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Exploring the potential of agricultural system change as an integrated adaptation strategy for water and food security in the Indus basin

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Abstract

Water security and food security in the Indus basin are highly interlinked and subject to severe stresses. Irrigation water demands presently already exceed what the basin can sustainably provide, but per-capita food availability remains limited. Rapid population growth and climate change are projected to further intensify pressure on the interdependencies between water and food security. The agricultural system of the Indus basin must therefore change and adapt to be able to achieve the associated *Sustainable Development Goals* (SDGs). The development of robust policies to guide such changes requires a thorough understanding of the synergies and trade-offs that different strategies for agricultural development may have for water and food security. In this study, we defined three contrasting trajectories for agricultural system change based on a review of scientific literature on regional agricultural developments and a stakeholder consultation workshop. We assessed the consequences of these trajectories for water and food security with a spatially explicit modeling framework for two scenarios of climatic and socio-economic change over the period 1980–2080. Our results demonstrate that agricultural system changes can ensure per capita food production in the basin remains sufficient under population growth. However, such changes require additional irrigation water resources and may strongly aggravate water stress. Conversely, a shift to sustainable water management can reduce water stress but has the consequence that basin-level food self-sufficiency may not be feasible in future. This suggests that biophysical limits likely exist that prevent agricultural system changes to ensure both sufficient food production and improve water security in the Indus basin under strong population growth. Our study concludes that agricultural system changes are an important adaptation mechanism toward achieving water and food SDGs, but must be developed alongside other strategies that can mitigate its adverse trade-offs.

Keywords Indus basin · Climate change adaptation · Water stress · Food security · Water security · Agricultural development · Sustainable Development Goals · Hydrological modeling

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1 Introduction

Water security and food security are strongly interlinked for the over 260 million inhabitants of the Indus basin (Kirby et al., 2017). The hydrology of the basin is strongly modified by massive water extractions and water transfers in support of one of the largest contiguous irrigation systems in the world. This system is crucial for regional food production, but also has a strong effect on the availability of water throughout the basin, especially in the areas surrounding the irrigation systems and regions further downstream during the dry season (Basharat et al., 2014). Conversely, relatively small changes in the timing or amount of water supply to the agricultural system can have a large effect on yield and, by extension, on regional food security (Rasul, 2014). This delicate water–food interdependency has become increasingly disbalanced. Irrigation water demands to sustain the steadily expanding agricultural system exceed surface water availability during the dry season and have driven a considerable share of irrigation water to be sourced from groundwater (Biemans et al., 2019). Such irrigation practices are unsustainable on the long term, as groundwater resources in many places of the basin are over-extracted (Cheema et al., 2014; Salam et al., 2020). Groundwater is in addition often brackish, leading to soil salinization (Salam et al., 2020). Furthermore, the enormous surface water extractions for food production cause environmental flows in the unique ecosystem of the Indus delta to not be met for large parts of the year (Laghari et al., 2012).

The current interdependencies between water and food security, and corresponding trade-offs, are likely to intensify in future (Rasul, 2014). Foremost, the basin is projected to face rapid economic development and population growth (Wada et al., 2019). The demand for food will consequently increase rapidly (Smolenaars et al., 2021). Self-sufficiency for staple crops, such as wheat, is an important policy goal for the riparian states (Bishwajit et al., 2013). The agricultural system of the Indus plains, regarded as the breadbasket of both Pakistan and India, will therefore likely face pressure to further expand and intensify food production (Vinca et al., 2020). Food production on the hot and arid plains may, however, be severely affected by increasingly harsh climatic conditions and more erratic water availability and precipitation patterns (Tariq et al., 2014). At the same time, the demand for water faces even steeper growth, especially for urban uses (Smolenaars et al., 2022; Wijngaard et al., 2018). The intersectoral competition over dwindling surface water resources, which are presently dominated by use for irrigation, will therefore aggravate (Laghari et al., 2012). This competition may drive further groundwater overuse (Lutz et al., 2022). Sustainable Development Goals (SDGs) for water (SDG 6) and food (SDG 2) security, but also those related to riverine ecosystem health (SDG 15), are therefore unlikely to be met unless integrated adaptation action is undertaken to peaceably reallocate water resources across competing players (Immerzeel et al., 2020).

The main interface for water and food in the Indus basin is the agricultural system, in particular through its land-use, and crop and water management practices (Wijngaard et al., 2018). The present and future properties of agricultural land-use and management practices here are shaped considerably by policy decisions (Singh & Park, 2018). The combination of being strategically important for both water and food, and partly steerable, designates agricultural change and development as an important component of integrated adaptation strategies that aim to reconcile water and food security (Fathian et al., 2023; Ostad-Ali-Askari et al., 2017; Wada et al., 2019). The agricultural system must therefore evolve to manage the new challenges and priorities, imposed by climatic, economic and demographic changes, on both water management and food production. Yet, this interplay also demonstrates that the future trajectory of agriculture in the Indus basin is complex. Rather than a fully autonomous process that can be 'predicted,' the development of the agricultural system is a continuous product of evolving societal choices within hard biophysical constraints throughout the basin (Farah et al., 2019). Policy-making to guide this process in a sustainable direction therefore requires spatially explicit insight into the consequences of a range of alternative agricultural system futures that convey different visions for its position in the Indus water–food nexus (Biemans & Siderius, 2019). The integrated exploration of multiple future scenarios allows robust agricultural strategies to be identified for adaptation planning and for maladaptive trajectories to be avoided.

Most of the existing modeling research on future interactions between water and food security in the Indus basin has, however, assumed that future agricultural developments will follow a similar pattern to historical developments (Lutz et al., 2022; Vinca et al., 2020). In addition, several other studies did not account for any type of change in future land-use or crop choices (Droppers et al., 2022; Wijngaard et al., 2018; Yang et al., 2016). This suggests that there is a lack of quantitative information regarding the potential benefits and drawbacks of agricultural development strategies, other than a continuation of current practices, for adaptation policy making in the basin. In this study, we therefore used a modeling approach to explore how multiple alternative strategies for agricultural development may affect water–food interactions in the Indus basin under climatic and socio-economic changes. *The aim of this study is accordingly to assess what may happen to water and food security 'if' certain strategies for agricultural system change are adopted*. Hence, we explicitly do not attempt to forecast the future impact that agricultural changes may have on the water system of the Indus basin, but instead base our analysis on hypothetical 'what-if' premises. To do so, we first established three agricultural development narratives that represent different positions in the policy space between water and food security (i.e., priority on food, on water, or a balance). The narratives were then studied with a fully distributed crop-hydrology modeling framework under socio-economic and climate change.

The results of this study allow for novel insights into the impact of multiple contrasting directions for agricultural development, and corresponding strategic policy choices, on both future water and food security. This type of insight is presented both at high spatial resolution and aggregated at the basin level in relation to other important regional developments such as climate change and population growth. The information provided by these study outcomes is important for adaptation policy-making in the Indus basin as it supports a better understanding of the potential benefits and limitations of agricultural system changes as an adaptation mechanism to reconcile and achieve SDG2 and SDG6.

2 Methods

We conducted a scenario analysis, based on the SSP-RCP framework over the period 1950–2080, using a spatially distributed crop-hydrology model. Our methodological approach consisted of five steps:

1. First, we defined two regionally downscaled SSP-RCP forcing scenarios that provide a broad storyline for the development of population, economic, climatological and technological factors.
2. We developed three unique narratives for the future of the Indus agricultural system and embedded these within the downscaled SSP-RCP scenarios. This process defined

six internally consistent strategies for agricultural development in the Indus basin. An overview of the strategies can be found in Table 1.

3. Next, we quantified and spatialized the land-use change component of the agricultural development strategies at annual timesteps over the period 1950–2080 and at 5 arcmins resolution. This was done using observational statistics of historical crop production and yields at the state/provincial level for India and Pakistan from 1952 to 2015, in combination with a spatial dataset of crop distributions. We did this for both the Rabi (dry) and Kharif (wet) cropping seasons.
4. We used the spatial land-use projections and other strategy elements as input data for the fully distributed LPJmL crop-hydrology model. Besides land-use change, we also accounted in our model runs for yield gap closure, water management, climate change, and for changes in the water use of the domestic and industrial sectors as a result of socio-economic developments.
5. Lastly, we analyzed the spatial outputs of the model to determine how agricultural system changes affect water and food security in future and how these impacts may interact with other changes in the basin.

2.1 Forcing scenarios

The contextual core of our scenario analysis is determined by two integrated downscaled forcing scenarios from Smolenaars et al. (2021). These scenarios are regionalized versions of the SSP-RCP (Shared Socio-Economic Pathways & Representative Concentration Pathways) framework specifically for the Indus basin. We used the optimistic Prosperous (SSP1-RCP4.5, hereafter SSP1) and the pessimistic Downhill (SSP3-RCP8.5 hereafter SSP3) scenarios. For both scenarios, spatially explicit population and economic data were obtained through the scenario-specific datasets published by Smolenaars et al. (2021). Downscaled climate data for RCP4.5 and RCP8.5 were also available, consisting of an ensemble of four downscaled Global Circulation Models (GCMs) for each scenario (Lutz et al., 2016). These climate models were selected for their performance in representing historical climatic patterns for the Indo-Gangetic plains. This procedure used an envelope approach to ensure that a diverse range of future projections was selected from the available models with good performance. The models were subsequently downscaled and bias corrected to observational climate data for the reference period (1971–2000) to ensure an optimal representation of past, present and future regional climatic patterns. A more elaborate overview of the climate models and projections used in this study can be found in Lutz et al. (2016).

- *SSP1-RCP4.5: Prosperous*

  The SSP1-RCP4.5 scenario assumes socio-economic development in the Indus basin will follow a sustainable and moderate trajectory. Population growth decreases rapidly, stabilizing by 2050 at approximately 350 million people, but the basin's population is increasingly concentrated in highly developed urban centers. Similarly, economic growth, though steady, is characterized by an emphasis on sustainable development, smart and clean technologies, and the optimized use of resources. There is a balance between different societal needs with considerable emphasis on nature-based prac-

Table 1 Overview of land-use and management changes for each of the agricultural development strategies in relation to SSP forcing scenarios

Strategy elements	Status quo		Water limited		Food priority	
	SSP1	SSP3	SSP1	SSP3	SSP1	SSP3
Agricultural land-use						
Food crops mix	Same crop mix as present	Same crop mix as present	Rice largely replaced by oilseeds, pulses and maize	Rice largely replaced by oilseeds, pulses and maize	Rice–wheat systems continue to grow more dominant	Rice–wheat systems continue to grow more dominant
Cash crops Mix	Sugarcane gradually replaces cotton	Sugarcane gradually replaces cotton	Sugarcane is rapidly replaced by cotton in the Kharif season, and oilseeds and pulses in the Rabi season	Sugarcane is rapidly replaced by cotton in the Kharif season, and oilseeds and pulses in the Rabi season	Cotton replaced by oilseeds and pulses. Sugarcane continues to expand	Cotton replaced by oilseeds and pulses. Sugarcane continues to expand
Cropping (or land-use) intensity	Change in net sown area coupled to population growth	Change in net sown area coupled to population growth	Change in net sown area coupled to population growth	Change in net sown area coupled to population growth	Change in net sown area coupled to population growth	Rapid expansion to maximum cropping intensity in irrigated areas
Water management						
Irrigated share	All expansion of net sown area to rainfed production	Expansion of net sown area to both irrigated and rainfed production	All expansion of net sown area to rainfed production	All expansion of net sown area to rainfed production	Expansion of net sown area to both irrigated and rainfed production	All expansion of net sown area to irrigated production
Water management	Groundwater use is allowed without limits	Groundwater use is allowed without limits	Groundwater use is allowed, overextraction is not	Groundwater use is allowed without limits	Groundwater use is allowed without limits	Groundwater use is allowed without limits

Table 1 (continued)

Strategy elements	Status quo		Water limited		Food priority	
	SSP1	SSP3	SSP1	SSP3	SSP1	SSP3
Crop management						
Production intensity	Emphasis on sustainable resource use instead of economic gains reduces yield gap closure to 0.45% per year	Continuation of present rate of agricultural input-driven yield gap closure of 0.55% per year	Strong limitations on further intensification to save aquatic ecosystems, with further yield gap closure driven only by sustainable technological advancements at 0.30% per year	Some limitations on present-day intensification practices are imposed to reduce water quality impact, with yield gap closure reducing to 0.45% per year	Some limitations on inputs are compensated for by technological advancements, resulting in yield gap closure remaining stable at 0.55% per year	Unrestrained use of agricultural inputs, disregarding environmental impacts, increases yield gap closure to 0.70% per year

tices and improved international collaboration between riparian states. Global climate change is relatively moderate, being limited to the RCP4.5 trajectory.

- *SSP3-RCP8.5: Downhill*
  Contrastingly, the SSP3-RCP8.5 scenario assumes an increasingly regionalized Indus basin with considerable socio-economic problems. Population growth continues at its present rapid pace, reaching a population of 450 million by 2050 and over 600 million by 2080. Economic growth, on the other hand, remains limited with large income disparity and inequality throughout the basins. In this scenario, global climate change is severe, corresponding to an RCP8.5 scenario. The precarious climatic and socio-economic developments drive riparian states to increasingly focus on internal affairs and toward maintaining stability. As a result, land-use, water management, and agricultural development policies are largely focused on internal sufficiency and security, rather than sustainable and mutually beneficial practices at the basin-scale.

2.2 Agricultural system strategies

Next, we defined three 'what-if' narratives for the development of the Indus basin agricultural system; *Status Quo*, which continues current patterns, *Water Limited* which sees a radical shift toward sustainable water management, and *Food Priority* which prioritizes a self-sufficient food system. Each narrative reflects a different strategic position for agricultural system development in relation to the active policy discourse on the dependencies between water security and food security. The narratives were developed by reviewing scientific literature and national and regional policy documents ("Appendix 3"), followed by the consultation of regional experts and policymakers in Pakistan ("Appendix 2"). Each narrative consists of characteristics for the following aspects:

- Agricultural land-use: change in cropping intensity (net sown area) and the mix of food and cash crops.
- Water management: change in the ratio of rainfed to irrigated agriculture and the use of groundwater for irrigation.
- Crop management: change in annual yield gap closure (i.e., the production intensity).

To define agricultural development strategies, the narratives were embedded as scenario elements in the SSP-RCP forcing scenarios (Fig. 2d). The final characteristics of each strategy therefore depend on the agricultural system narratives and on the storyline and constraints of the respective forcing scenario. All strategies moreover share several central constraints:

- Agricultural land in the Indus basin is facing increasing competition from urban areas (Farah et al., 2019; Rasul, 2016). Yet, land-use intensity in large parts of the basin is still relatively low, as a considerable share of arable land is left fallow between years and seasons or is not connected to the irrigation system(Kirby et al., 2017). We therefore assume that the geographical area in use for agriculture will not expand further, but instead must intensify the cropping intensity. The total cropped area thereby stays the same, but the effective net sown area can still increase greatly. In addition, production intensification may occur through year-on-year yield-gap closure. Historical yield-gap closure was estimated as a reference point, using potential yield approximations by Kirby et al. (2017), and historical yield developments from Khan et al. (2021) and subregional agricultural statistics.

- Crops are divided into seven groups. The first groups are formed by the three major food crops of the basin (wheat, rice and maize), and cotton and sugarcane, the two major cash crops (Laghari et al., 2012). These crops together account for over 90% of total net sown area in the basin (Kirby et al., 2017). The sixth group is oilseeds and pulses, crops that used to be an important part of the Indus agricultural system, but that were outcompeted in the last few decades by rice–wheat systems and cash crops (Singh & Park, 2018). The last crop group consists of all other crops, including horticulture.
- In compliance with the timeframe of the SDGs, all strategic agricultural system changes start in 2015 (last common year of statistical data, see “Appendix 3”) and are assumed to be accomplished by 2030.

This produced the following narratives and strategies (see Table 1) for agricultural system development:

- *Status Quo: what-if the agricultural system continues to develop as it has done historically?*

  The first agricultural development narrative that we defined is a *Status Quo* premise, in which agricultural system changes continue alongside their historical and present trajectory. The net sown area of staple food crops is therefore assumed to continue to develop in relation to population (Kirby et al., 2017). Effectively, this means that the rice-wheat system, which over the last decades has become the main cropping system in the Indus basin (Singh & Park, 2018), remains dominant. In the SSP1 scenario, with moderate population growth, cropping intensity is assumed to increase only for rainfed areas to prevent further groundwater over-extraction. In the SSP3 scenario, cropping intensification occurs for both rainfed and irrigated areas, proportional to the current ratio of rainfed and irrigated agriculture of each crop group. The land-use for cash crops sees sugarcane continue to steadily replace cotton (Watto & Mugera, 2015). The net sown area for other crops, oilseed and pulses is assumed to remain static. Lastly, annual yield gap closure continues at its present rate in SSP3 and reduces slightly in the sustainable SSP1 scenario.
- *Water Limited: what-if the agricultural system develops with priority on water conservation?*

  The second agricultural development narrative, *Water Limited*, assumes that water scarcity forces a break from historical patterns and toward more water-efficient agricultural practices. For food crops, this means that the water-intensive cultivation of rice is diversified toward maize, oilseeds and pulses (Sidhu et al., 2021; Singh & Park, 2018). The ongoing replacement of cotton with water-guzzling sugarcane is halted (Kirby et al., 2017) and then reversed, with cotton overtaking the sugarcane area. Land-use intensification in this strategy is only allowed in rainfed areas. For predominantly irrigated crops, this means expansion of net sown area can only come at the expense, or the replacement, of other crops. Moreover, in the SSP1 scenario, the overuse of groundwater by the irrigation systems is phased out as it poses great challenges for environmental sustainability (Singh & Park, 2018). Concerns over water quality and soil health similarly demand a more moderate production intensification through the use of agricultural inputs, such as fertilizers (Shahbaz & Boz, 2022). This causes annual yield gap closure to slow down, especially in the sustainability-focused SSP1 scenario.

- *Food Priority: what-if the agricultural system develops with priority on internal food self-sufficiency?*

  The last agricultural development narrative that we defined is the *Food Priority* strategy. Here, achieving internal food self-sufficiency is the most dominant driving force for the development of agriculture in the region. This scenario prioritizes the allocation of scarce land and water resources toward food production for internal consumption. Continued rapid population growth in the SSP3 scenario therefore demands a rapid growth to full double cropping in irrigated areas (i.e., 200% cropping intensity). In terms of crops, the rice–wheat systems, which provide the two most important staple crops (Singh & Park, 2018), continue to grow in dominance, at the expense of other crop groups. Moreover, the export-based, and non-edible, cotton crop is gradually switched to food crops that are currently imported, such as oilseed and pulses (Kirby et al., 2017). The net sown area of sugarcane in addition increases to reduce sugar imports (Watto & Mugera, 2015). To optimally use the available land for food production, expansion of net sown area is primarily focused on irrigated areas. Lastly, production intensification is increased compared to the present in the SSP3 scenario and remains stable in the SSP1 scenario.

2.3 Quantifying and spatializing land-use projections

Next, we operationalized the agricultural land-use component of our six agricultural development strategies by creating land-use change projections that are a spatially explicit representation of the proposed changes in the narratives. To do so, we used an approach that is similar to that of Wijngaard et al. (2018) and Smolenaars et al. (2022), in which projected growth rates for each crop group are applied at annual timesteps to the spatially explicit MIRCA-2000 dataset of historical cropping intensity for 2005 (Portmann et al., 2010). An exact overview of the steps can be found in "Appendix 1."

We applied this procedure for each of the six strategies and for both cropping seasons (Rabi and Kharif). Over 96% of the Indus basin agricultural output, and the entirety of the contiguous Indus Basin Irrigation System, are located on the Indus plains. Significant changes to the Indus basin agricultural system in our assessment were therefore assumed to only occur in the lower Indus basin (see Fig. 1a). We accordingly only developed spatial land-use change projections for the Pakistani and Indian share of the Indus basin. For the upper Indus basin, the situation as provided by Smolenaars et al. (2022) was maintained. Our approach provided a set of six transient and spatial (5 arcmins) land-use change projections at seasonal timesteps for the lower Indus basin over the period 1950–2080 (see Fig. 2).

2.4 Modeling framework & protocol

To spatially determine the effect of agricultural system changes on future water and food security, we used a fully distributed modeling framework consisting of a one-way coupling between the *Spatial Processes in Hydrology* (SPHY) model (Lutz et al., 2014) and the *Lund–Potsdam–Jena managed Land* (LPJmL) model (Bondeau et al., 2007). The SPHY-LPJmL model coupling has been developed specifically to simulate the interaction between climate change, hydrology and food production in the river basins of High Mountain Asia. It has likewise been applied in multiple integrated studies of the water–food systems of South Asia (Biemans et al., 2019; Smolenaars et al., 2022; Wijngaard et al., 2018) that

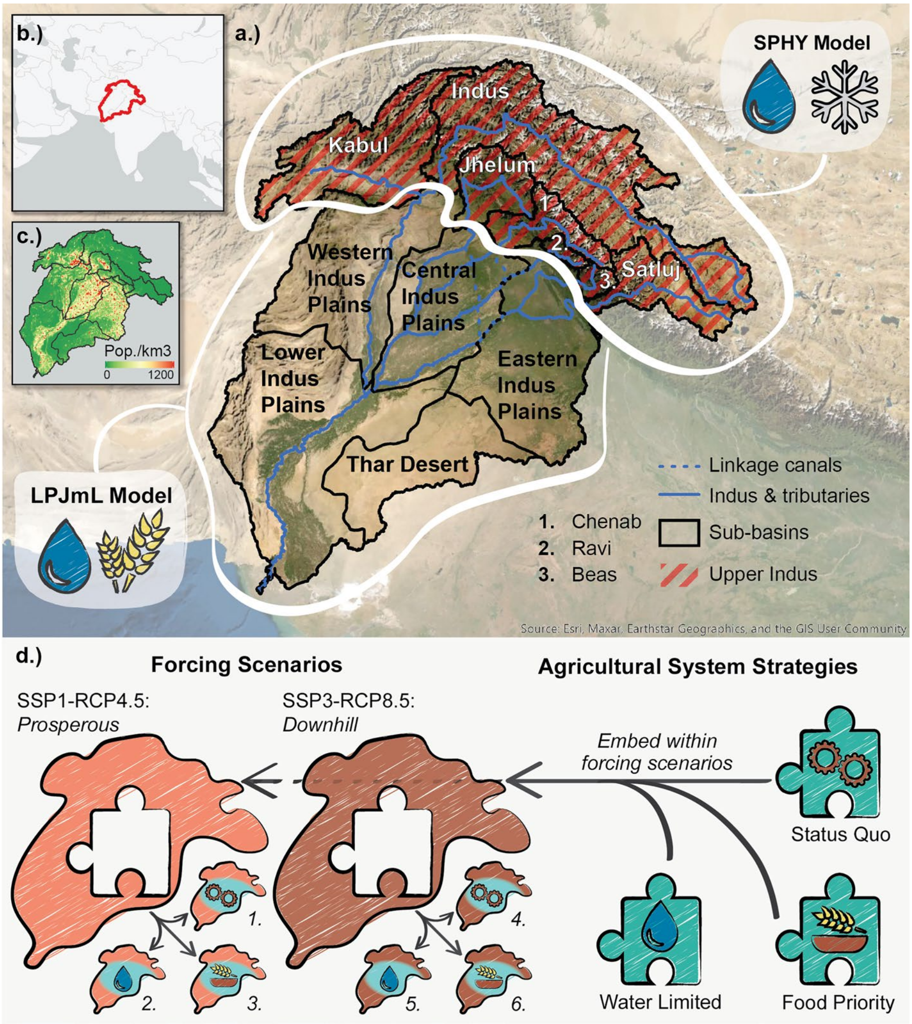


Fig. 1 Geography of the Indus basin with sub-basin delineation and applied models (**a**) with insets for the location of the basin in the wider region (**b**) and the 2010 population (**c**) density (Klein Goldewijk et al., 2011). In addition the conceptual representation of how agricultural development narratives are embedded within forcing scenarios to create the agricultural development strategies used in this study (**d**)

include the Indus basin. An elaborate description of the model coupling, calibration and validation can be found in Biemans et al. (2019). The modeling framework in this study consisted of two parts:

- For the mountainous, and glacier-dominated upper Indus, we used existing projections by the SPHY cryosphere-hydrology model. This model simulates run-off in mountainous areas at 5 km resolution and daily timesteps (Lutz et al., 2014). We used SPHY discharge projections for the upper Indus over the period 1980–2080 (Wijngaard et al., 2017) that were generated with the same climate-forcing data as used in this study

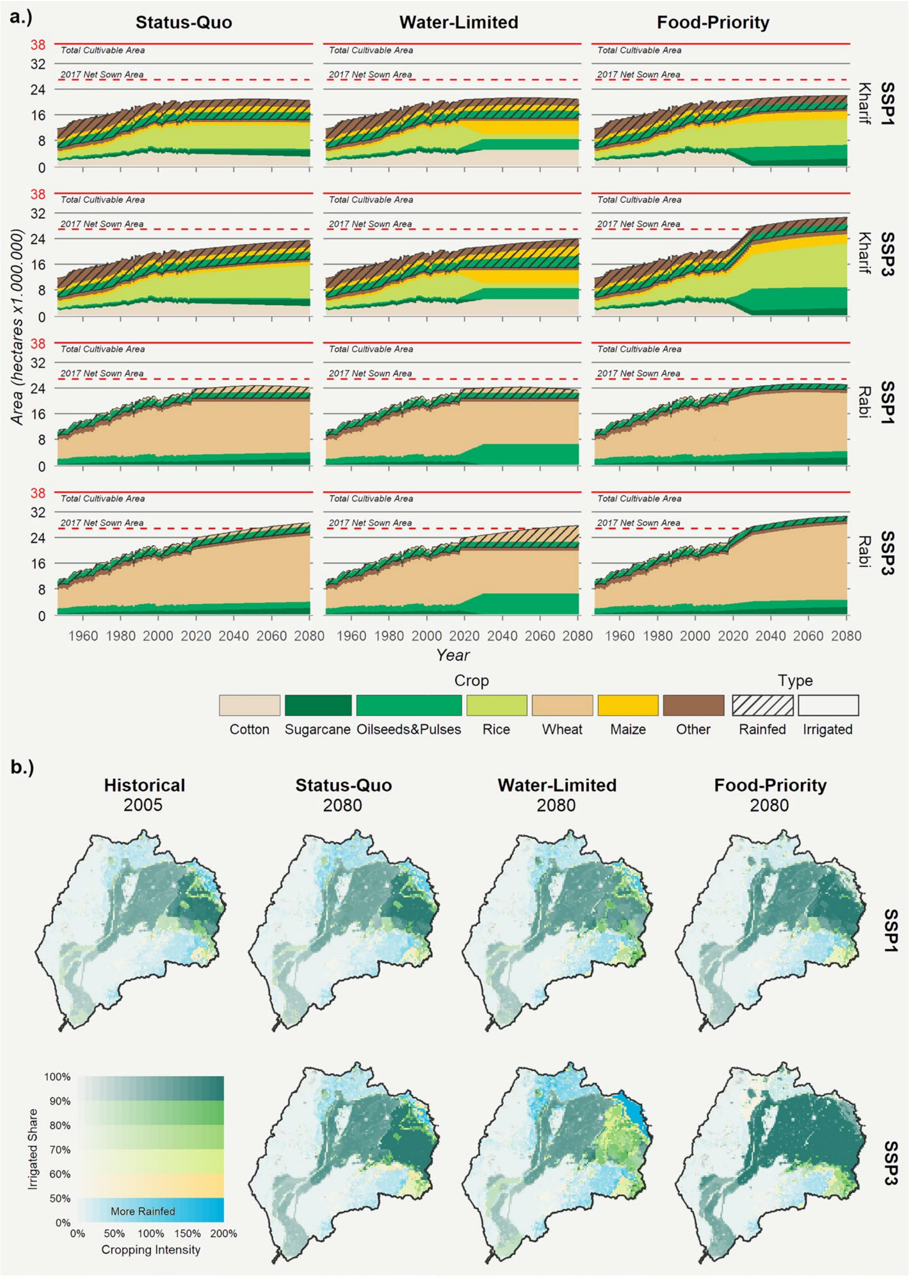


Fig. 2 Total net sown area per crop type group in the Indus basin, for each strategy, scenario and cropping season (**a**), and spatial cropping intensity and irrigation intensity (**b**). Note that areas marked in blue in this map are predominantly rainfed

(Lutz et al., 2016). We used both naturalized discharge and discharge that was corrected for present and future water usage in the upper Indus basin (Smolenaars et al., 2022).

- The SPHY discharge at the outlets of upper Indus tributaries was used as daily inflow in the LPJmL model, which we applied for the irrigation-dominated lower Indus basin. LPJmL is a crop hydrology model that dynamically simulates the interactions between agricultural practices and hydrology at 5 arcmin resolution and at daily timesteps (Bondeau et al., 2007). The version of LPJmL that we used is specific to South Asia and allows for the simulation of double cropping, reservoir operation and irrigation networks (Biemans et al., 2016). We recalibrated the crop yields of LPJmL at sub-national level for the 2003–2008 period and compared this to historical production statistics from 1980 to 2015, showing a good agreement (see "Appendix 4"). The dynamic input data for our LPJmL runs consisted of the SPHY inflow, the agricultural system strategies developed in this study, and downscaled climate forcing data for eight GCMs, including CO2 concentrations (Lutz et al., 2016). In addition, we accounted for the effect of changing water use of the domestic and industrial sectors due to socio-economic development. Spatial projections for these sectors, which are consistent with the scenarios used in this study, were obtained from Smolenaars et al. (2021) and Smolenaars et al. (2022) on the basis of the regression models by Bijl et al. (2016).

We applied the SPHY-LPJmL modeling framework for each of the agricultural system strategies, and for the two SSP-RCP scenarios with four RCMs per scenario. In these runs, we accounted for climate change, the change in water use by the domestic and industrial sectors, and access to groundwater. To decouple the effect of agricultural system changes from other drivers, we moreover did model runs in which we systematically omitted other drivers. First, we made runs in which we assumed no future agricultural system changes to occur, meaning land-use was kept in 2015 conditions, but climate change and changes in the water-use of the domestic and industrial sectors do occur. Similarly, we made model runs in which we separately omitted the effect of climate change, the change in water use by other sectors, and the unrestricted access to groundwater. Lastly, for each of these model setups, we also did runs with crop yields set at reference, potential or baseline conditions, to simulate the effect of annual yield gap closure. In this manner, we made a total of 154 transient model runs over the period 1950–2080. The simulations provided us with data at high spatiotemporal detail for discharge, water demand, groundwater use and crop yield under each of the strategies for agricultural system change.

2.5 Post-processing and indicators

In order to understand how agricultural system changes and other drivers affect water and food security we assessed model outputs using several indicators. For *food security* the following indicators were applied:

- Foremost, we assessed the degree to which food production can meet food demand, using the *caloric self-sufficiency ratio*. We used the FAO dietary energy supply target of 3000 kcal per capita per day(Hubert et al., 2010). This target maintains space for food waste and production losses before reaching the consumer and has been applied in similar modeling studies of future food security (Gerten et al., 2011; Liu et al., 2016).
- To assess the stability of food availability in the Indus basin, we quantified the *impact of climatic variability on food production*. We did this by quantifying, for each grid cell, the variance in net food production per timestep for each strategy between the four climate models (i.e., the variance being only due to climatic vari-

ability with all other factors being equal). Next, we determined the influence of this grid-cell variance on the total food production of the basin at the same timestep. We normalized this variance impact value between all scenarios and agricultural development strategies to allow intercomparison between strategies. This indicator demonstrates the climate robustness of each agricultural development strategy under climate change and highlights the areas within the basin that have the largest potential impact on basin-level food security in the event of a climate shock.

Similarly, for *water security*, we used the following indicators:

- We used the *water withdrawal to availability ratio* (Vörösmarty et al., 2000) at the sub-basin level to determine the effect of the agricultural system changes on water stress. Sub-basins in the irrigated plains of the lower Indus plains were determined at the irrigation-system level, as this is where water allocation decisions are made. For the upper Indus basin, the sub-basins defined in Smolenaars et al. (2022) and Wijngaard et al. (2017) were used. The higher the withdrawal to availability ratio, the more likely severe competition is to occur between different water use sectors, and therefore also with the environment. Likewise, this ratio is affected by more than just agricultural system change. In our simulations, changing water use in other sectors (through its effect on withdrawals) and climate change (through its effect on availability and through the effect of CO2 fertilization on crop water requirements) also affect the ratio. This indicator therefore allowed us to also distill the influence of these other drivers on water stress.
- Moreover, in the Indus basin groundwater is a dependable source of water that provides a buffer for the variable availability of surface water between years and seasons (Laghari et al., 2012). To determine to what extent the Indus water system is able to structurally supply sufficient surface water resources to meet societal needs, and thus suffers from water stress, we assessed the relative importance of groundwater as a water source. *Groundwater dependency* was operationalized by determining the total withdrawal of groundwater and the relative share of groundwater to total water extractions for irrigation.
- An overdependence on groundwater may similarly threaten its sustainability on the long term as a buffer in times of drought (Basharat et al., 2015). We assessed the status of groundwater sustainability at the grid cell level by estimating *groundwater depletion* as applied by Biemans et al. (2019). Groundwater depletion is estimated as the mean annual difference between groundwater recharge and extraction over multidecadal periods.
- To assess the effect of agricultural system changes on the environment, we determined the status of *environmental flows* in the Indus river. We used the *Variable Monthly Flow* (VMF) method by Pastor et al. (2019). This approach defines that a minimum of 30% (wet season) and 60% (dry season) of mean natural monthly discharge must be maintained in a river to sustain its environmental qualities. In our study, minimum monthly flow thresholds were determined for the lower Indus using LPJmL, with naturalized vegetation and reference climate for the period 1990–2010. We defined the wet season as May to October and the dry season as November to April (Laghari et al., 2012).

3 Results

3.1 Impact on food security

Our simulations demonstrate that future food production per capita differs strongly between the agricultural development strategies. However, differences are even greater between the SSP-RCP forcing scenarios. Foremost, Fig. 3a illustrates that without any agricultural system changes, per capita production in the basin quickly deteriorates. Population growth increases the food demand, while climate change slowly decreases its supply. This ensures that after 2030, the current food production system will structurally not produce enough food to sustain all inhabitants of the basin. Consequently, most regions of the basin will

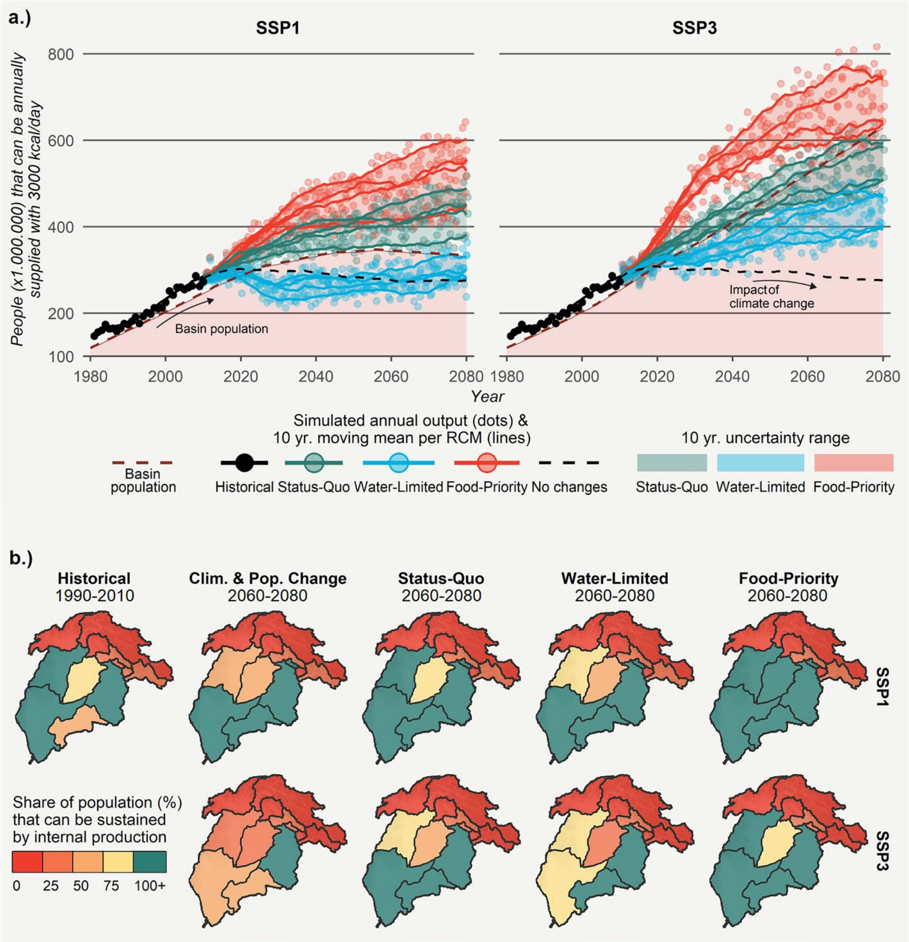


Fig. 3 Simulated availability of food, in relation to the demand for food, at the basin level (**a**), with dots representing the amount of people that can be supplied with sufficient food in a strategy per individually simulated year, and lines the 10-year moving mean of these years per Regional Climate Model (RCM). The maps (**b**) show the degree of food self-sufficiency at sub-basin level

not remain food self-sufficient, except the presently food-exporting Eastern Indus Plains of India (Fig. 3b).

Figure 3a also illustrates that under the *Water Limited* strategy, the basin cannot be self-sufficient in terms of food production either, regardless of the trajectory of population change. In SSP1, the over-extraction of groundwater is no longer available as a readily available supplement to surface water. This causes an initial drop in food production, which is only slowly restored over the course of the century by increasing production efficiency due to technological advancements that are assumed to occur under this strategy. Spatially, the impact on food production is largest in the most agriculturally productive regions of the Indus basin (see Fig. 2b and 11). Similarly, Fig. 4a shows that across all scenario-strategy combinations, the SSP1 *Water Limited* strategy is most sensitive to climatic variability. The omission of groundwater as an unrestricted source of water greatly affects the climate robustness of food production in this strategy (Fig. 4b). In contrast, the SSP3 *Water*

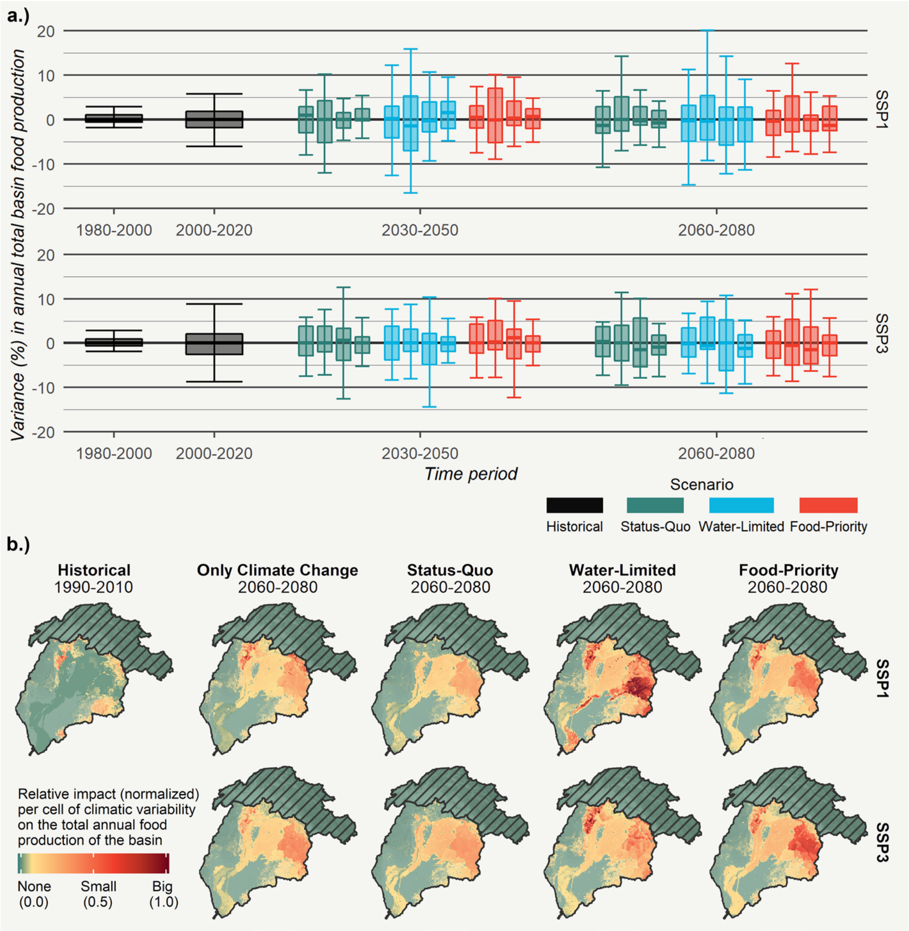


Fig. 4 Impact of climate variability for different agricultural development strategies on total food production (**a**) and hotspots for climate impact (**b**). Note that for the upper Indus basin, no simulated data were available due to the geographical scope of the LPJmL model covering only the lower Indus basin

Limited strategy allows present groundwater practices to persist, but not escalate further. Production intensification allows food production to increase on a similar water budget in this strategy. This growth does lag behind its historical pace, however, and is therefore not enough to keep up with projected population growth in this scenario. A switch in crop mix moreover causes the per capita availability of staple wheat and rice crops to drop sharply (Table 2).

On the other hand, in the SSP1 *Status Quo* strategy, production intensification and limited expansion of rainfed agriculture are sufficient to maintain the present rate of self-sufficiency in the basin. This even occurs under the most unfavorable of four climatic projections for the RCP4.5 scenario (see Fig. 3a). The *Status Quo* strategy in the SSP3 scenario similarly sees total food production show sufficient growth to keep up with population growth. However, toward the second half of the century, the impact of the more extreme RCP8.5 climate (Fig. 4b) gradually overtakes the positive impact of yield gap closure. In the SSP3-RCP8.5 scenario, only the *Food Priority* strategy manages to secure food self-sufficiency at the basin level by the end of the projected period. Figure 2b shows that this strategy moreover improves the food self-sufficiency ratio across several of the basin's sub-regions. The per capita availability of staple rice and wheat remains at current levels (Table 2), while the production of oilseeds, pulses and sugarcane strongly increases. This may reduce the need to import these crops. In the SSP1 scenario, *Food Priority* would see the Indus basin, especially the Indian and Pakistani Punjab, produce more than what is locally required. This suggests the region can maintain its role as a bread basket for the wider region (Bishwajit et al., 2013).

3.2 Impact on water security

The water withdrawal to availability ratio in the Indus basin is already high in the reference period. This indicates significant water stress (Fig. 5). Especially the intensively cultivated eastern half of the lower Indus basin faces a median withdrawal-to-availability ratio close to, or above, 1.0. This means that surface water supplies are structurally unable to meet demands. This similarly translates in considerable over-extraction of groundwater in these subbasins (Fig. 7b). Figure 5 demonstrates that the future of water stress and groundwater use here differs strongly between agricultural development strategies. However, Fig. 6 demonstrates that other drivers (i.e., climate change and changes in the water use for sectors other than agriculture) affect water stress by a similar magnitude. In particular, the positive relation between climate change and surface water availability (Lutz et al., 2019) and the effect of CO2 fertilization on crop water use (Jägermeyr et al., 2016) reduce water stress by up to 50% in some areas of the basin. Increasing water demands for non-agricultural purposes (i.e., domestic and industrial sector) on the other hand strongly increase the ratio of water withdrawal to availability. This effect is strongest in several upper Indus subbasins (see Fig. 6) where the domestic and industrial sectors account for a larger relative share of total water use due to the limited role of irrigated agriculture (Smolenaars et al., 2022). The central Indus plains, which contains several fast-growing cities, also see severe influence from this driver in the SSP3 scenario.

Figure 6 subsequently illustrates that the *Water Limited* strategy largely reduces agricultural water demand. This subsequently reduces the withdrawal-to-availability ratio in the lower Indus basin. The future water stress experienced in most subbasins therefore decreases both in median and extreme dry years despite the increase in non-agricultural water withdrawals (Fig. 5). Only several subbasins in the upper Indus demonstrate an

Table 2 Average crop production per capita (kg/cap/year of net crop production) and % change (between brackets) compared to the 2000–2020 baseline for the entire Indus basin. Future values account for changes in land-use and crop mix (as per the agricultural development strategies) and in climate

SSP	Period	Strategy	Wheat	Rice	Maize	Cotton	Sugarcane	Oilseeds and pulses	Other	Total (kcal/cap/years)
	1980–2000		192 (– 10%)	82 (– 16%)	25 (13%)	9 (3%)	288 (– 1%)	20 (6%)	116 (80%)	3328 (– 1%)
	2000–2020		213 (0%)	98 (0%)	22 (0%)	9 (0%)	292 (0%)	19 (0%)	64 (0%)	3359 (0%)
SSP1	2030–2050	Status-Quo	216 (1%)	78 (– 20%)	22 (– 2%)	11 (15%)	395 (35%)	19 (1%)	71 (10%)	3404 (1%)
		Water-Limited	133 (– 38%)	13 (– 87%)	47 (110%)	13 (48%)	13 (– 96%)	41 (118%)	49 (– 23%)	2372 (29%)
		Food-Priority	205 (– 4%)	84 (– 14%)	17 (– 23%)	9 (1%)	344 (18%)	37 (96%)	64 (0%)	4009 (19%)
	2060–2080	Status-Quo	225 (6%)	76 (– 22%)	21 (– 5%)	12 (31%)	527 (80%)	22 (14%)	85 (33%)	3747 (12%)
		Water-Limited	138 (– 35%)	13 (– 87%)	46 (106%)	17 (89%)	15 (– 95%)	46 (146%)	57 (– 10%)	2543 (– 24%)
		Food-Priority	262 (23%)	86 (– 12%)	27 (21%)	0 (– 100%)	638 (118%)	41 (118%)	106 (65%)	4529 (35%)
SSP3	2030–2050	Status-Quo	205 (– 4%)	84 (– 14%)	17 (– 23%)	9 (1%)	344 (18%)	17 (– 10%)	64 (0%)	3125 (– 7%)
		Water-Limited	152 (– 29%)	14 (– 86%)	47 (110%)	13 (47%)	11 (– 96%)	51 (168%)	58 (– 10%)	2578 (– 23%)
		Food-Priority	235 (10%)	110 (12%)	29 (28%)	0 (– 100%)	410 (40%)	47 (151%)	80 (24%)	4063 (21%)
	2060–2080	Status-Quo	171 (– 19%)	66 (– 33%)	13 (– 41%)	11 (17%)	327 (12%)	14 (– 24%)	57 (– 11%)	2732 (– 19%)
		Water-Limited	126 (– 41%)	10 (– 90%)	35 (55%)	17 (89%)	11 (– 96%)	42 (124%)	51 (– 21%)	2179 (– 35%)
		Food-Priority	195 (– 8%)	89 (– 9%)	18 (– 18%)	0 (– 100%)	389 (33%)	37 (95%)	69 (8%)	3490 (4%)

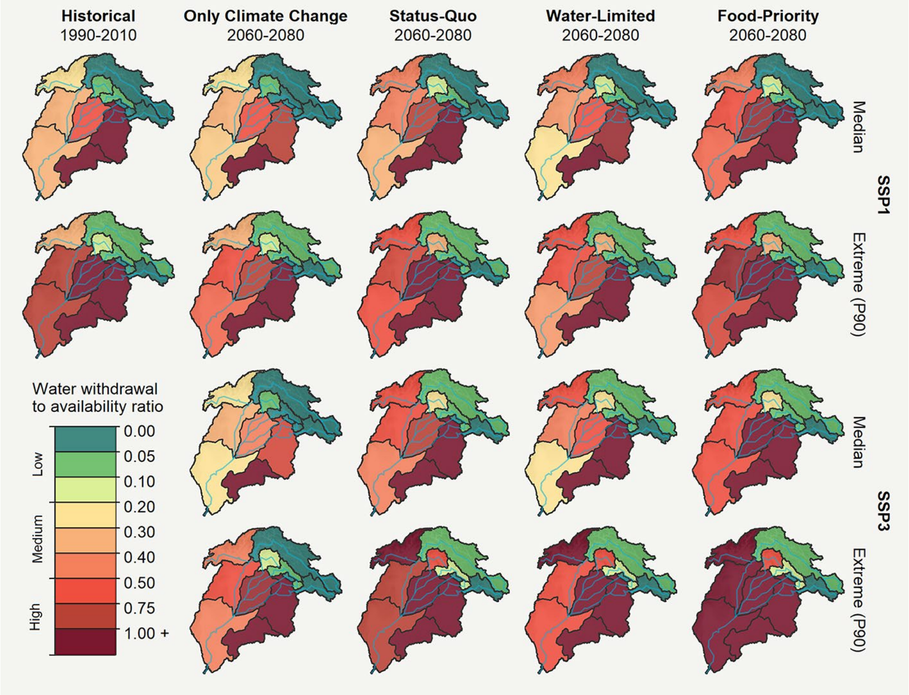


Fig. 5 Median and extreme (10 year) water stress (per the withdrawal to availability ratio) for historical situation (1st column), under only climate change (2nd column) and for all drivers including agricultural development strategies (3th, 4th and 5th column)

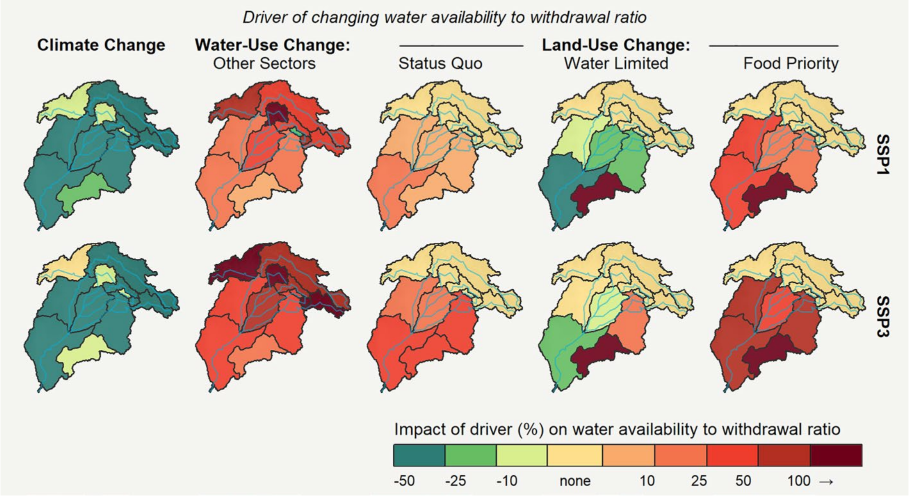


Fig. 6 Average isolated effect of climate change, changing domestic and industrial use and agricultural system change on future water stress (i.e., ratio water withdrawal-availability)

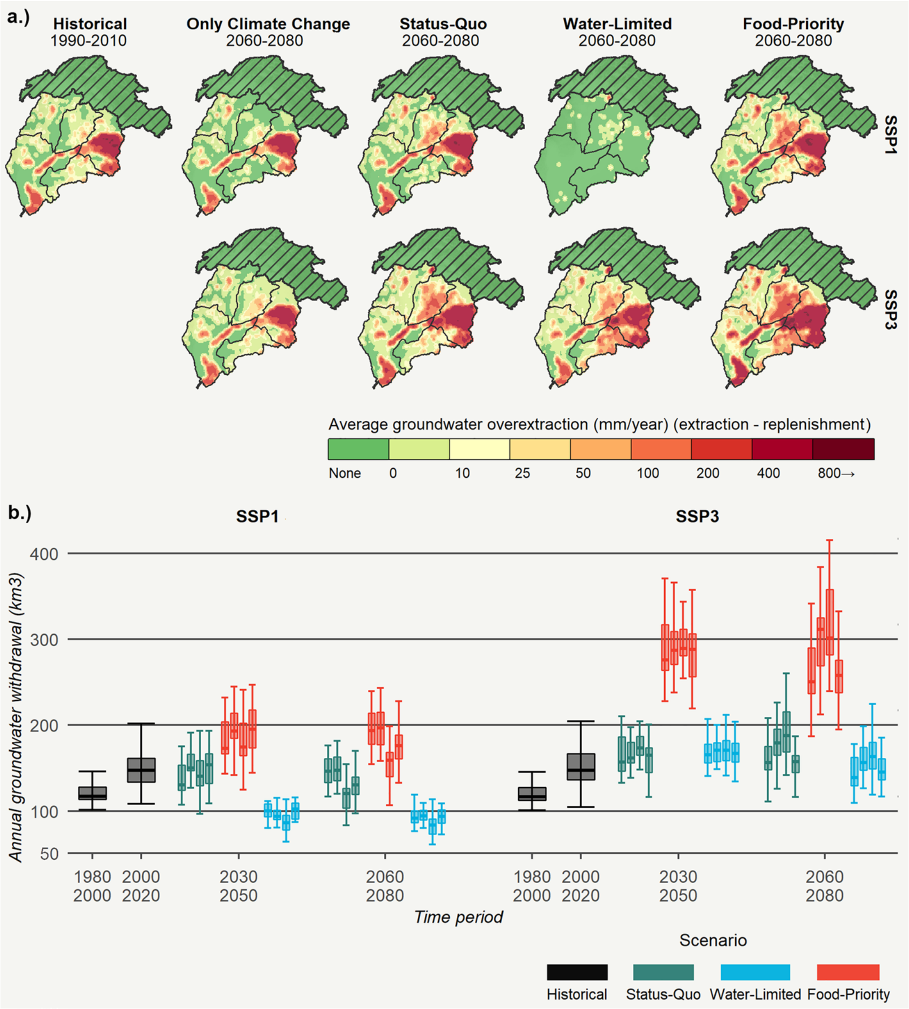


Fig. 7 Impact of agricultural system changes on total groundwater withdrawals in the basin (**a**) and spatial patterns of groundwater overextraction (**b**)

increase in water stress due to the aforementioned expansion in non-agricultural water use. The *Water Limited* agricultural system changes correspondingly reduce the demand for groundwater resources (Fig. 7a). In the SSP1 scenario groundwater use drops considerably compared to present levels, and over-extraction remains limited to several fast-growing cities that depend on groundwater resources to meet domestic and industrial water demands. The dependency on groundwater similarly drops in favor of surface water, especially in the heavily irrigated eastern Indus plains (Fig. 12). In SSP3, pressure from strong population growth requires groundwater use to increase slightly toward the middle of the century (2030–2050) and then reduce again. Over-extraction therefore remains similar to present levels, but becomes less concentrated in the eastern Indus plains, shifting toward the rapidly urbanizing central Indus plains instead (Fig. 7b).

In contrast, the *Status Quo* and *Food Priority* scenarios see an increase in both agricultural and non-agricultural water demand in the lower Indus and hence an increase in future water stress (Fig. 6). The intensification toward full double cropping in the *Food Priority* strategy results in a steep rise in water stress. Figure 7a moreover demonstrates that groundwater extractions must double to support such agricultural expansion. The central Indus plains, located largely in the Pakistani Punjab, demonstrate a similar pattern of groundwater over-extraction as is currently present in the intensively cultivated Indian provinces of Punjab and Haryana. The dependency on groundwater throughout the basin similarly increases strongly (see Fig. 12). The eastern Indus plains are already near full double cropping intensity and likewise face strong over extractions and groundwater dependency in the present. These areas therefore see few changes under these strategies. The *Status Quo* strategy sees groundwater use stay stable in the SSP1 scenario and groundwater over extractions increase slightly around the major cities of the Pakistani Punjab.

3.3 Environmental impact

The positive influence of climate change on meltwater availability also translates to environmental flows being met, on average, for a larger period of the year (Fig. 8). However, increased water consumption for domestic and industrial purposes largely negates these benefits, especially in the western tributaries of the Indus river. Changes in agricultural water demand brought on by the agricultural development strategies have similar impacts on environmental flows as they do on water stress. Under the *Water Limited* strategy, environmental flows considerably improve compared to the reference period (2000–2020) and to the situation without agricultural system changes. Especially in the ecologically important Indus delta (Laghari et al., 2012) minimum flow requirements are met more often in the SSP1 scenario. However, under the *Status Quo* and *Food Priority* strategies, the situation in the western tributaries worsens in comparison with the situation without agricultural system changes. This is especially the case downstream of the Jhelum river. In Fig. 6, the two easternmost tributaries demonstrate large increases in future discharge under climate

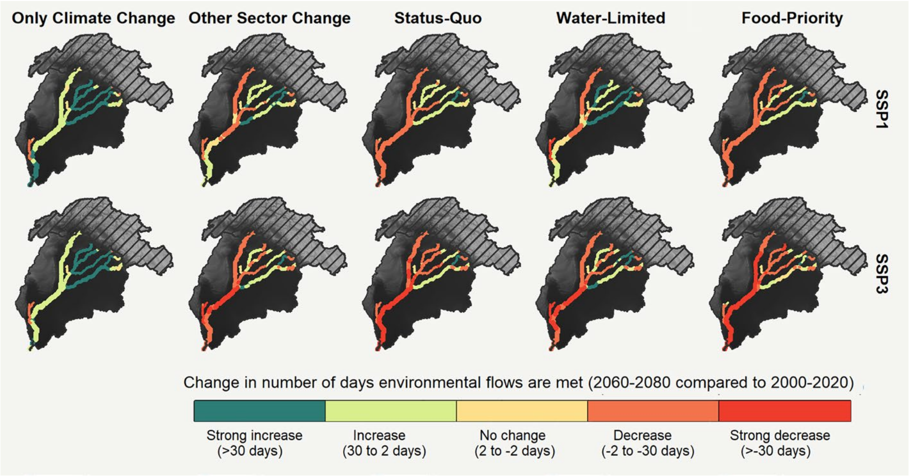


Fig. 8 Average future impact on environmental flows for the Indus river and main tributaries (average annual flow > 10 km^3) per strategy, on top of relief base map

change and subsequently see the status of environmental flows largely improve under all strategies and scenarios.

4 Discussion

4.1 Limitations and opportunities

In this study, we investigated the influence of three alternative agricultural development strategies on future water and food security in the Indus basin under two contrasting scenarios of integrated climatic and socioeconomic change. The *Water Limited* and *Food Priority* strategies were developed from the perspective of adaptation policymaking. By design, these strategies represent relatively extreme and hypothetical positions, embodying strongly divergent perspectives in the water–food debate. We assume for these strategies that rapid and structural changes based on top-down directives are implemented universally throughout the Indus basin by 2030. This requires strong institutional capacity, and the financial tools to effectively influence farm-level choices (Clapp, 2017). Such governance may be feasible in the optimistic SSP1-RCP4.5 scenario, but will be more challenging in the disrupted future of SSP3-RCP8.5 (Smolenaars et al., 2021). Our scenario analysis hence demonstrates the bandwidth of influence that agricultural system changes can have on water and food security and thus its potential in support of achieving SDG2 and SDG6. However, future studies could consider an incremental approach to agricultural system change, exploring individual measures and moderate sets of changes, as this may help identify more feasible initial policy priorities in the basin.

On the other hand, several autonomous farm-level changes are not accounted for in our policy-oriented strategies. For example, although we considered yield gap closure through increased nutrient use and crop management, other adaptations to farming systems such as different farm-level irrigation and water management techniques (Ostad-Ali-Askari, 2022), new crop varieties and changes in sowing and harvesting dates(Kirby et al., 2017) were not part of our assessment. Our results indicate that after 2050, climate change considerably decreases potential yields of several staple crops, especially due to higher temperatures. Farm-level adaptation and innovation could potentially moderate some of these impacts (Shahbaz & Boz, 2022; Tariq et al., 2014). However, the options to adapt to the projected severe heat stress in the Indus Basin are still relatively limited (Droppers et al., 2022). Further scenario-based modeling assessments focused on farm-level changes are required to understand the effect of such bottom-up changes, in addition to the top-down strategies considered here. For example, research by Jamil (2023) has shown that laser-land-leveling may be a promising technical intervention to simultaneously reduce irrigation water demands and boost yields. A thorough upscaling assessment must be conducted to explore if such measures are indeed as beneficial at the basin scale as they are at the field level.

Our assessment also did not consider the effect of agricultural system changes on water quality, and the effects of changing water quality on food and water security. Currently, pollution in the Indus river and its tributaries is rampant and has a considerable effect on human and ecosystem health (Rasul, 2016). A major source of water pollution is the improper use of agricultural inputs (Shahbaz & Boz, 2022). Similarly, extensive pumping of brackish groundwater to sustain irrigation systems in the lower Indus is driving soil salinization and reducing water quality (Salam et al., 2020). Both factors are likely to increase under agricultural system intensification, especially in the *Food Priority* strategy which relies heavily on additional nutrient use and groundwater irrigation. An increase in gray water footprint may decrease the surface water that is of suitable quality to be used in agriculture and subsequently negatively affect food production (Shahbaz & Boz, 2022). Similarly, it may drive additional groundwater over-extraction. This feedback loop will be of critical importance for the water stress experienced in the basin, especially in regions downstream (Yoon et al., 2015). Future studies should therefore look to integrate water quality and water quantity metrics in their assessment of water stress and water–food interactions in the Indus basin.

4.2 Implications and recommendations

The results of this study demonstrate clearly that the direction in which the Indus agricultural system develops will strongly affect the potential achievement of SDGs for food, water and aquatic ecosystems (SDG 2, 6 & 15). The degree and type of impact are, however, determined largely by other regional drivers. In particular, increasing water and food demands due to population growth were found to greatly increase pressure on indicators for the beforementioned SDGs. The *Water Limited* and *Food Priority a*gricultural development strategies are shown to be able to mitigate this impact for the respective sector they are targeted at, but at the same time compound the pressure on the other SDGs. The *Status Quo* strategy sees indicators for SDGs related to both water and food security deteriorate. No single strategy can ensure improvements for indicators of all SDGs under climate change and socioeconomic development.

Our results specifically show that, to remain food self-sufficient with a growing population, both production and cropping intensifications are needed for the Indus basin. This will require substantial increase in irrigation water use for agricultural purposes. Agricultural water demands must, however, increasingly compete with rising water demands for domestic and industrial purposes (Laghari et al., 2012). Similar to Kirby et al. (2017) we find that sustaining food production at current per capita levels in the *Food Priority* strategy therefore compounds stress on the Indus water system. Moreover, this also increases the dependence of agriculture on groundwater by over 50%. At present, highly intensive agriculture in the Indian share of the basin already structurally overexploits groundwater resources (Salam et al., 2020). This results in a drop in groundwater tables which may progressively limit its (economic) accessibility to agriculture (Muzammil et al., 2021). Previous studies have therefore deemed these agricultural systems to be untenable in the long term (MacAllister et al., 2022; Sidhu et al., 2021). The expansion of this agricultural model throughout the basin in the *Food Priority* strategy keeps per capita food production at present-day levels, but also sees similar groundwater issues aggravate in the Pakistani Indus plains. The pursuit of SDG2 through continued agricultural systems intensification thereby not only inflicts severe negative trade-offs on water security for society and the environment, putting SDG6 and SDG15 at risk, but may also accelerate the structural depletion of water availability for food production itself (i.e., water security of food security).

Conversely, we show that improvements to water security and improving environmental flows in the Indus basin are possible with a drastic shift toward sustainable agricultural water management in the *Water Limited* strategy. Total food production still increases, but our assessment demonstrates this to be outpaced by the growth in food demand in both SSP1 and SSP3. Food self-sufficiency can consequently not be achieved in large parts of the basin under this strategy. However, regional self-sufficiency is a critical economic factor in ensuring low-income households have stable access to food (Hubert et al., 2010).

Gaps in local availability may be compensated by food imports, but have a destabilizing effect on food prices and therefore food security for the most vulnerable groups (Clapp, 2017). Moreover, the riparian states of the Indus basin currently face severe trade deficits (MoCI, 2021; PBS, 2021). Agricultural products (i.e., basmati rice, cotton) are among the main regional exports and generate the capital required to import other food products, like edible oils. A shift away from export crops and an increased dependence on food imports may thus be economically infeasible. Similarly, the complex hydropolitical relations between riparian states dictate that food self-sufficiency is an important national security objective (Rasul, 2016) as trade disruptions cannot be discounted (Baer-Nawrocka & Sadowski, 2019). Agricultural system changes focused on achieving SDG6 and SDG15 in the Indus basin may therefore carry strong negative trade-offs for SDG2, especially in a future characterized by high population growth, limited economic development and political isolationism (SSP3).

The complexity of these SDG trade-offs highlights that environmental boundaries likely exist for the capacity of agricultural system changes in the Indus basin to both ensure future food self-sufficiency and improve basin-level water security. This suggests that agricultural development strategies must be supported by Climate-Smart technical innovations that can realize drastic improvements to crop-water productivity (Kirby et al., 2017). However, the trade-offs also demonstrate that a paradigm shift may additionally be needed with regard to the role of the agricultural system in the water–food Nexus of the Indus basin. Foremost, the discussion on basin-level food security must expand beyond rigorously ensuring regional food production (i.e., availability) matches demand. Increased food imports, in particular for non-staple but highly water-consumptive crops like sugarcane, appear important to reconcile sufficient food availability with sustainable water use on the long-term, especially under rapid population growth seen in SSP3. This additionally requires water–food adaptation, and future studies in support of this process, to focus not only on optimizing food production. The inclusion of other socioeconomic factors, such as household food access, economic development (Clapp, 2017) and the stability of inter-basin cooperation (Vinca et al., 2020), can make alternative strategies based on partial food imports more politically feasible and mitigate its disadvantages for food security. Agricultural system changes are therefore an important adaptation mechanism for water and food SDGs, but must be integrated into development pathways that convey a broader view on sustainable adaptation to balance or mitigate trade-offs between sectors.

5 Conclusions

This study shows that the direction in which the agricultural system develops will strongly influence the SGDs for water (SDG2 and SDG15) and food (SDG6) security in the Indus basin. Agricultural system changes can provide considerable support to achieve individual SDGs, but are also characterized by strong intersectoral trade-offs between water and food availability on the long-term. No single strategy is able to achieve improvements by 2060–2080 for all indicators at the same time. To maintain the per-capita production of staple crops at sufficient levels under population growth, a considerable increase in water for agriculture is needed. This is shown to strongly increase water stress and groundwater overexploitation throughout the basin, especially in the Pakistani central Indus plains. Agricultural system change focused on sustainable water management on the other hand can achieve a reduction in irrigation water use. This reduces water stress and provides space to growing water demands of sectors other than agriculture, but does have the consequence that food self-sufficiency cannot be achieved in many regions of the basin in future.

Our study therefore indicates that agricultural system changes are an important adaptation mechanism on the road to a water and food secure Indus basin. However, agricultural development must be incorporated within broader adaptation strategies that can offset its negative trade-offs, particularly when it comes to moderating agricultural water use. Subsequent studies may therefore assess the viability and implications of Climate-Smart innovations that can increase the crop water productivity of the current agricultural system. However, under continued high population growth, biophysical and societal limits on irrigation water availability may make a regionally self-sufficient food system unreconcilable with sustainable water management. Integrated adaptation strategies for water and food security in the Indus basin should therefore not only aim to achieve an increase in regional food production on a smaller water budget through technical interventions, but also emphasize socioeconomic changes that may lessen the drawbacks of potential increases in food imports for household and national food security.

Appendix 1: Translating agricultural development narratives to land-use projections

To translate the agricultural development strategies into tangible and quantitative land-use projections, we used a three-step approach:

1. First, for each crop group, we assessed the total net sown area per cropping season (Kharif/wet season, and Rabi/dry season) within the Indus basin over the historical period 1950–2015, using sub-national level agricultural statistics (see “Appendix 3”). For states or provinces that are not fully part of the Indus basin (such as Rajasthan), we determined the ratio of cropped area that lies within the basin boundaries in the year 2005 using the gridded MIRCA-2000 dataset (Portmann et al., 2010). These ratios were assumed to be constant over the entire historical period and applied to the historical net sown areas of these administrative entities as per the sub-national statistics. In case of missing sub-national data, national agricultural statistics were used to interpolate gaps. Specifically, we corrected the national net sown area of the affected crop group by the fraction that the relevant sub-national entity represented in the national total, in the closest years with available data.
2. Next, the historical change in net sown area for staple food crops (wheat, rice, maize) in both riparian states was correlated with the historical population change within the basin share of both riparian states. To obtain population figures, we used sub-national census data and the spatially explicit HYDE population dataset (Klein Goldewijk et al., 2011). The crop-and-country-specific coupling between net-sown area and population was then extrapolated to 2080 using the population projections for the Indus basin of both SSP-RCP scenarios. Similarly, the present rate at which sugarcane replaces cotton was determined and extrapolated over the

projected period. The net sown area of oilseeds and pulses, and the other crops group were left to 2015 conditions. This provided a set of baseline projections of net-sown area of the crop groups, for each SSP-RCP scenario and for both seasons. The proposed changes in crop mix, land-use intensity and irrigation intensity as per the three agricultural development narratives (see Table 1) were then applied to these baseline projections. We used state-level land-use statistics to determine the boundary constraints in terms of available fallow land and cropping intensity (see “Appendix 1”).

3. We spatialized the land-use projections for the agricultural development strategies using a similar approach to Wijngaard et al. (2018) and Smolenaars et al. (2022). First, the spatially explicit MIRCA-2000 dataset (Portmann et al., 2010) was cropped for the Indus basin and corrected, for both cropping seasons and countries, to align exactly with the net sown area statistics of the year 2005. We then applied at annual timesteps toward 2080 the projected change rates of each crop group in each country to the corrected 2005 crop map. The change rate was applied proportionally to the net sown area of a crop in each cell, up until the cell reached full potential cropping intensity, in which case any surplus area was divided proportionally over all other cells with remaining space. To account for the effect of agricultural-urban competition for land (Farah et al., 2019), urban areas were made unavailable when determining the full potential cropping intensity of a cell, using urbanization data by Smolenaars et al. (2021). Our approach thereby implicitly assumed that the cultivation of all crops remains in the same location as at present. This guarantees present biophysical suitability in terms of terrain and climate and ensures access to the irrigation network. We similarly applied the historical annual change rates to the 2005 base map up until reaching 1950 (Tables 3, 4, 5, 6, 7).

Table 3 Baseline trend extrapolation for wheat area in relation to population change

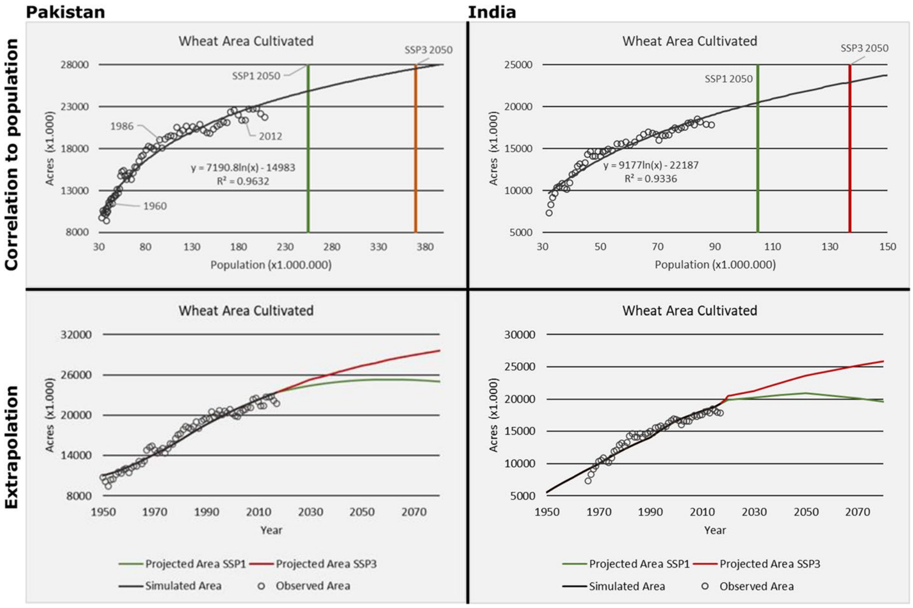


Table 4 Baseline trend extrapolation for rice area in relation to population change

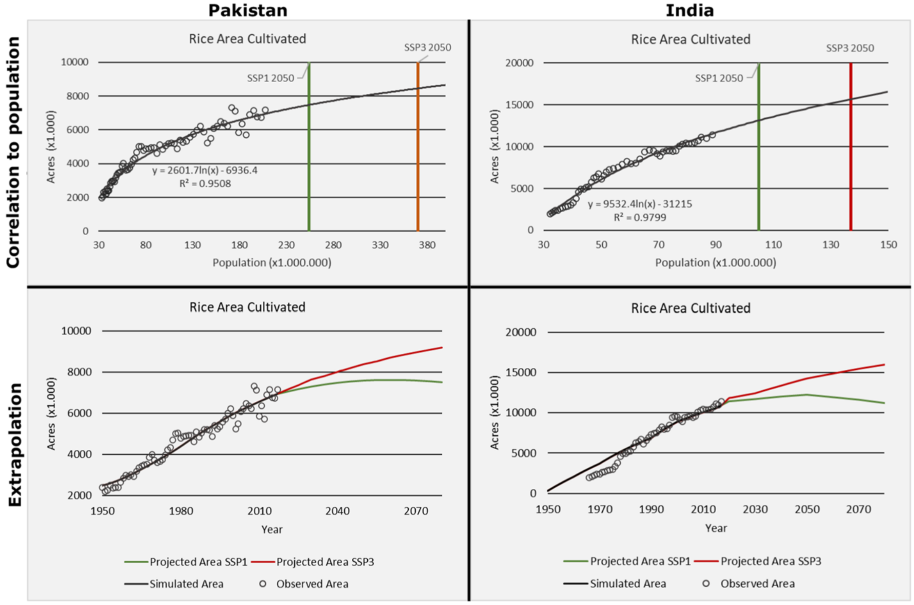


Table 5 Baseline trend extrapolation for maize area in relation to population change

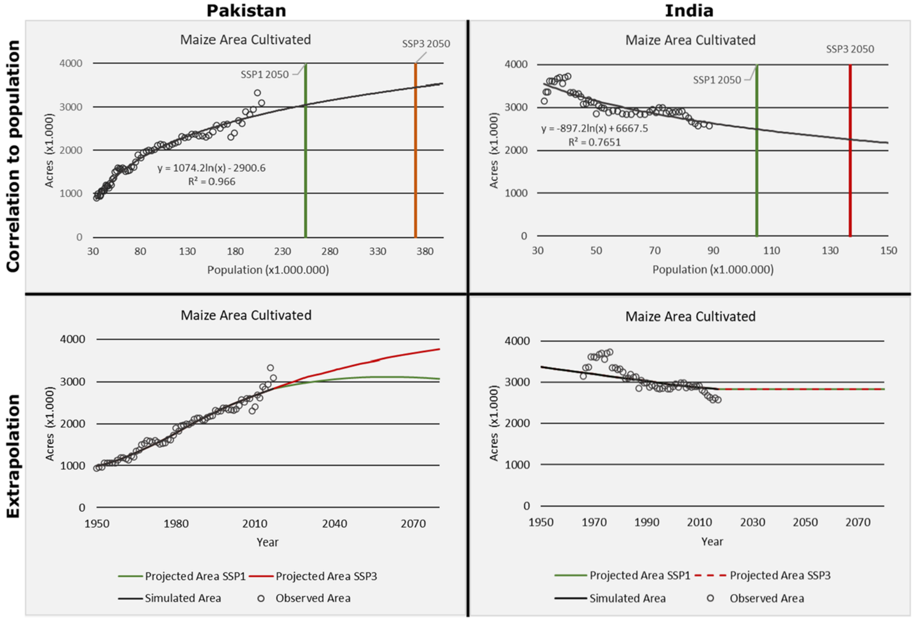


Table 6 Baseline trend extrapolation for cash crop area

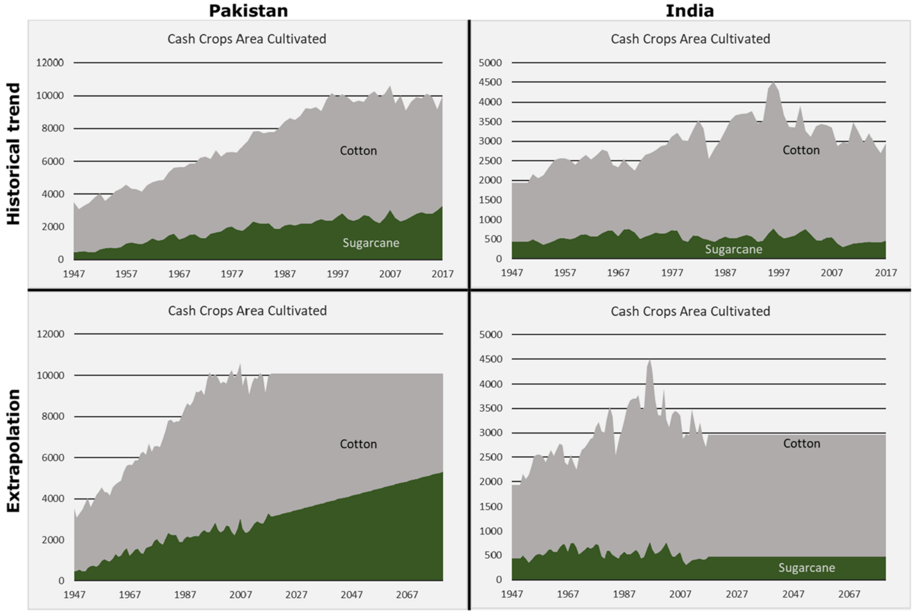
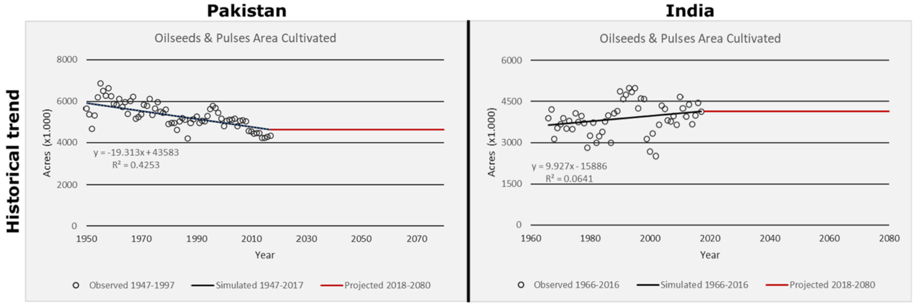


Table 7 Historical trend analysis oilseeds & pulses



Appendix 2: Workshop land-use futures

See Table 8 and Fig. 9.

Table 8 Factsheet stakeholder workshop land-use futures

Title	National consultation workshop; exploring future land-use innovations for water and food security in the Indus basin
Date	16-05-2022 from 10:00 until 16:00
Place	National Agricultural Research Center (NARC) Islamabad
Amount of participants	Between 22 and 32 at various stages of the workshop
Type of participants	The consultative workshop was attended by: Diverse representatives of the international scientific community, including senior scientists from the Pakistan Agricultural Research Council (PARC), the Pakistan Council of Research on Water Resources (PCRWR), the country head of the International Centre for Integrated Mountain Development (ICIMOD), and several early carrier researchers from various local universities NARC crop experts on wheat, rice, sugarcane, cotton, fodders and grassland, oilseed crops, pulses, vegetables, fruit orchards, and other horticultural crops Government officials from the Federal Ministry of Food Security and Research of Pakistan
Objective	To gather local insights from land and water management experts, crop experts, and other relevant stakeholders and policymakers that can support and validate the development of plausible and diverse agricultural system change scenarios for the Indus river basin
Approach	The consultative workshop started by providing an overview of different modeling tools for geospatial analysis used by the authors of this study to quantify the impacts of agricultural system changes on the water and food security of the Indus basin. Subsequently, an overview of three future agricultural development strategies was provided. These strategies were developed earlier using the literature review and local knowledge by the project's local partners. Next, the floor was opened for multiple rounds of consultative process and participants discussion to validate or edit the developed agricultural development strategies. Lastly, the participants were briefed on several Climate-Smart Agriculture innovations that are currently being piloted, and their importance and limitations were discussed
Key results	The primary outcome of the workshop is that most local experts approved and validated the developed land-use scenarios. Participants showed great interest in learning the upscaling assessment methods, as this is one of the missing links in the current literature for Pakistan. Almost all of the experts agreed with replacing the high water delta crops with low water delta in a *Water Limited* strategy. However, it is essential to mention that senior researchers also stressed the current and future economic importance of certain high water delta crops, as they are one of the significant sources of foreign exchange, and thereby somewhat mitigate the trade deficit of the riparian states of the Indus basin. Subsequently, for the *Food Priority*, the participants agreed with the continued expansion of these crop categories to boost exports and limit imports. In addition, it was argued that the narratives at the core of the current strategies focus largely on water and food in biophysical terms. The economic impact of changes is, however, clearly of importance as well, and it was deemed important by participants to reflect more in the study on this aspect of agricultural system change

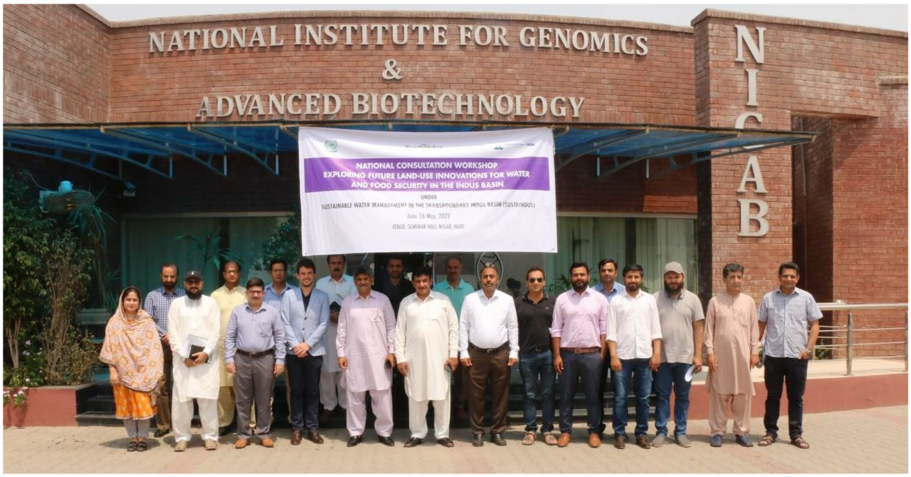


Fig. 9 Participant group photo at the start of the stakeholder workshop

Appendix 3: Supplementary data sources for agricultural narrative construction

See Table 9.

Table 9 Overview of policy documents, regional statistics and reports used to develop agricultural system narratives and translate these into strategies

Content description	Country	References
Survey and perspective report on future of the agricultural economy	Pakistan	Finance Division Government of Pakistan (2021). Pakistan Economic Survey: Agriculture. I. Ahmad
Pakistan agricultural yearbook of facts	Pakistan	Ministry of National Food Security and Research (2016). Agricultural Yearbook. J. Humayun
Pakistan agricultural and land-use statistics	Pakistan	Ministry of National Food Security and Research (2018). Agricultural Statistics of Pakistan 2017–18. M. A. Talpur
Pakistan land utilization statistics	Pakistan	Pakistan Bureau of Statistics (2021). Land Utilization Statistics https://www.pbs.gov.pk/sites/default/files/tables/agriculture_statistics/table_3_land_utilization_statistics.pdf
Agricultural profile of the Punjab province	Pakistan	Punjab Agricultural Department (2017). Punjab Agriculture Profile. Agriculture Department
Punjab long term agricultural strategy report	Pakistan	The Urban Unit Technical Paper 5 Agricultural Development. Punjab Spatial Strategy 2047. W. Khan, Planning and Development Department under Government of the Punjab
National food security strategy	Pakistan	Ministry of National Food Security and Research (2014). National Food Security Policy. S. H. K. Bosan, Government of Pakistan
National food system strategy	Pakistan	Ministry of National Food Security and Research (2021). National Pathways for Food Systems Transformation in Pakistan. T. Khurshid, Government of Pakistan
Water for agriculture analysis and strategy	Pakistan	Qureshi, R. and M. Ashraf (2019). "Water security issues of agriculture in Pakistan." PAS Islamabad Pak 1: 41
National Water Strategy	Pakistan	Ministry of Water Resources (2018). National Water Policy. S. Aziz, Government of Pakistan
Agricultural profile of the Punjab state	India	Grover, D., et al. (2017). State Agricultural Profile-Punjab
Punjab agricultural perspectives report	India	Indian Council for Research on International Economic Relations (2017). Getting Punjab Agriculture Back on High Growth Path: Sources, Drivers and Policy Lessons. A. R. Gulati, Ranjana; Hussain, Siraj
Punjab farmer guide & land-use statistics	India	Department of Agriculture & Cooperation Mechanisation & Technology Division. (2022). Punjab Farmers' Guide, Ministry of Agriculture, Government of India https://farmech.dac.gov.in/FarmerGuide/PB/index1.html
Haryana farmer guide & land-use statistics	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Haryana State Farmer Guide, Ministry of Agriculture, Government of India https://farmech.dac.gov.in/FarmerGuide/HR/index1.html

Table 9 (continued)

Content description	Country	References
Rajasthan farmer guide & land-use statistics	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Agricultural Mechanization Guide for Rajasthan, Ministry of Agriculture, Government of India. https://farmech.dac.gov.in/FarmerGuide/RJ/index1.html
Jammu and Kashmir farmer guide & land-use statistics	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Jammu & Kashmir Farmers' Guide, Ministry of Agriculture, Government of India https://farmech.dac.gov.in/FarmerGuide/JK/index1.html
National agricultural statistics	India	Statistics, D. o. E. a. (2018). Agricultural statistics at a glance. Dept. of Agriculture and Co-operation, Ministry of Agriculture, Government of India. S. P. C. Bodh
India state-wise agricultural and land-use statistics	India	Directorate of Economics and Statistics (2022). State Wise Area Production & Yield Statistics (1966 to 2016), Department of Agriculture and Cooperation, Ministry of Agriculture and Farmers Welfare, Government of India https://eands.dacnet.nic.in/APY_96_To_07.htm
Water for agriculture analysis and strategy	India	Dhawan, V. (2017). Water and Agriculture in India, Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture (GFFA) 2017, German Asia–Pacific Business Association
National food system and land-use strategies	India	Food and Land Use Coalition India (2019). Sustainable Food and Land Use Systems in India, National Roundtable. M. Anand
National sustainable agriculture plan	India	Expert Scientific Committee (2019). Policies and Action Plan for a Secure and Sustainable Agriculture. R. S. Paroda, Government of India
National agricultural economy plan	India	Chand, R. (2019). Presidential Address, Transforming Agriculture for Challenges of 21st Century. Indian Economic Journal, December. 102 Annual Conference Indian Economic Association Niti Aayog Government of India

Appendix 4: Additional figures

See Figs. 10, 11 and 12.

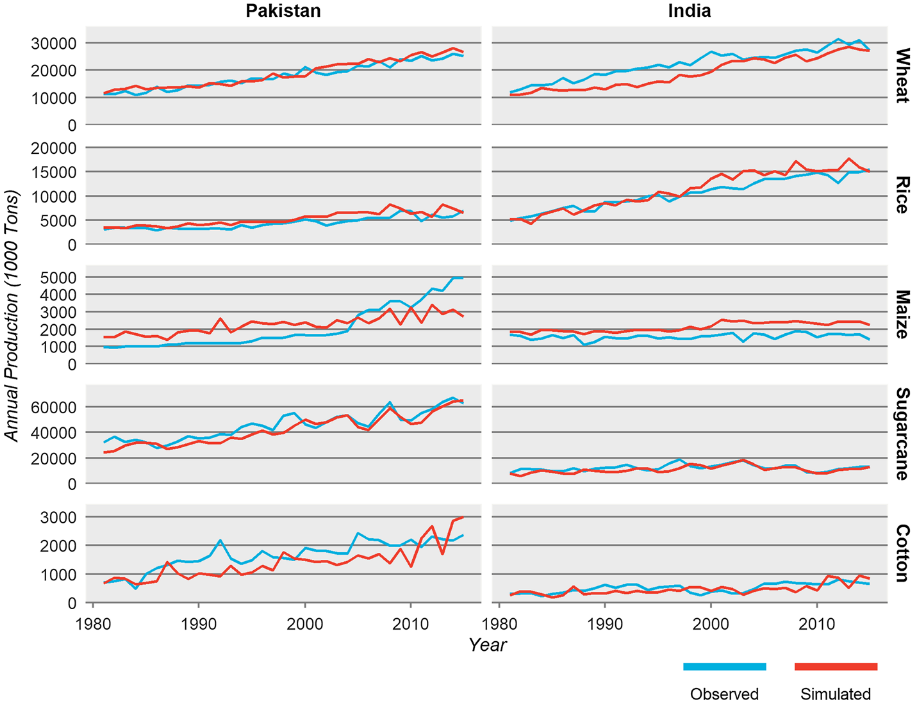


Fig. 10 comparison of simulated to observed total production for five major crops

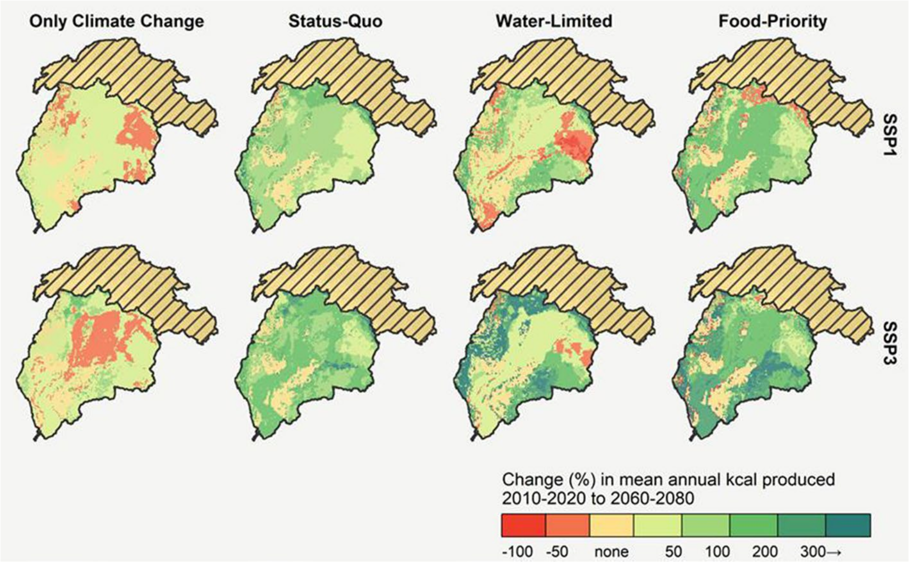


Fig. 11 Change in total kcal produced at the grid cell level

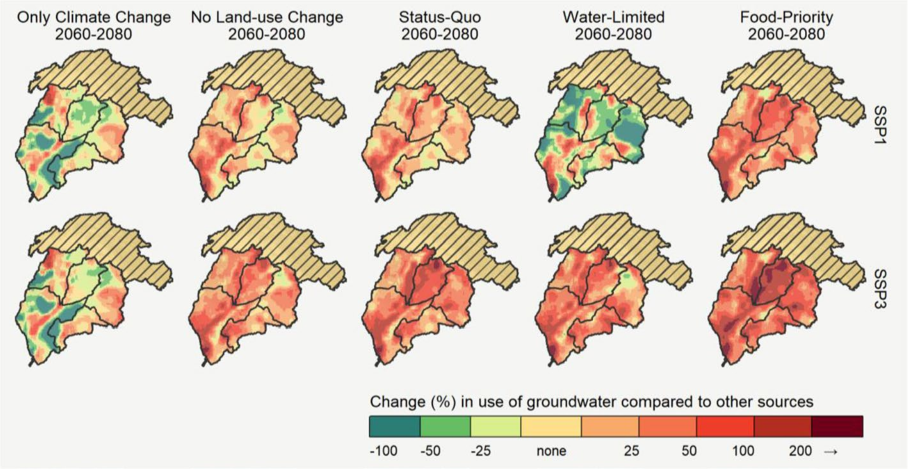


Fig. 12 Average change in groundwater dependency under specific drivers

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Data availability Simulated data available at: https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:257119.

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