater depletion (Fig. 5). Average groundwater depletion rates of 7cm and 2cm water are estimated in the Indus' eastern

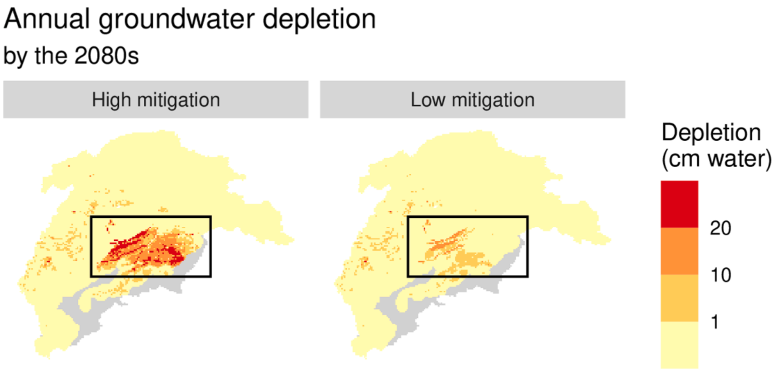


Fig. 5. Simulated 2080s annual median groundwater depletion for production focus management. Eastern Indus area is indicated with a rectangle.

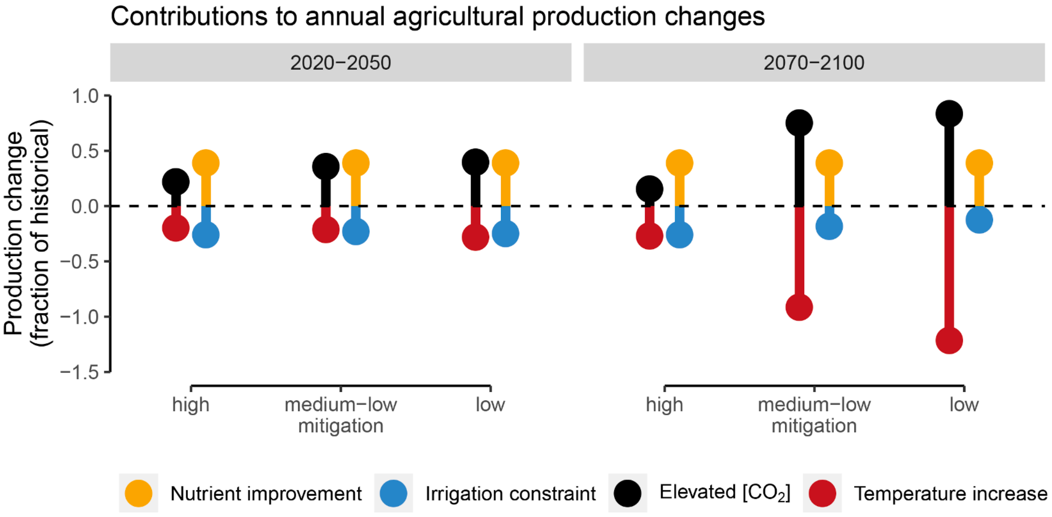


Fig. 6. Simulated annual median agricultural (wheat plus rice) production changes due to climate change and management adaptation. Colors indicate the individual contributions of (black) elevated [CO_2], (red) temperature increases, (yellow) nutrient improvements and (blue) water constraints. Contributions are given as a fraction of the 1980s (historical) production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

region during the 2080s for high and low mitigation scenarios respectively. Assuming a soil porosity of 0.13 Jabeen et al. (2020), these rates are equivalent to a groundwater table drop of at least 58m and 12m respectively between 2000 and 2100 (accumulated depletion over time).

Under sustainability-focused management, irrigation withdrawals will have to be constrained by 20% and 15% (57 and 36 km^3 y^{-1}) for the 2030s and by 19% and 7% (55 and 16 km^3 y^{-1}) for the 2080s high and low mitigation respectively. Note that these constraints are less under low mitigation scenarios, due to increased water availability and decreased irrigation demands (Section 3.2). As a result of these constraints, the upper and lower bounds of the sustainability-focused production is decreased as compared to production-focused management (Fig. 4). Under improved fertilizer application, sustainability-focused production can achieve 68% (between 6 Mt and 14 Mt) of the production-focused production increases (average of all periods and mitigation scenarios).

Even so, whether production increases are possible by the 2080s strongly depends on the climate-change mitigation scenario. Although baseline production is expected to decrease under all climate-change scenarios, management adaptation can compensate for these decreases under high climate-change mitigation. However, management adaptation will be insufficient to maintain production under low mitigation. This discrepancy is due to the relative contributions of management adaptation, elevated [CO_2] and temperature increases in these scenarios (Fig. 6). While reduced management adaptation and elevated [CO_2] will contribute positively to sustainable agricultural productivity, the negative contribution of temperature increases outweighs these factors under low climate-change mitigation by the 2080s.

4. Discussion

Our study comprehensively assessed the possibilities and limitation of management adaptation in the Indus' agriculture under various climate-change scenarios. Our results indicate that the relative contributions of climate change and management adaptation to the Indus' future irrigated agriculture are markedly different in time and per climate-change mitigation scenario. During the 2030s, management adaptation will be sufficient to achieve sustainable and increased agricultural productivity. Although irrigation constraints are necessary to avoid unsustainable water withdrawals, nutrient management improvements can increase agriculture productivity and compensate for these irritation constraints. Note that implementing these management adaptations will require substantial investments in agricultural inputs (e.g. fertilizers) and organization (e.g. water policies) that may be economically or practically difficult or environmentally unsustainable (Chang et al., 2021; Giller et al., 2009; Godfray et al., 2010; Qureshi, 2020; van Steenbergen and Oliemans, 2002).

However, towards the 2080s, agricultural production in the current agricultural landscape (e.g. land use and growing seasons) will strongly depend on worldwide climate-change mitigation efforts. Especially

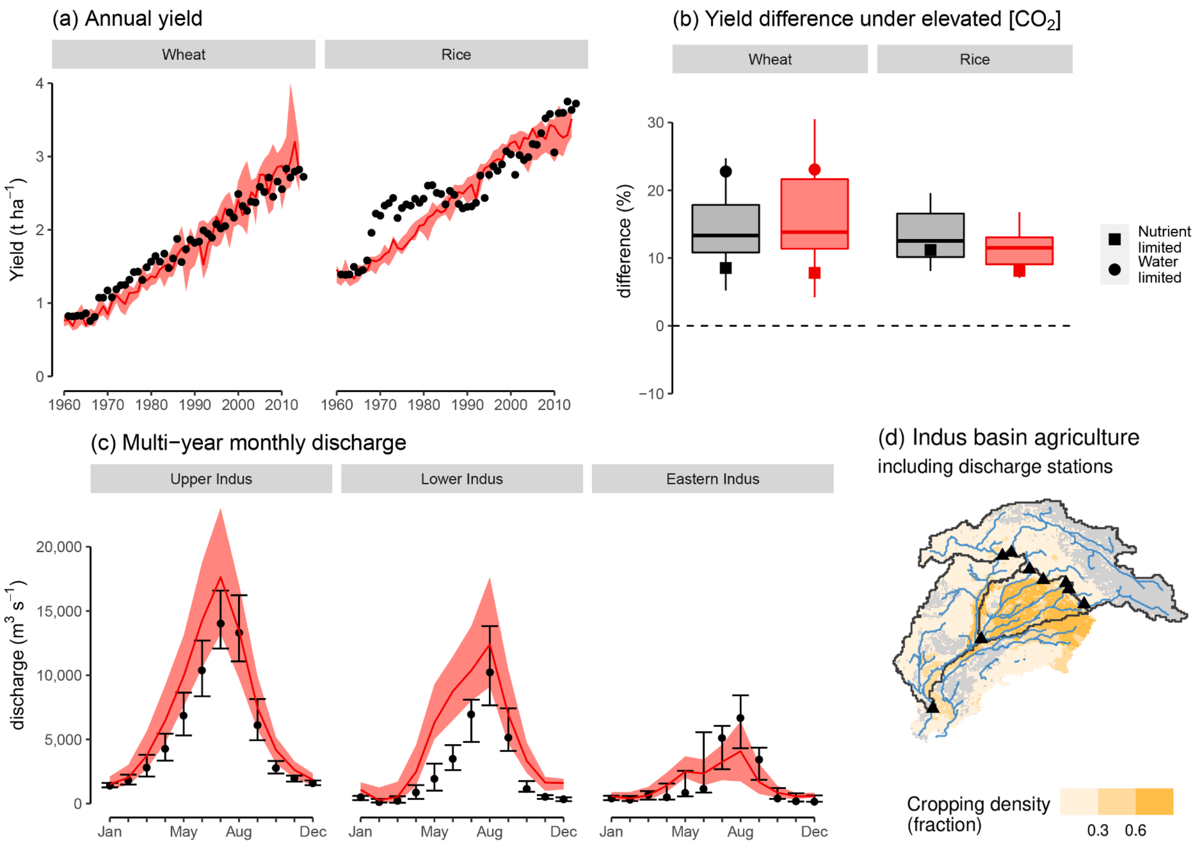


Fig. A1. Comparison between (red) simulations and (black) observations of (a) Pakistan's national annual wheat and rice yields (FAOSTAT, 2021), (b) yield differences under elevated [CO$_2$] for wheat and rice free air carbon enrichment (FACE) experiments (Bloom et al., 2014; Hasegawa et al., 2017; Kimball et al., 2017; Yang et al., 2006) and (c) multi-year monthly station discharge (GRDC, 2019; GOP, 2021). Discharge stations, station sub-basins and cropping densities are shown on the bottom right (d). Points in the FACE experiment comparison indicate mean yield differences for (square) nutrient and (circle) water limited experiments. Error bars indicate observed interannual variability (1st to 3rd quartile), while the colored ribbons indicate simulated interannual and intermodel variability (1st to 3rd quartile for discharge and minimum to maximum for yield). Note that discharge observations are a composite of various periods, while simulations cover 1970 to 2000. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table A1
Comparison between simulated and reported irrigation water withdrawals, groundwater withdrawals and groundwater depletion rates in the Indus basin. Note that time periods vary between studies.

Region		Our study	reported
Pakistan	Irrigation withdrawal (km^3 y^{-1})	188	173 - 192 (AQUASTAT, 2021; Hussain et al., 2011; Laghari et al., 2012; Qureshi, 2011; Simons et al., 2020; Young et al., 2019)
	Groundwater withdrawal (km^3 y^{-1})	55	52 - 63 (AQUASTAT, 2021; Hussain et al., 2011; Laghari et al., 2012; Qureshi, 2011; Watto and Mugera, 2016; Young et al., 2019)
India	Irrigation withdrawal (km^3 y^{-1})	86	94 - 97 (Laghari et al., 2012; Saleth and Amarasinghe, 2010; Sharma et al., 2008)
	Groundwater withdrawal (km^3 y^{-1})	56	27-55 (Laghari et al., 2012; Saleth and Amarasinghe, 2010)
UIP[a]	Groundwater depletion (cm water y^{-1})	9	0.9 - 12 (Cheema et al., 2014; Iqbal et al., 2016; Rodell et al., 2009; Salam et al., 2020; Tiwari et al., 2009)

[a] Upper Indus plains.

under low climate-change mitigation scenarios, temperature increases and associated crop heat stress will result in substantial reductions in agricultural productivity that cannot be compensated by elevated [CO$_2$] or management adaptation. Moreover, additional canopy temperature increases resulting from reduced transpiration cooling under elevated [CO$_2$], not included in our study, will further increase heat stress severity (Kimball, 2016). Nevertheless, climate-change will positively affect water abundance (i.e. the difference between water demands and availability). Crop water-use efficiency will increase due elevated [CO$_2$], and precipitation increases will enhance water availability. In addition, permanent glacier melting, not included in our study, will temporarily increase summer streamflows even further (Immerzeel et al., 2013; Lutz et al., 2016).

While our study shows that heat stress impacts outweigh the elevated [CO$_2$] benefits in the Indus basin, this net effect varies worldwide. In particular in regions where temperature increases do not exceed optimal crop growing temperatures, generally higher latitude regions, agricultural productivity increases can be expected under climate change (Deryng et al., 2014; Ortiz et al., 2008; Wassmann et al., 2009). Furthermore, changes in water abundance will depend on the net effect of water demand decreases and water availability changes (Elliott et al., 2014). For example, water abundance increases have been reported for Morocco where crop water-use efficiency increases counterbalance precipitation decreases (Bouras et al., 2019), while crop water-use efficiency increases insufficiently compensate for precipitation decreases and water demand shifts in the Colorado basin (Rajagopalan et al., 2018). However, few studies fully consider changes in both river-basin water availability and irrigated crop productivity under climate change and management adaptation, as in our study.

In order to achieve sustainable food security the Indus basin, further agricultural adaptation is needed. Under high mitigation scenarios, water management improvements should be prioritized to achieve sustainable water use. Irrigation withdrawals should be constrained to enable long term sustainable agricultural production and avoid transgressing environmental streamflow requirements for riverine ecosystems. Practices such as enhanced groundwater recharge during the wet season, when water is abundant, may provide renewable groundwater storage that can be withdrawn during the dry season, when irrigation demands are high (Khan et al., 2008). Importantly, improving the region's irrigation efficiency may not always be beneficial, as unused irrigation withdrawals are partially reused later (Grafton et al., 2018; Simons et al., 2020) (Section 2.2). Care should be taken to increase irrigation efficiency through reductions in evaporation losses, while accounting for return flows that contribute to groundwater recharge and dry season water availability.

Under low mitigation scenarios, agricultural changes are required to avoid production decreases. A transition to shorter growing seasons or other, more heat resistant, crops should be considered to cope with the temperature increases (Davis et al., 2018; Teixeira et al., 2013), especially for wheat. Development of heat resistant and high yielding crop varieties will also reduce production diminution (Bita and Gerats, 2013; Bustos et al., 2013; Gulnaz et al., 2019; Wu et al., 2019). Note that crop transitions would be highly transformative to the Indus' food system, as wheat and rice are currently important in both agricultural exports and local dietary preferences (Ahmad and Farooq, 2010). Therefore, such transitions would need thorough corroboration of the suitability and productivity of these new agricultural production systems.

If these agricultural changes are planned appropriately, and increases in heat stress can be avoided, the Indus agriculture could also benefit from climate-change. Elevated [CO_2] will increase agricultural productivity, while water abundance increases will enable sustainable intensification and expansion of irrigation systems. Note that groundwater pumping intensification and expansion should be considered carefully. While our simulations are in range of the reported gross groundwater depletion rates (see Annex A), the effect of groundwater depletion on local river streamflow and groundwater tables may be more severe than appears in our simulations. Depending on the pumping approach and the surrounding geohydrology, river streamflow depletion and groundwater table lowering patterns may differ substantially in time and space (de Graaf et al., 2019; Gleeson and Richter, 2018).

Whether or not the Indus region can attain future food security remains ambiguous. Food demands are rising rapidly due to population growth and socioeconomic developments (Beltran-Peña et al., 2020; Fader et al., 2013; Zulfiqar and Hussain, 2014), and outweigh the possible production increases presented here. Further cropland intensification and expansion are likely possible but should confirm to the above-mentioned sustainable water use and crop transitions to enable food security. A greater dependence on food imports, with its political and economic challenges, seems unavoidable (Clapp, 2017; D'Odorico et al., 2014; Porkka et al., 2013).

5. Conclusions

By the 2030s, elevated [CO_2] and nutrient and water management adaptation will be able to achieve increased and sustainable agricultural production in the Indus basin. Production increases up to 14 Mt (or 35% of the historical production) are possible, even when considering sustainable water use. Achieving sustainable water management would require a substantial reduction in irrigation withdrawals between 15% and 20%. However, due to increases in precipitation and decreases in crop water demands, irrigation constraints resulting from sustainable water management will be reduced compared to the historical context.

However, towards the 2080s climate-change effects will decrease agricultural production between 11% and 30% compared to the 2030s values. This decrease is due to increased crop heat stress that outweighs the benefits of elevated [CO_2] on crop productivity and water demands. Especially under limited worldwide mitigation efforts, agricultural productivity will drop below its historical value, regardless of management-adaptation strategies. These results clearly show the limits to agricultural management adaptation, and only of further adaptation or strong worldwide mitigation will secure the Indus' food productivity.

Code and data availability

All code for the VIC-WOFOST model is freely available at github.com/bramdr/VIC (tag VIC-WOFOST.1.1.0; DOI 10.5281/zenodo.5482521) under the GNU general public license, version 2 (GPL-2.0). VIC-WOFOST documentation can be found at vicwur.readthedocs.io. Documentation and scripts concerning input data used in our study is freely available at github.com/bramdr/VIC_support (tag VIC-WOFOST.1.1.0; DOI 10.5281/zenodo.5482542) under the GNU general public license, version 3 (GPL-3.0). The data that support the findings of this study are available from the corresponding author on reasonable request.

Author contributions

BD setup and ran the model simulations and together with IS evaluated the results. All authors discussed the results and commented on the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Validation

The Indus' agricultural yields were validated based on Pakistan's national annual wheat and rice yield data from the food and agriculture organization (FAOSTAT) (FAOSTAT, 2021). Simulated national annual yields realistically represented the observed yields (Fig. A1a), with a root mean squared error of 0.2 and 0.3 t ha^{-1} for wheat and rice respectively. Also, the simulated yield trend, driven by fertilizer application increases, generally matches the observations. Some deviation from this trend can be observed for rice around 1975, and is attributed to a temporary increase in nutrient-use efficiency (Shahzad et al., 2019). Moreover, simulated recent interannual variability is larger than observed. This indicates a larger simulated climate sensitivity than observed.

The effects of elevated [CO_2] on crop growth were validated based on several free air carbon enrichment (FACE) experiments: Arizona (united states of America) FACE for wheat (Bloom et al., 2014; Kimball et al., 2017) and Wuxi (people's republic of China) FACE for rice (Hasegawa et al., 2017; Yang et al., 2006). While the performance of individual experiments varied, the relative effect of elevated [CO_2] on simulated crop growth was adequately captured. Yield differences between ambient and elevated [CO_2] were within range of observed values (Fig. A1b). Moreover, our simulations also captured the effects of irrigation and fertilizer limitations on these differences. Irrigation limitations would increase the relative yield differences, as water demands under elevated [CO_2] were reduced. Contrastingly, fertilizer limitations would decrease the relative yield difference, as increased carbon assimilation under elevated [CO_2] was not possible due to nutrient constraints. Further information on the FACE validation, including crop growth timeseries, is given in Supplementary Information S2.

The Indus' hydrology was validated based on station discharge observations from the Pakistan water and power development authority (WAPDA) (GOP, 2021) in the upper Indus and the global runoff data centre (GRDC) (GRDC, 2019) in the eastern and lower Indus (Fig. A1d). The upper Indus discharge, which is the sum of 7 discharge stations, is relatively pristine and is the main source of surface water availability for irrigated agriculture (including more than 60% of total rainfall in the basin). The eastern and lower Indus discharge, both consisting of one discharge station, are heavily modified and reduced as a result of reservoir operation and water withdrawals. Simulated upper Indus discharge performance was good (Fig. A1c), with a Nash-Sutcliffe efficiency (NSE) of 0.8. However, water availability during the early wet season is overestimated, mainly due to overestimations in the western upper Indus. This discharge estimate is further exacerbated in the lower Indus, since in the eastern Indus discharge, which is responsible for around two-thirds of all water withdrawals, is heavily reduced. Therefore, while eastern Indus discharge performance was reasonable, with a NSE of 0.6, lower Indus discharge performance was poorer, with a NSE of only 0.3. Note, however, that this streamflow overestimation in the western Indus has little impact on our results, as the majority of agricultural croplands and (unsustainable) water withdrawals are located in the eastern Indus (Ali et al., 2021; Cheema et al., 2014; GOP, 2022). Further information on the hydrological calibration and validation, including discharge timeseries for individual discharge stations, is given in Supplementary Information S3.

Simulated water withdrawals, groundwater withdrawals and groundwater depletion rates were compared with various other studies (Table A1). Our estimated surface and groundwater withdrawals are within range of other studies, except in India where total irrigation withdrawals were lower and groundwater withdrawals were slightly higher than reported. Note that, while our estimate fits well within the reported range, some uncertainty exists surrounding the Indus' groundwater depletion rates.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2022.108971.

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