communications earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-01070-3 OPEN

Spatial adaptation pathways to reconcile future water and food security in the Indus River basin

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Irrigated wheat production is critical for food security in the Indus basin. Changing climatic and socio-economic conditions are expected to increase wheat demand and reduce irrigation water availability. Therefore, adaptation of irrigated wheat production is essential to achieve the interlinked Sustainable Development Goals for both water and food security. Here, we developed a spatial adaptation pathways methodology that integrates water and food objectives under future climate change and population growth. The results show that strategic combinations between production intensification, laser land leveling, and targeted expansion of irrigated areas can ensure wheat production increases and irrigation water savings in the short term. However, no adaptation pathways can ensure long-term wheat production within the existing irrigation water budget under rapid population growth. Adaptation planning for the Sustainable Development Goals in the Indus basin must therefore address both climatic and population changes, and anticipate that current food production practices may be unsustainable.

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The Indus plains, shared by India and Pakistan, are one of the most productive agricultural zones in the world. The region is considered the breadbasket of South Asia and produces sufficient food to sustain over 300 million people[1]. Agriculture on the arid Indus plains depends strongly on irrigation, which has led to the largest contiguous irrigation system in the world[2]. During the monsoon season, precipitation and meltwater in the upper Indus basin provide ample surface water for downstream irrigation through a vast system of tributaries and canals[3]. However, in the dry rabi season, mountain water availability and precipitation are limited, and irrigation demands are largely met through groundwater extractions[4]. In the most intensively cultivated areas of the plains, this has caused groundwater tables to drop by several centimeters per year[5]. Overuse of scarcely available surface water during the dry season causes extensive damage to aquatic ecosystems of the Indus river and tributaries[2]. The crop responsible for the majority of dry season irrigation water demands is winter wheat[6]. Wheat, however, is also a staple crop for regional diets and is considered a key pillar of food security[7]. Regional self-sufficiency in terms of wheat production is an important policy objective for the riparian states of the basin and is important to support the zero-hunger Sustainable Development Goal (SDG2).

The future outlook for wheat production and the feasibility of maintaining self-sufficiency are highly uncertain. The Indus basin population has nearly doubled during the last decades, and a continuation of population growth is expected for the coming decades[8], resulting in increased wheat demand[9]. Wheat yields are also sensitive to heat stress, which will increase as climate change impacts progressively become more severe[10]. In addition, the availability of surface water for irrigation is changing. This is due to a combination of a shift in the timing of snow melt with climate change[11] and growing water demands from other water-use sectors[12]. Without adaptation, these combined processes will increase groundwater dependence for agriculture in the Indus basin during the late monsoon and dry season[13]. This is likely to exacerbate existing trade-offs between short-term objectives for wheat production and food security, and long-term objectives for water security. Singh and Park[14] characterized the current relation between staple crop production and groundwater use in the most intensively managed agricultural systems in the Indus basin as unsustainable. Adjusting wheat production on the Indus plains to rapidly changing circumstances is therefore needed to maintain both sufficient wheat production toward achieving SDG2 and to support long-term sustainable water management (SDG6).

Previous studies investigated options for integrated water-food adaptation in the Indus basin by analyzing the effect of large sets of adaptation measures[1,15]. These studies evaluated the full potential of particular adaptation strategies, but do not demonstrate the magnitude, timing and sequencing of actions required to attain explicit societal objectives through time for water and food security. The adequate design and timing of adaptation are challenging to anticipate for the long term due to highly uncertain climatic and socio-economic changes. Tanaka et al.[16] instead used an 'adaptation pathways approach' to develop quantitative adaptation steps that incrementally counteract climate change impacts on global wheat production. The sequential nature of adaptation pathways embraces uncertainty and allows adaptation to develop flexibly alongside the trajectory of future changes[17]. Pathways are however a relatively new approach, and quantitative applications have mainly focused on climate change adaptation toward clearly-defined sociotechnical objectives, such as flood defenses[18]. Methods to quantitatively integrate additional societal processes, both as stressor and as source for multiple contesting objectives, remain limited. Additionally, pathways approaches are often applied at local to regional scales without a spatial scale (i.e., one-dimensional). Most pathways subsequently demonstrate the type and timing of adaptation, but not the location. This leaves existing approaches with little capacity to represent the scale gap between policy objectives at the regional level and the diversity in local conditions in which adaptation toward these objectives must occur[19].

Here, we present an adaptation pathways approach that is spatiotemporally explicit and capable of simultaneously pursuing multiple water and food security objectives (Fig. 1). This approach is therefore better able to represent the unique adaptation context of irrigated wheat production in the Indus basin in which both land and water use strategies need to be addressed. We applied the approach to construct four sets of pathways with different objectives and priorities for future wheat production and irrigation water savings (Fig. 1 and Table 1). The pathways address climatic and population changes for the optimistic SSP1-SSP1-RCP4.5 (moderate climate change, population stabilization) and pessimistic SSP3-RCP8.5 (extreme climate change, continued population growth) scenarios[20]. Pathway construction considered three distinct adaptation measures:

- Laser land leveling (LLLV), which is a promising technical intervention shown at the farm level to improve both wheat yields and reduce irrigation water demands[21].
- Production intensification to best practices for crop and farm management (BSPR).
- The expansion of irrigated wheat production area through the partial (PART) or full (FULL) reappropriation of irrigation water savings.

Combinations between these three measures provide five different levels of adaptation (so-called adaptation options). We spatially simulated the effect of these adaptation options and climate change on wheat yields and irrigation water demands with the fully distributed LPJmL crop-hydrology model[4]. In addition, we used the model to determine how climatic and population changes affect future wheat availability and irrigation water demands in the absence of adaption (i.e., Reference pathways). The ensemble of pathways shows, through space (i.e., two-dimensional) and time, the long-term feasibility and trade-offs of integrated adaptation aiming to achieve both SDG2 and SDG6. The methodology developed in this study in addition provides important advancements for thresholds-based pathways approaches[18] by illustrating how multiple competing objectives can be integrated and expressed with an explicit spatial dimension.

Results

Pressure of climate change and population growth. The Reference pathways demonstrate in Fig. 2 that climate change will reduce wheat production by 14% in 2080 compared to 2015 in the SSP1-RCP4.5 scenario and almost 20% in the SSP3-RCP8.5 scenario. In combination with population growth, this causes annual wheat production per-capita to reduce from 200 kg currently (i.e., 2015) to approximately 145 kg in SSP1-RCP4.5 and only 60 kg SSP3-RCP8.5 (see Fig. 2b). In Pakistan, meeting per-capita wheat consumption, estimated at 150 kg per annum, is an important production threshold for national policy[7]. Even with minimal population growth and moderate climate change (SSP1-RCP4.5), wheat production will thus not be adequate to ensure food security in the basin by 2040 if no adaptive actions are taken. Figure 3 shows that climate change, through the combined effects of precipitation change, CO_2 fertilization and shortening growing seasons due to higher temperatures[22], will decrease irrigation water demands. In the SSP1-RCP4.5 scenario, water demands considerably reduce in the first part of the century and stabilize after 2050. The SSP3-RCP8.5 sees this downward trend continue over the entire projected period as climate change remains

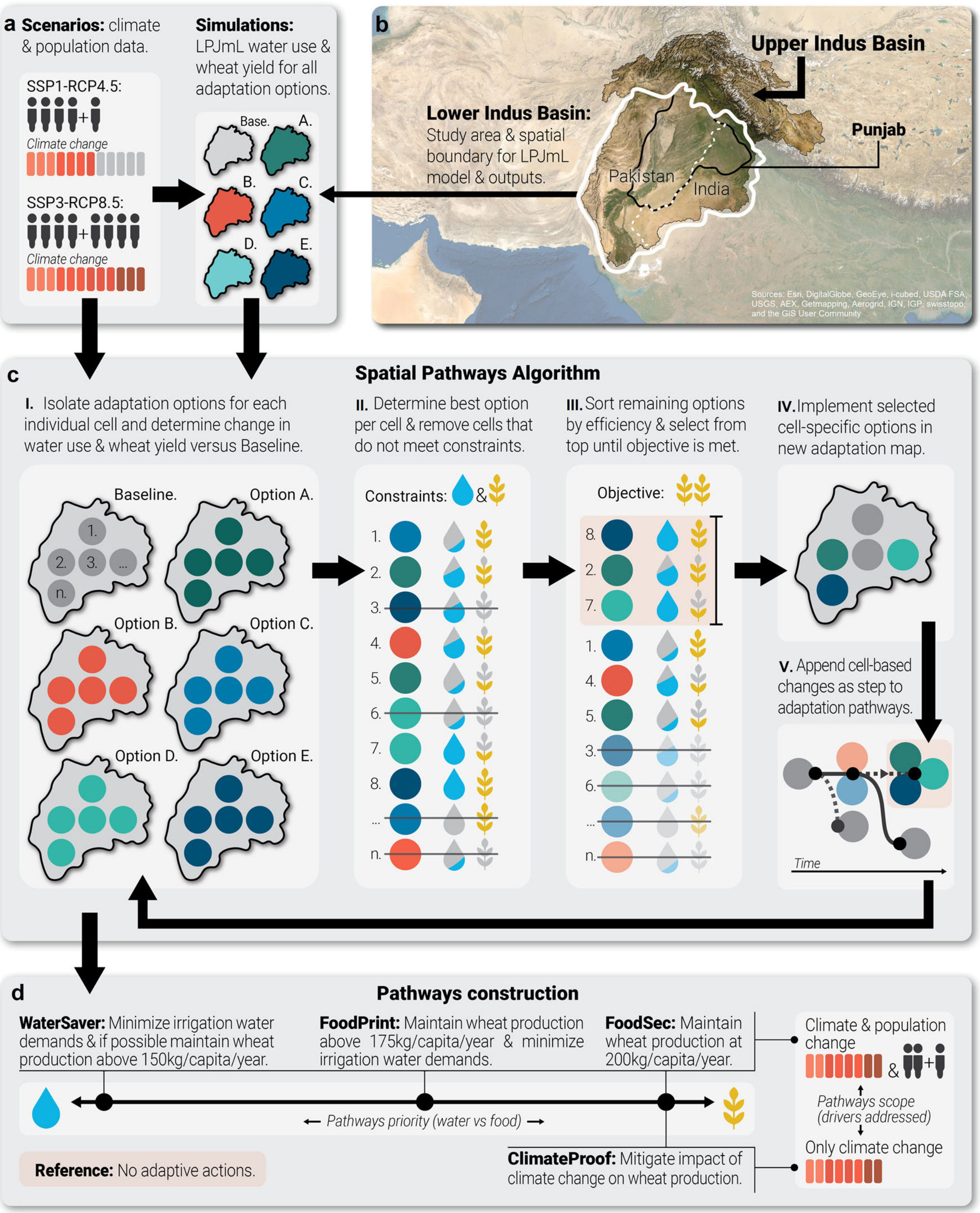

Fig. 1 Conceptual summary of the Spatial Pathways Algorithm and its application to the Indus basin. **b** Geographical overview of the study area, highlighting the transboundary lower Indus basin and the central position of the Punjab as a major agricultural region. The white dotted line approximates the border between India and Pakistan. **c** Conceptual representation of the major procedures within the Spatial Pathways Algorithm in relation to the input data generated by the LPJmL model for two integrated scenarios of climatic and socioeconomic change (**a**). The five different colors in the figure (greens, blues, and orange) conceptually represent five different adaptation options, while the gray represents a situation without adaptation (i.e., the baseline). The colors are consistent between the methodological steps depicted in the figure, and demonstrate how data on each adaptation option is processed throughout the algorithm to go from spatially explicit input data to cell-specific adaptation options and ultimately to the next set of steps in the adaptation pathways. The numbers as seen in the baseline of step I and in the listed adaptation options of steps II and III conceptually represent identifiers for individual cells within the selection procedure of the Spatial Pathways Algorithm. **d** An overview of the constructed pathway, highlighting their objectives, prioritization in relation to water and/or food security and the drivers they aim to address (see also Table 1 in "Methods").

unmitigated. The reduction in irrigation water demands in both scenarios is significantly stronger than the decrease in wheat production. This means that the water footprint of irrigated wheat will likely decrease, especially in the SSP3-RCP8.5 scenario.

Trade-offs for safeguarding future food security. The ClimateProof Pathways aim to mitigate the negative impact of climate change on wheat production with the fewest possible adaption steps. In the SSP1-RCP4.5 scenario, this can be achieved with

Table 1 Configurations of objectives and constraints for pathways construction.

Configuration name	*Objective*	*Constraints*		
		Wheat yield	**Irrigated area**	**Water budget**
Reference	None	None	No change	None
ClimateProof	Mitigate the negative effect of climate change on wheat yield.	Maintain total wheat production at 2015 levels.	No change	None
WaterSaver	Minimize the basin-level water footprint of irrigated wheat.	Maintain wheat production per capita at least at 150 kg per year.	Reduce as much as possible, prioritizing cells with highest water footprint.	Decrease as much as possible at the basin level. Demand in cells may increase only if it benefits the basin-level water footprint.
FoodPrint	Increase wheat production, if possible through options that decrease the water footprint.	Maintain wheat production per capita at least at 175 kg per year.	Reduce if possible, sustainable expansion to limits of water budget if required to meet wheat target.	Demand in cells may not increase, but can use water may not exceed that of the Reference baseline.
FoodSec	Maximize wheat production.	Maintain wheat production per capita at least at 200 kg per year.	No reduction, sustainable expansion to limits of water budget if required to meet wheat target.	Grid-cell water demand may increase, but to expand the area, it may not exceed the 2015 water demand.

Each set of pathways is provided during construction with a unique set of constraints for minimum wheat production, the total size of the irrigated area and the allowable irrigation water budget. Within these constraints, pathways continuously seek to achieve adaptation objectives ranging from reducing irrigation water use to optimizing wheat yields.

gradual production intensification until around 2050 in the regions of the Pakistani share of the basin, which at present have the lowest yields (Fig. 4 and Supplementary Fig. S2). The population also stabilizes by 2050, which ensures that climate change adaptation alone is enough in this scenario to maintain wheat production per capita above the 150 kg threshold (Fig. 2). To address the progressively severe climate impacts of SSP3-RCP8.5, the ClimateProof pathways require continuous adaptation steps throughout the entire 21st century, including widespread implementation of laser land leveling in the Punjab region of Pakistan. The Indian share of the Punjab region currently has considerably higher yields (Supplementary Fig. S2), leaving limited room for improvement or compensation for the negative impact of climate change. This region is consequently not targeted in the ClimateProof pathways. Rapid population growth causes per capita wheat availability to reduce below 150 kg per capita by 2030. This indicates that ensuring future food security in the SSP3-RCP8.5 scenario requires more than climate change adaptation, but also actions to address and prevent the negative effects of future demographic changes.

The other pathways aim beyond climate change adaptation and explicitly account for food production challenges as a result of population changes. The primary goal of the FoodSec pathways is to sustain 200 kg per capita wheat production and retain the basin's position as a breadbasket that supports food security beyond its borders[23]. Figure 5 shows that these pathways require significantly more extensive and immediate adaptation steps than the ClimateProof pathways to address the impact of both climate change and population growth. In the SSP3-RCP8.5 scenario, the FoodSec pathways can only sustain this adaptation process until 2060, at which point all adaptation options for the entire basin have been utilized (Fig. 4) and the 200 kg per capita objective can no longer be met (Fig. 2). This requires that all future reductions in irrigation water demands from adaptation and climate change will be used for the expansion of irrigated wheat production. The FoodSec Pathways therefore do not achieve any irrigation water savings compared to the 2015 baseline in the SSP3-RCP8.5 scenario. Per capita wheat production does however remain above the 150 kg threshold (Fig. 2) by 2080. This indicates that the FoodSec pathways can ensure basin-level self-sufficiency is maintained. In the SSP1-RCP4.5 scenario, the 200 kg per capita wheat production objective can be achieved with relatively few adaptation steps and only minimal additional irrigation water requirements compared to the Reference pathways (Fig. 3). Adaptation in this scenario is targeted largely at intensifying wheat production in the Pakistani Punjab.

Barriers for combined water-food adaptation. Rather than ensuring future food security, the priority of the WaterSaver pathways is to minimize irrigation water demands. The only adaptation options allowed to sustain wheat production above 150 kg per capita are those that simultaneously improve its water footprint. These pathways initially opt for adaptation in the Indian Punjab, which is the most intensively cultivated area of the basin[24] and has the highest relative irrigation water demand (Fig. 5 and Supplementary Fig. S2). In the SSP1-RCP4.5 scenario, this approach can sustain wheat production at 150 kg per capita (Fig. 2) while reducing irrigation water demands by over 50% (Fig. 3). Reductions in irrigation water requirements are enhanced by increases in wheat production in the more water-use efficient northern share of the Punjab, which allow southern areas with lower water productivity to be withdrawn from production (Fig. 4). This more than halves the water footprint of irrigated wheat at the basin level by 2080 compared to 2015. The WaterSaver pathways are however unable to achieve the 150 kg per capita wheat

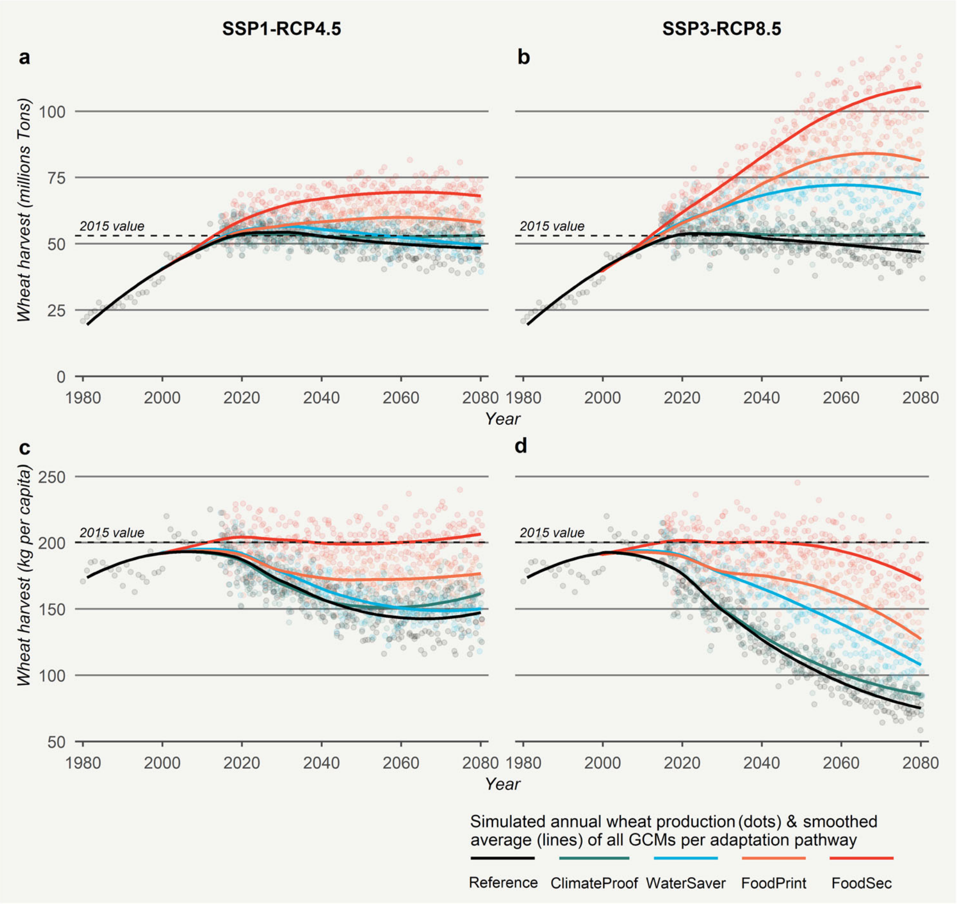

Fig. 2 The effect of adaptation pathways on irrigated wheat production and availability (1980–2080). a, **b** Total historical wheat production in millions of tons/year and projected future production for the adaptation pathways. **c**, **d** Relative historical wheat production per year in kg/capita and projected future production for the adaptation pathways while accounting for population changes. The dots represent the individual simulated production per year for each of the GCMs (i.e., four dots per pathway per year). The lines represent the smoothed average of all GCMs using a locally estimated scatterplot smoothing (LOESS) function.

threshold after 2050 in SSP3-RCP8.5 (Fig. 2). Constraints on adaptation options that are not favorable for the water footprint mean that some adaptation options, such as production expansion, are not available in parts of the basin (Fig. 4). This results in considerably lower adaptive space for food security compared to the FoodSec pathways. Nevertheless, Fig. 3 shows that the WaterSaver pathways are the only pathways that significantly reduce irrigation water demands compared to the Reference pathways in the SSP3-RCP8.5 scenario.

The FoodPrint pathways similarly aim to minimize the water footprint of irrigated wheat production but do allow for some expansion of irrigated areas as a last resort to ensure sufficient wheat production. Ample adaptation options are available in the SSP1-RCP4.5 scenario that can combine an increase in wheat production with reductions in irrigation water demands. The adaptation steps of the FoodPrint pathways accordingly follow a similar trajectory to those of the WaterSaver pathways (Fig. 4), prioritizing laser land leveling in high water-use areas of the Indian Punjab. However, in the SSP3-RCP8.5 scenario, these two pathways diverge after 2050 as the FoodPrint pathways ultimately take adaptation steps that are not beneficial to the water footprint to maintain per capita wheat production. As a result, irrigation water demands for the FoodPrint pathways decrease sharply in the near future, but increase again after 2050 (Fig. 3). Irrigation water demands by 2080 are nevertheless considerably lower than 2015 demands. The additional adaptation steps, shown in Fig. 2, allow the FoodPrint pathways to maintain wheat production at sufficient levels for a considerably longer period than the WaterSaver pathways. However, per capita wheat production still falls below 150 kg by 2070. This illustrates that only the FoodSec pathways can ensure future self-sufficiency for wheat production in the basin in the SSP3-RCP8.5 scenario.

Discussion

Implications for future water and food security in the Indus basin. The pathways of this study demonstrate that smart combinations of production intensification, laser land leveling and targeted expansion of irrigated area can simultaneously increase wheat production and reduce irrigation water demands in the Indus basin. However, the extent to which adaptation to achieve water (SDG6) and food (SDG2) security here can be reconciled in the long term depends largely on the development of external drivers. For a future with severe climate change impact and continued population growth, mutually beneficial adaptation options alone are insufficient to sustain per capita wheat production. Pathways that prioritize food security therefore require adaptation steps that enhance wheat yields in the Pakistani share of the basin, which are nonbeneficial to the basin-level water footprint of irrigated wheat production. Meanwhile, pathways that aim to reduce irrigation water demand focus mainly on improving water productivity in the already high-yielding Indian

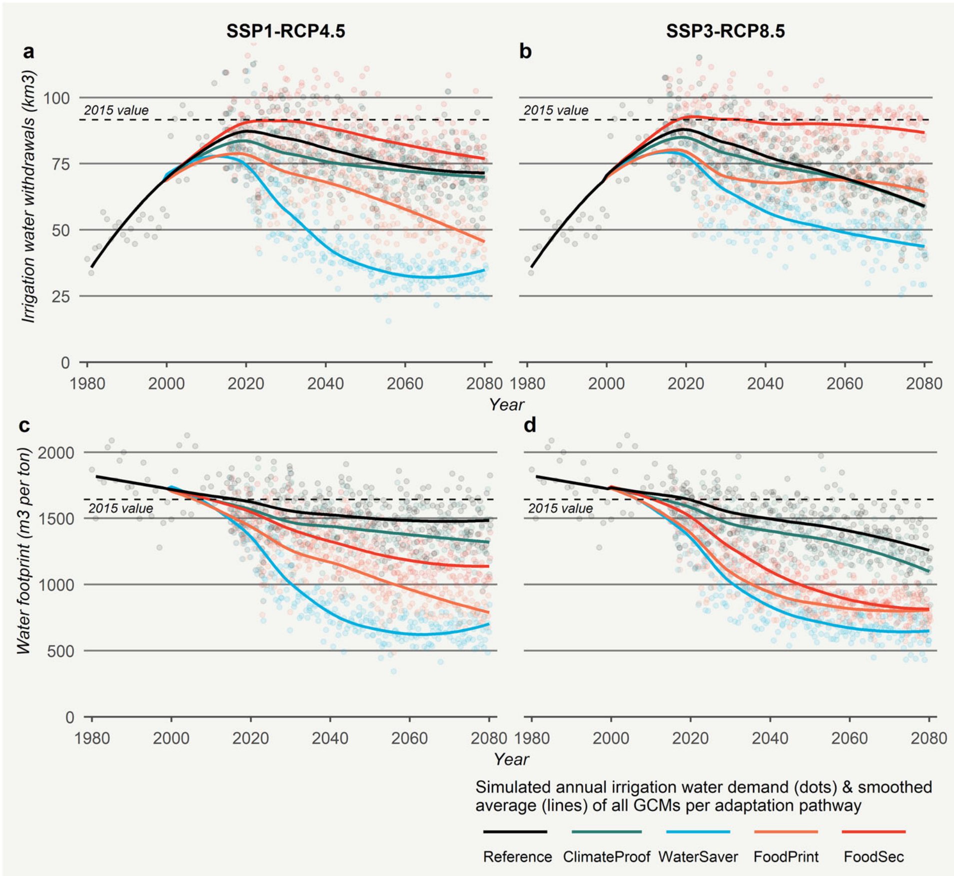

Fig. 3 The effect of adaptation pathways on water demand for irrigated wheat production (1980–2080). a, **b** Total historical water withdrawals in km3/year and projected future water demand for the adaptation pathways. **c**, **d** Relative historical water demand per year in m3 per ton of wheat produced and projected future water demand for the adaptation pathways. The dots represent the individual simulated water demand per year for each of the GCMs (i.e., four dots per pathway per year). The lines represent the smoothed average of all GCMs using a locally estimated scatterplot smoothing (LOESS) function.

Punjab. These adaptation steps therefore provide only limited wheat production gains and consequently cannot meet minimum wheat production thresholds in the long term. In contrast, in a future with moderate climate change and population stabilization, a range of adaptation objectives for SDG2 and SDG6 can be achieved. Pathways that address adaptation for both climate and population change from the outset in addition perform better for both objectives in the long run compared to those that focus solely on climate change adaptation.

An important methodological note is that the pathways approach used to obtain these findings is model-based and therefore inherently represents a simplified subset of the system of interest[17]. Our pathways approach considered three biophysical indicators, namely yield, water demand and sown area, to construct pathways for the Indus agricultural system. The sustainable management of these resources is a boundary condition to achieve water, food and climate SDGs[25]. However, robust adaptation planning requires an understanding of how such factors interact with the broader decision-making context[18]. Our approach demonstrates if-and-how specific measures make wheat production more water-efficient but does not consider for instance the economic cost of their implementation or upkeep, nor the required farmer knowledge. Whether the ensuing pathways are feasible is thus determined by societal priorities- not only by the technical parameters and targets assessed in this study. Similarly, although the measures supplied to the algorithm are promising in terms of adaptation potential, myriad strategies exist that may offer complimentary effects[1]. The investigated measures are all technical interventions, which essentially optimize wheat production. The corresponding pathways thus fundamentally seek to preserve and strengthen the existing system of wheat production. Our results demonstrate however that maintaining this system is challenging under an SSP3-RCP8.5 future. Subsequent studies should therefore look to complement our threshold-based pathways approach with transformation-oriented pathways approaches[26] that explore adaptation options for systemic change beyond technical optimization.

Benefits of spatial and multi-objective pathways for adaptation planning. The pathways constructed in his study are not directly actionable adaptation strategies. They do, however, illustrate the technical potential of different adaptation measures to support varying compositions of water, food and climate SDGs under future uncertainty. The identification of potential adaptation steps is made more substantial by the fact that our pathways approach is spatially explicit. The spatial dimension allows pathways to acknowledge that the suitability of adaptation measures is not distributed homogenously throughout the basin but instead follows patterns in space that are determined by both local biophysical circumstances and the overarching objectives of adaptation. Despite being essentially regional in scope, our approach is thus able to include diversity in local conditions in pathway construction for key factors that determine the technical fitness of specific measures. The approach developed in this study therefore provides an important step in bridging the scale gap between regional adaptation planning and the representation of

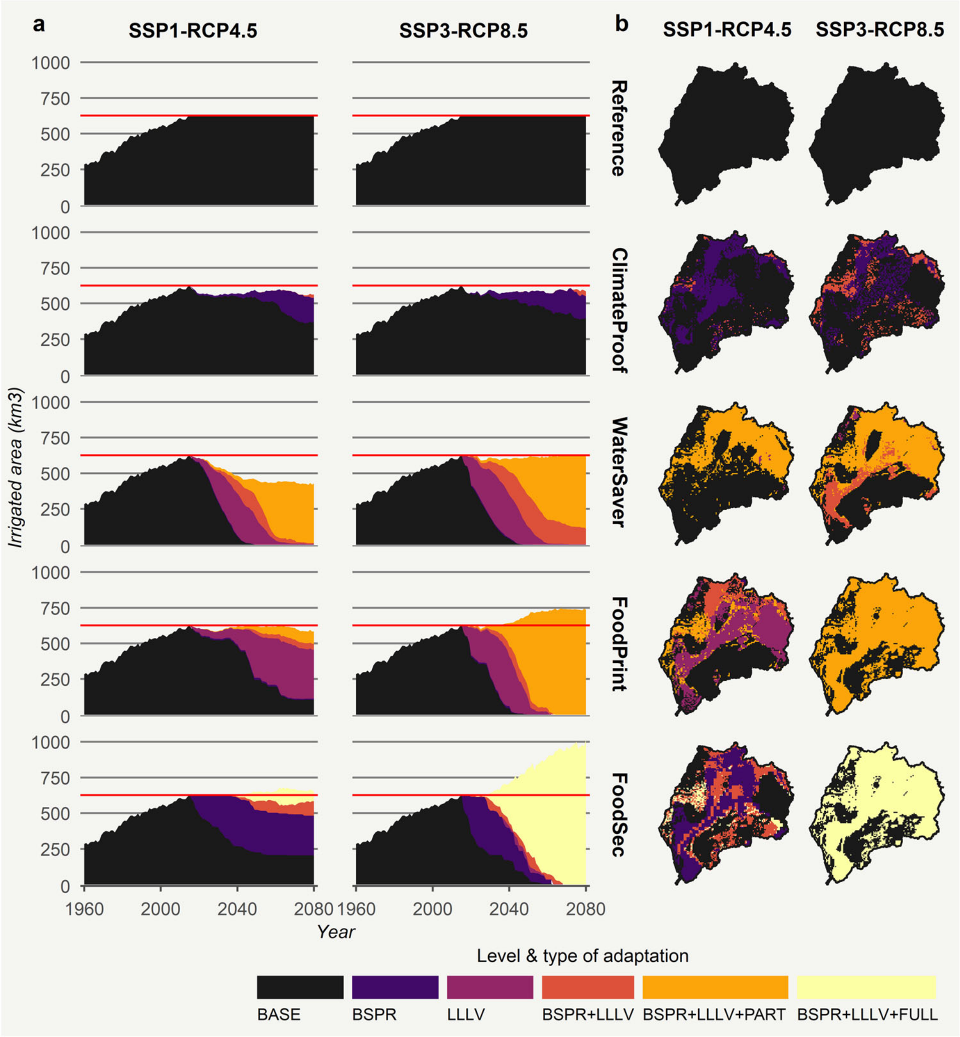

Fig. 4 Pathways evolution through time and space. a Total area of irrigated wheat under specific adaptation options over the projected period for each of the adaptation pathways (average of all four GCMs). The red line illustrates the 2015 area of irrigated wheat. **b** The final adaptation map for each of the pathways in 2080, forming the end of the projected period (mode of the four GCMs for 2080).

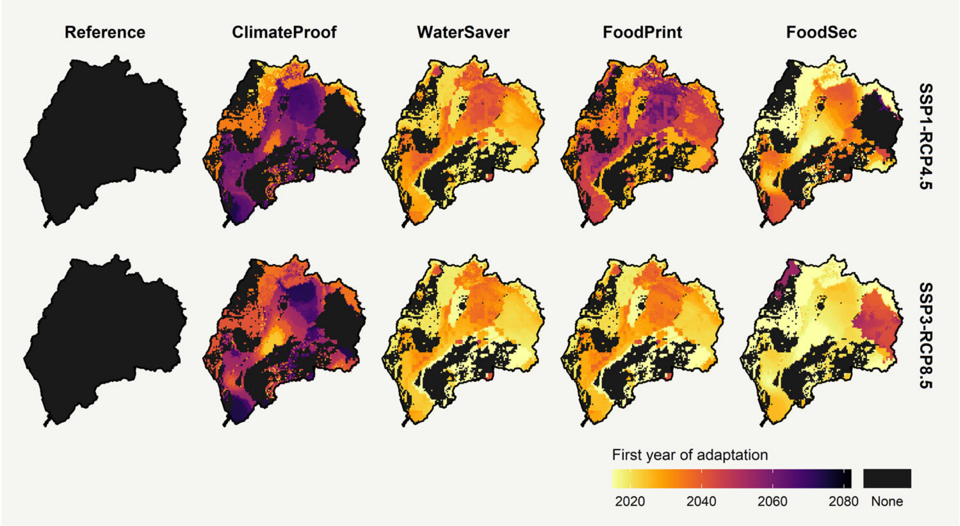

Fig. 5 Spatial overview of the sequential implementation of adaptation options. First year in which adaptation steps are taken for each of the adaptation pathways (average of all four GCMs). Note that cells that were not adapted during pathways construction remain black.

local conditions, which constitutes a barrier to the policy relevance of pathways approaches[19]. For the Indus basin, this allows our pathways to consistently highlight an initial set of local complementary actions that together reduce the basin-level water footprint of irrigated wheat while increasing total production. Since the basin already faces severe water stress[27] and increasing urban-rural competition over water resources[12,28], these localized adaptation steps provide a tangible premise for short-term action with limited risk of maladaptation regarding future trade-offs between water and food security.

Contrary to previous pathways assessments for wheat production[16], which focused solely on the uncertainty and impact of climate change, our approach also accounted for the effect of population change in pathways development. In addition, we explicitly introduced contesting constraints for water use alongside wheat production objectives. Our pathways therefore provide insight into the interaction between multiple adaptation objectives and drivers in the long term. This integration of climate change with societal development and SDGs addresses an important methodological advancement for the pathways learning goals formulated by Werners et al.[18]. Our approach finds similar results to Wijngaard et al.[22] and Rasul[28] in that population change, rather than climatic change, will likely be the dominant challenge for interlinked water and food security in the Indus basin. As forcing scenarios and corresponding pathways diverge, adaptation steps for the medium-to-long-term similarly become more uncertain. In an SSP1-RCP4.5 future, continued adaptation is objective-dependent. Population stabilization ensures additional wheat production gains are not required for food security, but further measures are needed to reduce groundwater dependency[29] or provide space for other crops that are currently imported, like oilseeds and pulses[6]. Conversely, unabating pressure by drivers in SSP3-RCP8.5 demands continuous adaptation to meet wheat production thresholds and forces negative trade-offs between water and food objectives. These drivers moreover increase water and land demand for other societal purposes[1]. Adaptation strategies must therefore establish clear priorities, or pursue fundamental system changes.

The pathways approach developed in this study provides adaptation planning in the Indus basin with both robust short-term options and a flexible framework to evaluate long-term objectives for integrated water and food security. Our approach provides several important conceptual insights and methodological lessons for adaptation pathways development. First, by dynamically integrating multiple drivers and objectives, our approach allows pathways to acknowledge trade-offs and dependencies that are crucial to account for in the design of holistic adaptation strategies. Second, we demonstrate that adding a spatial dimension to pathways improves their capacity to consider for the variation in local conditions for adaptation planning at regional scale. These innovative features allow our pathways to capture how contesting objectives interact between the local and regional scale and therefore to better represent the regional context in which adaptation occurs. Subsequent Indus basin studies could expand our approach to include the impact of socio-economic changes on water-use sectors other than agriculture and introduce dynamic water security targets. This may enable pathways assessments to also explore consequences of adaptation changes for intersectoral water competition[12] and upstream-downstream dependencies[3]. Incorporating economic constraints and objectives may similarly be valuable to further delineate future priorities for adaptation planning[30]. Our approach can be applied to other regions where water and food security strongly interlink with climatic and socio-economic changes. Contextually similar complex river basins where irrigation plays a strong role, such as the Nile, Ganges and Mekong[31], may be of particular interest.

Methods

To construct adaptation pathways for the Indus basin, we used a three-step approach:

1. First, we used the LPJmL crop-hydrology model to make six datasets of spatial simulations for wheat yield and irrigation water demand. Each dataset accounts for climate change and considers a different combination of adaptation measures to be implemented throughout the entire Indus basin.
2. Then, we developed the Spatial Pathways Algorithm, which creates pathways that determine with annual timesteps the location and type of adaptation steps required to optimally achieve user-defined objectives for irrigation water savings and wheat production. The algorithm used the six simulated datasets to obtain spatial information on adaptation options for pathways construction.
3. Lastly, we applied the algorithm to construct pathways for five configurations of adaptation objectives and constraints, within the setting of two contrasting scenarios of future climatic and socio-economic change. Both scenarios contain four climate change models, meaning that a total of 40 unique pathways were constructed.

Spatial simulations of wheat yield and irrigation water demand. Since the aim of our study is to develop adaptation pathways that include a spatial dimension, we required spatially explicit information on wheat yields and water demands in the Indus basin with and without adaptation. To obtain this data, we made spatial simulations of wheat production (rainfed and irrigated) and corresponding water requirements in the basin for historical conditions and under future climate change with various degrees of adaptation. The irrigation systems of the Indus basin, and hence virtually all irrigated wheat production, are located on the Indus plains[32]. We therefore focused our spatial simulations on the lower Indus basin (see Fig. 1). Simulations were made at 5 × 5 arcmin resolution over the period 1950–2080 with daily timesteps, using a version of the LPJmL crop-hydrology model[33] that was adapted specifically to simulate water-food interactions in irrigation-dependent South Asian river basins (Biemans et al., 2019). An elaborate model description can be found in Lutz et al.[13] and a conceptual overview of model processes is found in Supplementary Fig. S3. The model was calibrated to historical wheat yield statistics at the state (India) and provincial (Pakistan) level in the basin in ref. [1]. After calibration, the simulated total wheat production and average wheat yield in the basin show strong agreement with the trajectory observed statistics over the 1950–2015 period (see Supplementary Fig. S1). In addition, the blue water footprint of irrigated wheat production (i.e., irrigation water withdrawal per unit of wheat produced) as simulated by LPJmL was compared to values by other studies in the case study area (see Supplementary Table S1 and Supplementary Fig. S2). This validation step demonstrates that the water footprint used in this study for the reference period falls well within the range suggested by scientific literature.

Using this model setup, we first made simulations for two scenarios of climate change (see Table 2), each consisting of four downscaled GCMs (General Circulation Models)[34]. We used spatially explicit historical land-use data for the Indus basin developed by[1] as input data to the LPJmL model. For the period 2016–2080, land use was kept constant to 2015 conditions. This setup provided us with a dataset of baseline simulations of historical and future wheat production, and irrigation water demand under two scenarios of climate change, without considering for any land-use change or adaptation measures (see Supplementary Fig. S2). In addition to the no-adaptation baseline, we developed datasets in which adaptation does take place. Three distinct adaptation

Table 2 Overview of forcing scenarios.

Name	Climate		Population (millions)				
	Type	Models	Type	2015	2030	2050	2080
SSP1-RCP4.5	Moderate	BNU-ESM CMCC-CMS CSIRO-Mk3-6 INMCM4	Stabilization by 2050	271	315	351	334
SSP3-RCP8.5	Extreme	BCC-CSM1-1 CANESM2 CMCC-CMS INMCM4	Continued rapid growth	271	352	470	631

Each scenario contains a climatological component, consisting of four GCMs, and socio-economic projections that revolve around the direction and speed of population growth.

measures were considered: improved farm and crop management, laser land leveling, and the sustainable expansion of irrigated area. We made five spatial datasets of yield and irrigation water demand simulations which assume distinct combinations of these measures (i.e., adaptation options) are implemented in the entire basin. The following five datasets of adaptation options were developed with simulations for each climate model:

- Best practices (BSPR): farming systems in the basin intensify wheat production to the level currently seen in the Indian Punjab, which literature[24,35,36] shows is close to the upper limit of yields that current farming systems in the region can attain through improved nutrient input and crop and water management, without requiring additional technical interventions. Although intensification may increase irrigation water demands, it will also strongly increase yields. These simulations were developed similarly to the original baseline simulation using LPJmL but with farm management parameters across the basin set instead of the value found after calibration[1] for the Indian Punjab.
- Laser land leveling (LLLV): the entire basin practices laser land leveling, a highly promising and relatively low-cost technique that allows water to be distributed equally throughout a field[21]. Precision leveling ensures uniform sub-surface infiltration, resulting in strong reductions in irrigation water demand and small, but significant, benefits for crop yield. To simulate the effect of his measure, we corrected the baseline simulations to increase irrigated wheat yield and decrease irrigation water demand (i.e., without adaptation) with field level values for the Indus basin, based on the soil type in each respective cell[21]. An overview of the values used in this study in comparison to other studies can be found in Supplementary Table S2. This table demonstrates that the improvements that are assumed to occur through laser land leveling in our align with outcomes suggested by similar experiments.
- Best practices and laser land leveling (BSPR+LLLV): farming systems intensify to best practices and in addition employ laser land leveling. In this case, we applied the field-level laser land leveling values[21] to the wheat yield and irrigation water demand simulations of LPJmL with management parameters set to those of the Indian Punjab.
- Best practices and laser land leveling with sustainable expansion (BSPR+LLLV+PART): farming systems in the basin shift to best practices and implement laser land leveling. In addition, this adaptation option assumes that water saved through these adaptation changes may still be used at the farm level. At the cell level, any reduction in irrigation water withdrawals in the simulations which account for both best practices and laser land leveling (in comparison to the baseline simulations without adaptation) may therefore be used to proportionally expand the irrigated area. This means that this adaptation option is only implementable after water savings (e.g., due to laser land leveling) have been achieved. Expansion is limited to cells equipped for irrigation and by the remaining area in each cell according to the MIRCA2000 spatial dataset[32] updated to 2015[1].
- Best practices and laser land leveling with sustainable expansion within historical water budget (BSPR+LLLV+FULL): the entire basin shifts to best practices and employs laser land leveling. This option assumes that irrigation water allocation at farm level remains the same over the entire projected period, using the 2015 values as reference point. Grid cells with decreases in irrigation water demand, whether due to the effect of CO2 fertilization or the implementation of adaptation measures, may sustainably expand the irrigated area, up until irrigation water demand reaches the level of 2015. The expansion to full historical water use can only be implemented as a next step after partial expansion has been achieved. This expansion too is limited by the remaining area in each grid cell.

Spatial Pathways Algorithm. Second, we developed the *Spatial Pathways Algorithm* that creates, through space and time, adaptation maps that optimally achieve user-determined water and food security objectives. The algorithm operates under constraints imposed for the required wheat production, the total irrigated area and the total irrigation water demand. This approach is methodologically similar to previous threshold-based pathways approaches[16–18,37] that determine when a clearly-defined quantitative objective (i.e., threshold) will no longer be met and what adaptation steps are most suited to prevent this. However, our approach additionally considers each of the five adaptation options in each cell as a unique adaptation option toward achieving objectives at the basin level. We therefore consider not only the 'when' and 'how' of adaptation planning, but also highlight the 'where' by adding an explicit spatial dimension to the pathways.

Specifically, the Spatial Pathways Algorithm shifts individual cells on a yearly basis between baseline conditions without adaptation, and the five different adaptation options described in the previous paragraph (see Fig. 1). This process creates annual 'adaptation maps' which spatially demonstrates the adaptation steps that must be taken in any given year to achieve specific objectives. The algorithm takes the six spatial simulations of wheat yield and irrigation water demand as input data for the construction of adaptation maps. Each map, for each year, is therefore a combination of these six datasets and the water-use and yield values associated with them. Spatial adaptation pathways with yearly timesteps are formed by appending all annual maps into a series of adaptation steps. The algorithm starts in 2015 with all grid cells in baseline conditions (i.e., no adaptation and 2015 irrigated area). For each subsequent year, the algorithm cycles through the following steps:

- First, the algorithm determines whether the wheat production threshold is likely to be met in the upcoming year, and, if this is not the case, determines the expected production gap. To do so, the average total wheat production (irrigated and rainfed) for the preceding five years is determined under the latest adaptation map. The basin-level aggregated production is then compared to the production threshold for the subsequent year. If this threshold is not met, the difference between the expected production and the required production determines the production gap.
- If there is a projected production gap, the algorithm then determines for all grid cells how much wheat production and irrigation water demand would change in each cell if it were to shift to any of the other adaptation options, as compared to the values under its present adaptation status (see Fig. 1, step I). As there are a total of six adaptation options, this creates five potential changes per cell. For each cell, the most beneficial option is selected (see Fig. 1, step II). Depending on the objective of the adaptation run, this means either the option that demonstrates the largest reduction in water footprint (i.e., irrigation water used per unit of wheat produced), or the option which increases most the yield per unit area, is selected. Adaptation options that are not allowed due to the pathways constraints (e.g., increase in irrigation water demand) are eliminated. Given the same criteria used to select the best adaptation option per cell, all cells and their selected adaptation option are then sorted to create a cell-specific ranked list of adaptation options (see Fig. 1, step III).
- Based on this ranking, the algorithm iteratively selects the cell-based adaptation options, until the cumulative production increase in all of the newly adapted cells equals the production gap (see Fig. 1, step III). If there is no production gap, and the objective of the run is to decrease the water footprint of irrigated wheat, adaptation options that bring about the strongest decrease in the basin-level water footprint are selected instead. The cells that are not chosen for implementation maintain the adaptation status of the previous year.
- If there is no production gap, but instead projected overproduction of wheat for the upcoming year, the algorithm will reduce the current irrigated area until the projected overproduction is eliminated, provided the pathways constraints allow such a change. The reduction of area takes a similar approach to the adaptation option selection step. Depending on the pathways objectives, cells are ranked either from the largest to the smallest water footprint, or the lowest to highest yield per unit area. Based on this order, cells are then iteratively selected to be taken out of production, until the projected overproduction for the subsequent year is eliminated. This step ensures that wheat production is concentrated in as few cells as possible, which benefits the spatial coherence of adaptation pathways.
- Lastly, the changes are implemented to the present adaptation map, thereby forming the new adaptation map for the next year (see Fig. 1, step IV). The updated adaptation map is appended to the series of previous adaptation maps to form the next set of steps in the adaptation pathways (see Fig. 1, step V).

Pathways objective setting and construction. To set the boundary conditions for our Spatial Pathways Algorithm, we established five different adaptation configurations (see Table 1). Each configuration consists of a primary objective, and of constraints for the desired wheat production, the total irrigated area and the irrigation water budget. These constraints provide the setting within which the Spatial Pathways Algorithm must develop an optimal pathways to achieve the objective using combinations of the five adaptation options. The configurations were designed to represent a range of different prioritizations and degrees of action for water use and wheat availability. The following five configurations were established:

- The Reference configuration assumes that no adaptation options are implemented in the Indus basin. Hence, the 2015 agricultural system is maintained over the entire projected period, regardless of the impact of climate change and population growth. This pathways is a 'baseline' to understand the consequences of not undertaking any adaptive action.
- The objective of the ClimateProof configuration is to mitigate the negative effect of climate change on wheat production as efficiently as possible. Adaptation steps are therefore only taken if required to maintain wheat production at 2015 levels under changing climatic conditions. This setup prioritizes cell-specific adaptation options that demonstrate the largest increase in yield per unit area. The irrigated area may reduce if wheat production is projected to surpass 2015 levels, starting with areas with the lowest yield per unit area. Expansion of irrigated area is not allowed in this setup. No further constraints in terms of water use are considered.
- The WaterSaver configuration has the objective of reducing the basin-level water footprint of irrigated wheat as much as possible. An annual wheat production threshold of 150 kg per capita is maintained as a food security constraint[7]. This configuration prioritizes adaptation options that decrease the water use per unit area of cells. Adaptation options that increase irrigation water demand in a cell are not allowed unless these increase the yield in the respective cell and its water footprint is below average. The subsequent yield increase in such high water-use efficiency cells may then be used to proportionally reduce the irrigated area in less water-efficient cells, thus improving the basin-level water footprint and reducing the area under irrigation. The total area under irrigation may however not expand beyond the 2015 level, even if this means the wheat production threshold cannot be met.
- The objective of the FoodPrint configuration is to ensure sufficient wheat availability with the lowest possible water footprint. The wheat production threshold is therefore higher, at 175 kg per capita per year, to maintain a buffer in case of unfavorable climatic conditions. Similar to the WaterSaver setup, adaptation options that are most beneficial to lowering the basin-level water footprint are prioritized. In case of projected overproduction, the irrigated area may reduce, starting with cells with low water productivity. However, this configuration does allow for the expansion of the total irrigated area and the implementation of adaptation options that increase water demand if this is required to meet the wheat production threshold. Such adaptation options are implemented only after all adaptation options that do benefit the water footprint are exhausted.
- Lastly, the FoodSec configuration has the objective to ensure wheat self-sufficiency at all costs. The wheat production threshold remains at its current level of 200 kg per capita per year[1] thereby maintaining the position of the basin as a breadbasket for the region. This

configuration prioritizes adaptation options that increase the yield per unit area, regardless of its effect on irrigation water demand. The total irrigated area may not decrease, but expansion is allowed as long as irrigation water demand in a cell does not exceed the 2015 level.

Lastly, we applied the Spatial Pathways Algorithm for each of the five configurations under both climate change scenarios (RCP4.5 and RCP8.5, see Section 2.1). The wheat production constraint of some configurations is additionally affected by population change. We therefore combined our climate change scenarios with population projections for the Indus basin in ref. [9]. These projections are regionally downscaled versions of the global Shared Socio-Economic Pathways (SSPs) and can therefore be consistently coupled with the RCP scenarios[38]. We selected the Indus basin projections that correspond to SSP1 (population stabilization) and SSP3 (continued strong population growth), as these are internally consistent with respectively the RCP4.5 and RCP8.5[20] climatic futures and present the most contrasting future outlooks. The two integrated scenarios we used to force our pathways assessment therefore represent a 'best case' (SSP1-RCP4.5, hereafter SSP1) and 'worst case' (SSP3-RCP8.5, hereafter SSP3) outlook for the Indus basin (see Table 2). This selection of scenarios allows our pathways to generate adaptation strategies for the broadest possible bandwidth of future developments, thereby enhancing the identification of adaptation options that are robust for all future circumstances. In the end, pathways were constructed for five adaptation configurations, under two integrated scenarios, each consisting of four climate models and one population projection. This means that we developed a total of 40 unique adaptation pathways.

Data availability

The data generated by the Spatial Adaptation Pathways Algorithm and used to construct the figures in this article is stored open-access in an online data repository[39]. The input data for the Spatial Adaptation Pathways Algorithm scenario data were generated with the LPJmL model (https://github.com/PIK-LPJmL/LPJmL).

Code availability

The base code for the LPJmL model and all relevant documentation are publicly accessible (https://github.com/PIK-LPJmL/LPJmL). The code of the Spatial Pathways Algorithm is available upon request from the authors.

Received: 2 June 2023; Accepted: 24 October 2023;
Published online: 06 November 2023

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Acknowledgements
The work of all the authors is supported by the SustainIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University. H.B. would like to acknowledge partial funding from Wageningen University and the Food Security and Valuing Water research program supported by the Dutch Ministry of Agriculture, Nature and Food Security. S.D. acknowledges partial support from the Sustainable Development Investment Portfolio (SDIP), the Department of Foreign Affairs and Trade (DFAT), the Government of Australia, the Swiss Agency for Development and Cooperation (SDC) and core funds from ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom. The views and interpretations in this publication are those of the authors, and they are not necessarily attributable to their organizations.

Author contributions
Each of the listed authors provided the following valuable contributions to the study: W.J.S. conceptualized and designed the methodological approach, collected the data, developed and applied the Spatial Pathways Algorithm, performed the data analysis and wrote the original draft paper. W.J.-W.S. supported the conceptualization of, and reflection on, the methodological approach, and aided in writing the original draft paper. B.v.d.B. supported the conceptualization of, and reflection on, the methodological approach, and aided in writing the original draft paper. M.K.J. was responsible for regional validation and interpretation of model outputs and provided part of the data on the effect of laser land leveling on irrigated wheat production. S.D. supported the interpretation of pathways outcomes for sustainable development, and reviewed and edited the final draft. A.L. supported the interpretation of pathways outcomes for sustainable development, and reviewed and edited the final draft. W.I. reviewed and edited the final draft, and supervised the research project. F.L. supported the conceptualization of the methodological approach, edited the final draft, and supervised the research project. H.B. supported the conceptualization of the methodological approach, edited the final draft, and supervised the research project.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01070-3.

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Peer review information *Communications Earth & Environment* thanks Joao Paulo Moura and the other anonymous reviewer(s) for their contribution to the peer review of this work. Primary handling editor: Martina Grecequet. A peer review file is available.

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