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The Impacts of Climate Variability on Crop Yields and Irrigation Water Demand in South Asia

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Abstract: Accurate (spatio-temporal) estimation of the crop yield relation to climate variables is essential in the densely populated Indus, Ganges, and Brahmaputra (IGB) river basins of South Asia for devising appropriate adaptation strategies to ensure regional food and water security. This study examines wheat (*Triticum aestivum*) and rice (*Oryza sativa*) crop yields' sensitivity to primary climate variables (i.e., temperature and precipitation) and related changes in irrigation water demand at different spatial (i.e., province/state, districts and grid cell) and temporal (i.e., seasonal and crop growth phase) scales. To estimate the climate driven variations in crop yields, observed and modelled data applying the Lund-Potsdam-Jena managed Land (LPJmL) model are used for six selected study sites in the IGB river basins over the period 1981–2010. Our statistical analysis underscores the importance of impacts assessments at higher spatio-temporal scales. Our grid cell (aggregated over study sites) scale analysis shows that 27–72% variations in wheat and 17–55% in rice crop yields are linked with temperature variations at a significance level of $p < 0.001$. In the absence of irrigation application, up to 39% variations in wheat and up to 75% variations in rice crop yields are associated with precipitation changes in all study sites. Whereas, observed crop yields show weak correlations with temperature at a coarser resolution, i.e., up to 4% at province and up to 31% at district scales. Crop yields also showed stronger sensitivity to climate variables at higher temporal scale (i.e., vegetative and reproductive phases) having statistically strong negative relationship with temperature and positive with precipitation during the reproductive phase. Similarly, crop phase-specific variations in climate variables have considerable impacts (i.e., quantity and timing) on irrigation water demand. For improved crop water planning, we suggest integrated climate impact assessments at higher spatio-temporal scales which can help to devise appropriate adaptation strategies for sustaining future food demand.

Keywords: climate variability; crop growth phases; irrigation; crop yield

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1. Introduction

South Asia, including India, Pakistan, Nepal, and Bangladesh, is one of the most densely populated agrarian regions in the world. Agriculture provides 70% of the livelihood in India [1] and 66% in Pakistan [2] with more than 45% of the land is already in use as cropland [3]. Multiple and double cropping systems are often used in the region to produce the desired food demand during the two main cropping seasons i.e., kharif (June–September) and rabi (November–March) with wheat (*Triticum aestivum*) as a major crop sown in rabi and rice (*Oryza sativa*) in kharif [4–6]. Agriculture contributes 21% of the gross domestic product (GDP) in Pakistan [7], 14% in India [8], 29% in Nepal and 16% in Bangladesh. The agriculture sector consumes up to 91% of the total water use in South Asia [9]. Water availability and demand in the region are highly variable within and between the years [10,11]. Water availability in the region is dominated by monsoon rainfall, which originates from the Bay of Bengal and ends in the western part of South Asia, and accounts for 60–90% of the total annual precipitation [12]. India receives approximately 87% of its annual total precipitation during the monsoon season [13], Pakistan receives 55–60% [14], Bangladesh 72% [15] and Nepal 80% [16]. This spatiotemporal gradient of precipitation determines the seasonal distribution of irrigation water availability and demand in the region [4].

The irrigation system in the Indo-Gangetic Plain is the World's largest water system on Earth [17], encompassing more than 40% of the total cropped area in the region [18]. Up to 70% of the total agricultural production in India is from irrigated land [19]. Agricultural production in Pakistan is largely dependent on irrigation water [20] and consumes 90% of the water withdrawals for food production [21]. The surface water and groundwater resources are commonly used for irrigation purposes in the region [22]. A large part of the kharif season crop water demand in Bangladesh, India and Nepal is fulfilled by monsoon rainfall. Whereas, agricultural production in the rabi season is mostly supported by groundwater extractions [23]. Groundwater extraction is largest in India exceeding 230 km^3 annually and about 85% of these withdrawals are used for agricultural production [9,22,24]. However, in Pakistan, most of the agriculture production during the kharif season depends on water either from snow and glacier melt or from groundwater resources, whereas, during the rabi season, it mostly depends on groundwater extraction [4,25–27]. Hence, any changes in the monsoon onset or the meltwater cycle can cause serious problems to food production in the region [28]. Human interventions (irrigation water withdrawals) have already caused discernible impacts on the hydrological cycle [29]. On top of that, land use change and climate change have revealed additional negative impacts on the agricultural production in most of the arid and semi-arid regions of South Asia [30–33]. Moreover, the region is already water-stressed and declared as a climate change hotspot [34].

An increase in climate variability (natural variations (changes) in the climate variables) within and between years is inevitable, with substantial shifts in monsoon onset, precipitation frequency, intensity and, hence, change in the water cycle in South Asia [35]. Increased climate variability not only causes floods and droughts, and changes water availability patterns, but also affects net crop production by influencing biochemical and metabolic processes [36,37]. In some regions, extreme high temperatures have a strong negative impact on crop growth and development [38–41] thus reducing yields significantly by shortening of the growing season length. Yield loss is even larger if extreme temperatures (both high and low) coincide with sensitive crop growth phases e.g., the reproductive phase [42–45]. Water stress (droughts or floods) is another critical climatic driver, which may cause major crop yield loss in Asia [46,47]. As inter-annual variations in crop yields are largely impacted by climate variability [48,49], detailed knowledge of crop yield sensitivity to climate variables and associated changes in crop water demand are crucial to assure a sustainable and increased future food supply in the region [50,51].

Multiple-cropping patterns and rapidly growing technological advancement in the field of agronomy have increased the crop production many folds in the region [52] However, to achieve a further sustainable increase in crop yields, implementation of long-term appropriate adaptation measures are required to reduce crop yield vulnerability to changing climate [48] Various studies have been conducted to assess the impacts of changing climate on irrigation water availability and use by crops [53,54]. A few studies have focused on estimating the crop specific seasonal irrigation water demand in South Asia [4]. Moreover, studies on crop yield sensitivity to int(e)r(a)-annual variations in climate variables and associated changes in crop water demand in South Asia are still limited. Therefore, our main research question is: "To what extent is the variation in irrigated crop yields and irrigation water demand determined by int(e)r(a)-annual climate variability?". Our hypothesis is that variability in yield and water demand strongly depends on climate variations in the most sensitive crop growth phases. To analyse this, the following sub-questions are addressed:

- In which growth phases are crops most sensitive to climate variations?
- What is the relationship of climate variables with yield and irrigation water demand during sensitive crop growth phases?

In this study, the relationship of irrigated crop yield and irrigation water demand sensitivity to climate variables at seasonal (sowing to harvest) and crop phase specific scale have been estimated in the Indus, Ganges and Brahmaputra (IGB) river basins. We used observed yield statistics and a crop-water model (LPJmL) for our analysis.

2. Material and Methods

2.1. Study Area

The Indus, Ganges and Brahmaputra river basins (Figure 1a) drain surface areas of around 1,116,000 km^2, 1,001,000 km^2, and 528,000 km^2, respectively, and represent a range of diversified hydroclimatic, topographic, and cultural contexts [9]. The Indus river basin spreads over parts of China, India, Afghanistan and Pakistan and is surrounded by high altitude mountains of which more than 50% is above 4000 mean above sea level [55,56]. The Indus River system is the largest source of fresh water (153 BM^3 year^{-1}) for Pakistan [57]. The Ganges-Brahmaputra (GB) river basins are the world's third-largest freshwater system and host more than 700 million people [58]. Water availability in GB river basins is highly seasonal, mainly nourished by monsoon rainfall in summer.

Impacts of climate variables on irrigated crop yields and irrigation water demand variations are evaluated for the major wheat and rice-producing study sites from East to West in the lower parts of IGB river basins. The analysis was carried out at four aggregation levels i.e., the national level for Nepal and Bangladesh, the sub-national level for India and Pakistan (state and province level, respectively), district level (major wheat and rice producing districts in Punjab Pakistan) and at the grid cell level (i.e., 5 arc-minute resolution aggregated over national and sub-national level for the selected study sites) of the model. At a national level, only the Terai region of Nepal in the Ganges basin and the Bangladeshi districts i.e., Nilfaman, Laimomohat, Kurigram, Rangpur, Gaibandha, Bogra, Sirajgang, Halughat and Phulphar in the Brahmaputra river basin are considered. Figure 1a shows the five selected districts in Punjab Pakistan and main six study sites at national and sub-national level i.e., Punjab Pakistan (PunjabP), Punjab India (PunjabI), Haryana (HAR), Uttar Pradesh (UP), Terai region Nepal (NPL) and Bangladeshi districts (BAN) in the IGB river basins.

There is a range of temperature and precipitation gradient from East to West and from North to South in seasons (Figure 1b–e). Usually temperatures are negative (−6 to −22 °C) in the upper parts of the IGB river basins throughout the year with a substantive rain during rabi season (Figure 1d). Monsoon rains dominate during the kharif season in the IGB river basins and decrease gradually from East (>4000 mm) to West (100 mm) (Figure 1e). Distribution of the rain pattern (monsoon rainfall and snow glacier melt) in location and time determine the rainfed and irrigated crops cultivation in the region.

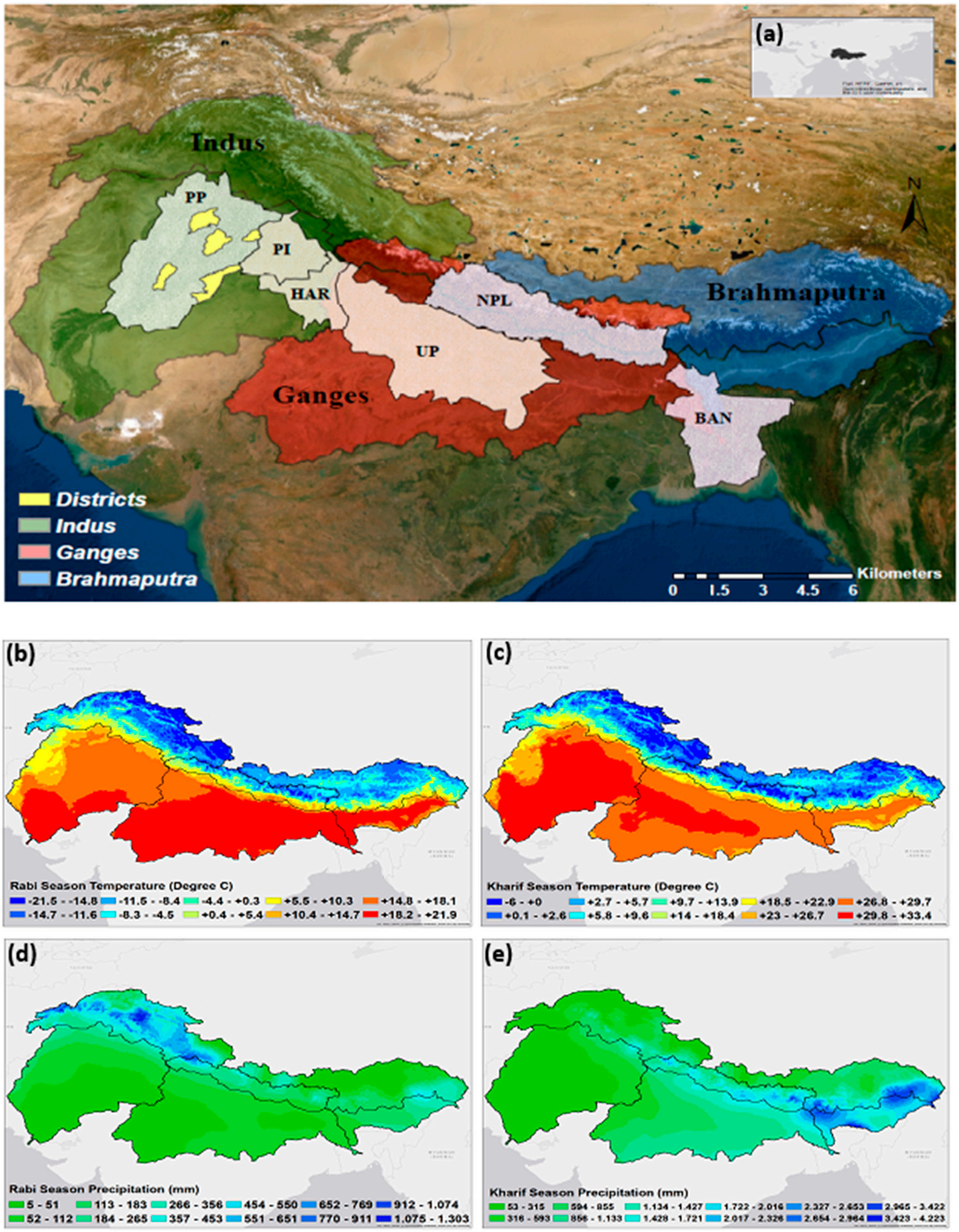

Figure 1. Area map showing upper and lower parts of the Indus, Ganges and Brahmaputra (IGB) river basins with selected study sites including districts in Punjab province Pakistan, Punjab Pakistan (PP), Punjab India (PI), Haryana (HAR), Uttar Pradesh (UP), Terai region Nepal (NPL) and Bangladeshi districts (BAN) (**a**), 30 years mean rabi season temperature (°C) (**b**), 30 years mean kharif season temperature (°C) (**c**), 30 years mean rabi season precipitation (mm) (**d**) and 30 years mean kharif season precipitation (mm) (**e**) maps during 1981–2010 over whole IGB river basins. Climate data (i.e., temperature and precipitations) at 5 arc-min spatial resolutions has been acquired from HI-AWARE data archive, particularly developed for the IGB river basins [59].

2.2. Data

2.2.1. Yield Statistics and Literature Review

To estimate the relationship strength of crop yields with climate data for the selected study sites at the province and state level, wheat and rice yield statistics for the period 1981–2010 have been acquired from Food and Agriculture (FAO) crop yield archives (http://www.fao.org). To investigate the importance and need of higher spatial scale, crop yield relationship with climate variables has also been investigated at districts level only for Punjab Pakistan. For this, yields statistics of major wheat and rice producing districts of Punjab Pakistan are acquired from the Pakistan Bureau of Statistics (PBS) report (http://www.pbs.gov.pk) of the year 1981–1982 to 2008–2009. Observed climate data of seasonal temperature and precipitation of the same districts are taken from the Pakistan Meteorological Department (PMD) for the period 1981–2009.

Crop yield sensitivity to climate variables during certain crop growth phases has been identified based on a literature review. There are main four crop growth phases starting from crop sowing to harvest. These phases include initial/ seedling, vegetative, reproductive and ripening phases. The initial phase consists of sowing, initial seedling/germination and transplantation phases. The vegetative phase consists of tillering and stems elongation phases. The reproductive phase consists of booting, heading and flowering phases. Ripening phase consists of milky, dough and grain maturity phases. All phases span a period of certain length which depends on phenological heat units required to complete a specific phase. In this section, we specifically reviewed the impacts of heat and water stress on crop production throughout the cropping season, particularly focusing on climate-sensitive crop growth phases. We have used a number of keywords to search the relevant literature, i.e., sensitive crop growth phases of wheat and rice crops, heat stress on crop production, impacts of climate variability on crop production, climate extremes and yield losses in South Asia etc. We have reviewed more than seventy papers published in international journals and included findings from twenty-five papers in our study mainly from South Asian countries.

2.2.2. Lund-Potsdam-Jena managed Land (LPJmL-3.5.003) Model Simulated Data

To analyse the impacts of climate variables on crop yields and irrigation water demand at higher spatiotemporal scale, process-based hydrological and vegetation Lund-Potsdam-Jena managed Land (LPJmL) model has been used. LPJmL simulates key ecosystem processes such as photosynthesis through coupled carbon and water fluxes [60–62], carbon allocation, evapotranspiration and phenology development of 9 plant functional types (PFTs) [62], and of 12 crop functional types as agricultural crops (CFT's) [60]. The model includes explicit representation of human impacts on water resources through irrigation water demand, withdrawals and supply [63] and dams/reservoir operation [64]. The LPJmL model has already been widely used, also for IGB river basins, to assess water availability and requirements for food production under changing climate [65–67], effects of precipitation uncertainty on river discharge [10], terrestrial vegetation and water balance evaluation [68] and simulation of cropping systems using climate-dependent sowing dates [69]. Recent development includes the implementation of double cropping system to estimate crop specific seasonal irrigation demands [4] and water saving potentials by the implementation of different irrigation systems [70].

Considering the complex hydro-meteorological dynamics and multi-cropping patterns in South Asian, the modified and calibrated model version adjusted for south Asian terrain has been used [4]. This model version includes improved spatial resolution i.e., from 0.5 degrees to 5 arc-min, high resolution gridded climate dataset developed for the IGB river basins [59], representation of a groundwater reservoir with groundwater withdrawals and groundwater depletion rates, representation of large scale irrigation through extensive canal systems [9]. Model has been well tested and calibrated in the IGB river basins by representation of multi-cropping with zone-specific monsoon dependent sowing dates for both kharif and rabi season [4].

In the LPJmL modelling setup, temperature and water supply through precipitation are the two main drivers responsible for the crop development and growth [60]. LPJmL simulates crop phenological development from crop emergence (0) to maturity (1) using a thermal model known as Phenological Heat Unit (PHU) [60,71–73]. In LPJmL, irrigation occurs daily and is calculated as the minimum amount of water needed to fill the upper two soil layers to field capacity plus the amount needed to fulfil the atmospheric demand [63].

For this paper, the LPJmL model is forced with a bias-corrected, statistically downscaled gridded climate dataset of daily mean air temperature, daily total precipitation, net longwave and downward shortwave radiation datasets at 5 arc-min spatial resolution for a period of 30 years from 1981–2010 over the whole IGB river basin area. This dataset is specifically developed for the IGB river basins based on the WATCH Forcing data ERA-Interim (WFDEI) [59]. Additionally, the model requires several non-climatic variables as listed in Table 1.

Table 1. List of climatic and non-climatic input variables.

Climatic and Non-Climatic Input Variables						References
Climatic Variables (Dynamic)						
Variable	**Unit**	**Frequency**	**Resolution**	**Data Availability**	**Domain**	
Average Temperature	°C	Daily	5 arc-min × 5 arc-min	1981–2010	IGB	[59]
Precipitation	mm	Daily	5 arc-min × 5 arc-min	1981–2010	IGB	[59]
Long wave Radiation	W m^{-2}	Daily	5 arc-min × 5 arc-min	1981–2010	IGB	[59]
Short wave Radiation	W m^{-2}	Daily	5 arc-min × 5 arc-min	1981–2010	IGB	[59]
Non-climatic variables (Static)						
Land use MIRCA2000 dataset including: coordinates, country code and land use type of rainfed and irrigated agricultural land						[73]
Soil type and soil characteristics based on Harmonized World Soil Dataset (HWSD) soil dataset						[74]
Drainage direction, stream network and void fill digital elevation model (DEM) for river routing using HydroSHEDS dataset						[75]
Dams and reservoirs information (location, purpose and capacity) using Global Reservoirs and Dams Database (GRanD)						[76]
CO_2 concentration (ppmv) using global annual mean CO_2 values						[4]
Zone specific monsoon dependent dates for rice in kharif and 1st November for wheat crop in Rabi						[4]
Representation of irrigation canal network						[70]

Simulation Protocol

The LPJmL model is first run to establish an equilibrium between the carbon pools (soil and vegetation) and water fluxes (i.e., soil and surface water). For this, the model is run for two spin-up periods i.e., 1000 years with natural vegetation and 300 years with land use, using daily climate input of WFDEI with the repeated climate of the years 1901–1930. Subsequently, the model is run separately for wheat and rice crops using crop-specific seasonal land-use information. For wheat, in the rabi season, 1st November is used as a single sowing date throughout the study domain. For rice in the kharif season, zone-specific monsoon dependent sowing dates are used [4]. In our modelling setup, the irrigation system (i.e., surface irrigation) and the crop sowing dates remained the same throughout the simulation period and no other management and adaptation options were taken into account.

To estimate the impacts of temperature and precipitation variations on crop yield production and irrigation water demand, the LPJmL model is run using two different irrigation options i.e., no irrigation (INO) and potential irrigation (IPOT). The INO option assumes that the crop water requirement is met by precipitation only. Whereas, under the IPOT option, an unlimited amount of water is available for irrigation from different sources i.e., lakes, reservoirs and groundwater resources to fulfil the crop water requirement. Impacts of temperature variations on crop yields are estimated using IPOT model run output, whereas for analysing precipitation variation impacts on yields, the output from two model runs is combined. From both model runs, crop yields only from irrigated crop land areas is used.

Phenological Development Phases

To extract the crop phase specific temperature, precipitation and irrigation water demand data, we used the crop and location-specific phenological development variable simulated by LPJmL. In LPJmL, the crop phenology value ranges from 0 at sowing to 1 at maturity [60]. Figure 2 shows the three main phenological development phases i.e., vegetative, reproductive and ripening over the growing season.

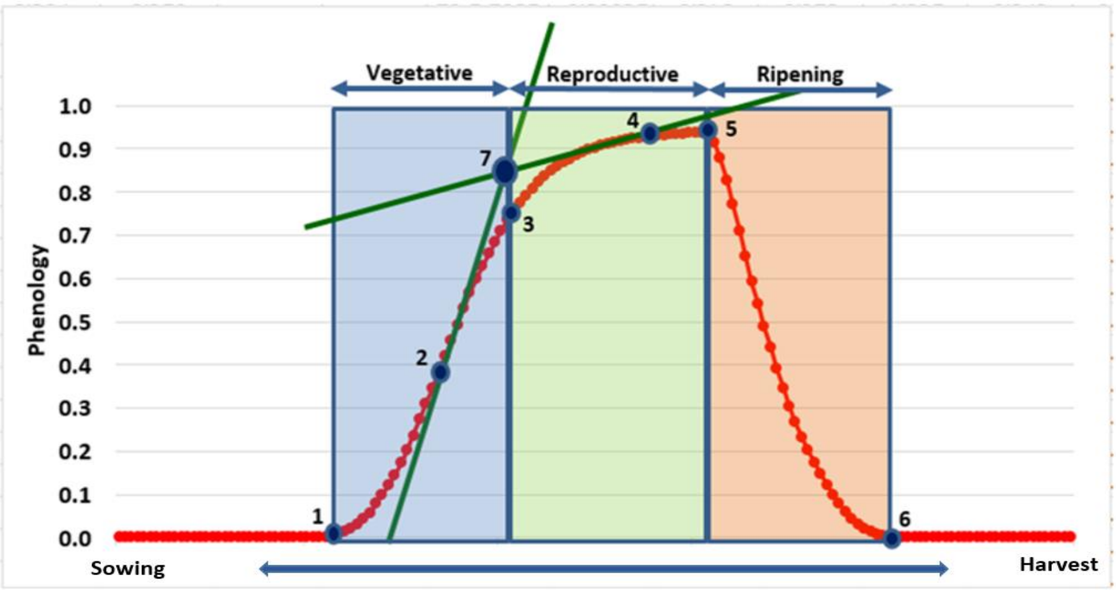

Figure 2. Phenological development phases (See text for explanation of the numbers).

To define the length of the different phenological crop growth phases, that is year, location and crop-specific, we developed an arbitrary method that could be applied consistently over the region and the years for the different crops (Figure 2). We estimated the length of a crop growing period as the number of days with the phenological values above 0.001, i.e., days between point 1 to point 6 for each year, each crop and each location. The start of the vegetative phase was taken as the day when the phenological value rises above 0.001, i.e., point 1. To determine the end of the vegetative and start of the reproductive phase (point 3), we calculated the slope of the phenological curve at two points, i.e., first, at the point where the phenology curve shows the maximum slope value during the rising part of the curve (point 2) and second, at the point ten days before the phenology curve reaches its maximum value (point 4). The point of intercept of the lines from these two slopes (point 7) represents the end day of the vegetative and start of the reproductive phase (point 3). The end of the reproductive phase is taken as the day when the phenology value starts to drop (point 5). The end of the ripening phase is taken as the day when the phenology value becomes less than 0.001 (point 6 in Figure 2).

For each year and each grid cell, crop-specific start and end dates of each phenology phase were used to extract crop-specific temperature, precipitation and irrigation water demand data for the different phenology phases using a script developed in R version 3.6.1.

2.3. Analysis

To estimate the crop yield sensitivity to climate variables at different spatial (i.e., province/state, districts and grid cell) and temporal (i.e., seasonal and crop growth phase) scales over the period 1981–2010, seasonal wheat and rice crop yields data from yield statistics (i.e., Food and Agriculture Organization (FAO) for provinces and states in the IGB river basins and Pakistan Bureau of Statistics (PBS) for districts in Punjab Pakistan) and LPJmL model (at grid-cell scale aggregated over province, states in IGB river basins) are used. The LPJmL model is used which is well tested and calibrated over IGB river basins [4,9]. Observed climate data at district level is acquired from Pakistan Meteorological Department (PMD). However, for province level analysis, statistically downscaled climate data at 5 arc-min spatial resolution is used from HIAWARE project [59]. The grid cell (aggregated at province level) scale irrigation water demand data at two temporal scales (i.e., seasons and crop growth phases) are used from LPJmL model simulations. The model was especially used to analyse the relationships at higher spatial and temporal scales (i.e., grid cells and daily time steps) than for which yield statistics are not available.

To compare climate-driven variations in the observed yields, existing long term technological and management changes and trends influencing observed crop yields are removed using a regression model [77]. We applied a linear regression model where the detrended yield is considered the result of climate variability mainly [78]:

$$dtYLD_{obs} = YLD_{obs} \; - prYLD_{obs} \tag{1}$$

where $dtYLD_{obs}$ is the detrended observed yield, YLD_{obs} is the original observed yield and $prYLD_{obs}$ is predicted observed yield which is obtained by multiplying the time factor with slope of the trend line.

Due to observed climate and yield data limitations (spatial and temporal coverage), we are looking in to the changes in relationship strengths between climate variables, crop yields and crop water demand at different spatial and temporal scales. The crop yield relationship with climate variables at province and state level has been estimated using observed and LPJmL model simulated data.

To analyse the relationship of climate variables with crop yields and irrigated crop water demand, first we computed the area-weighted average seasonal crop yields (i.e., wheat and rice) cultivated over irrigated areas of the selected study sites. We have also estimate the area-weighted average seasonal and phase-specific climate variables (i.e., temperature and precipitation) and irrigation water demand over six study sites. The relationship between climate variables and crop yield is estimated using Pearson correlation coefficient (r) [79] as given:

$$r\;(tavg\;,\;YLD) = \frac{\sum_{i=1}^{n}(tavg - \overline{tavg}) \times (YLD - \overline{YLD})}{\sqrt{\sum_{i=1}^{n}\left(tavg - \overline{tavg})\right)^2 \times \sum_{i=1}^{n}\left(YLD - \overline{YLD})\right)^2}} \tag{2}$$

$$r\;(prec\;,\;YLD) = \frac{\sum_{i=1}^{n}(prec - \overline{prec}) \times (YLD - \overline{YLD})}{\sqrt{\sum_{i=1}^{n}\left(prec - \overline{prec})\right)^2 \times \sum_{i=1}^{n}\left(YLD - \overline{YLD})\right)^2}} \tag{3}$$

where $tavg$, $prec$ and YLD are the temperature, precipitation and crop yields and $\overline{tavg}$, $\overline{prec}$ and $\overline{YLD}$ are mean of temperature, precipitation and crop yields respectively. The statistical significance of the relationship (p-value) is also estimated at three different significance levels i.e., $p < 0.001$ or 99.9% confidence level (***), $p < 0.01$ or 99% confidence level (**), $p < 0.05$ or 95% confidence level.

To what extent the variation in crop yields and irrigation water demand is determined by climate variables, the Coefficient of determination (R^2) is estimated. For this, we used a linear regression model (by checking the linearity of our data first, we decided to assume a linear relationship for the investigated ranges for all data as demonstrated by the scatter plots) and the least square method to estimate the relationship between climate variables (independent) and crop yields (dependent) [80]. Based on our linear regression results, we have calculated the coefficient of determination which presents how much variations (%) in crop yields is caused by the climate variables.

3. Results

3.1. Crop Yield Sensitivity to Climate Variables at Different Spatial Scales (Observed Data)

To assess, to what extent the variations in crop yield are determined by climate variables and to investigate the importance of spatial scale, crop yield sensitivity to climate variables has been evaluated at two spatial scales. First, at the province and state level for the six selected study sites in the IGB river basins (Table 2) and second for five selected districts in Punjab Pakistan as given in Table 3. The climate-induced variations in crop yields are estimated using the coefficient of determination (R^2). Table 2 shows the correlation coefficient (r) and coefficient of determination (R^2) calculated between crop yields and climate variables. R^2 explains percentage variations of both wheat and rice crops yield explained by temperature and precipitation over six study sites.

Table 2. Correlation coefficient (r) and Coefficient of determination (R^2) in % calculated between detrended observed wheat and rice yields based on FAO statistics with statistically downscaled temperature and precipitation over six study sites in the IGB river basin during 1981–2010 period. Bold numbers show the strong correlation, i.e., more than 0.30 between crop yields with climate variables.

States	Wheat Yield vs. Temperature and Precipitation				Rice Yield vs. Temperature and Precipitation			
	Temperature		Precipitation		Temperature		Precipitation	
	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)
Punjab Pakistan	0.10	0.9	**−0.46**	20.8	0.08	0.7	−0.02	0.0
Punjab India	−0.06	0.4	−0.09	0.8	0.13	1.7	0.15	2.2
Haryana	−0.17	2.9	−0.28	7.7	−0.14	1.8	0.10	1.0
Uttar Pradesh	−0.08	0.6	−0.18	3.1	−0.13	1.6	−0.07	0.4
Nepal	0.06	0.4	0.02	0.0	−0.12	1.3	**0.35**	11.9
Bangladesh	−0.20	4.0	0.03	0.1	−0.03	0.1	−0.05	0.2

Table 3. Correlation coefficient (r) and Coefficient of determination (R^2) in % calculated between observed wheat and rice yields based on PBS yields with observed temperature and precipitation in five major wheat and rice producing districts in Punjab Pakistan during 1982–2009 period. Bold numbers show the strong correlation, i.e., more than 0.30 between crop yields with climate variables and star shows the statistically significance level.

Districts	Wheat Yield vs. Temperature and Precipitation				Rice Yield vs. Temperature and Precipitation			
	Temperature		Precipitation		Temperature		Precipitation	
	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)
Bahawalnagar	**0.52** **	26.9	−0.06	0.4	0.13	1.6	−0.17	2.7
Faisalabad	**0.55** **	30.7	0.04	0.2	0.23	5.3	0.31	9.8
Lahore	**0.54** **	28.7	−0.46	21.3	−0.01	0.0	−0.23	5.5
Multan	**0.37**	13.5	−0.01	0.01	0.04	0.1	0.08	0.6
Sargodha	0.23	5.5	−0.29	8.4	0.04	0.2	0.30	9.1

** sign indicates significant at 0.01 level of significance.

Observed data analysis revealed that weak correlation of crop yields with temperature (i.e., ranges from −0.20–0.10 for wheat and −0.14–0.13 for rice) and precipitation (i.e., ranges from −0.46–0.03 for wheat and −0.07–0.35 for rice) which vary largely between seasons and locations. Estimation of crop yield variations caused by climate variables at a coarse spatial resolution does not indicate a strong relationship, as only a small proportion of variance in observed yield is explained by the climatic variables. Weak correlations between crop yields and climate variables at coarser spatial scale i.e., province and states, may be linked with averaging out of the climatic variations. Table 2 illustrates that both wheat and rice yields show a weak relationship with temperature and precipitation for different study sites at the sub-national scale (i.e., correlation values of six study sites in Table 2). For wheat crop in the rabi season, 3%, 8% and 21% variations are caused by precipitation in Uttar Pradesh, Haryana and Punjab Pakistan. Whereas, small (up to 4%) variations in wheat yield in Bangladesh are linked with temperature changes with no impacts of precipitation changes in Eastern IGB river basin. For rice, less than 2% variations are associated with temperature changes with no significant impacts of precipitation on rice yield during the kharif season, except in Nepal, where 12% variations in rice yields are linked with precipitation variations.

To explore the importance of climate impact assessments at higher spatial scale, crop yield relationship with climate variables has also been evaluated at district scale. For this, only those wheat and rice crop producing districts in Punjab Pakistan have been selected, which had a reliable and common length of meteorological weather station data. Table 3 shows the statistical analysis based on correlation coefficient and coefficient of determination for seasonal (wheat and rice) crop yields and climate variables over the period 1982 to 2009 for five districts in Punjab Pakistan.

Estimation of crop yields variation linked with climate variables at comparatively higher spatial scale (i.e., districts compared to province) show the relatively stronger relationship (Table 3). Temperature variations in winter explain a relatively large share of the wheat crop yield fluctuations (up to 30%) in all districts. Precipitation does not explain much of the variations in both cropping seasons except in Lahore and Sargodha where about 20% and 8% variation in wheat yield is linked with precipitation variations respectively during the rabi season. Weak relationship of both wheat and rice yields with precipitation (i.e., ranges from −0.46–0.04 for wheat and −0.23–0.31 for rice) is obvious, as precipitation variation during crop growing season are supplemented by irrigation water supply.

Our results suggest that rabi yield variations are strongly impacted by temperature variations as compared to variations in precipitation (i.e., 5% to 31% by temperature and 0.01% to 8% by precipitation). On the other hand, precipitation variations show a relatively larger contribution to rice yield variations as compared to temperature fluctuations. On average, a maximum of 21% variations in wheat yield is explained by temperature, whereas, only 6% variations in wheat yield are explained by precipitation variation in the selected districts of Punjab Pakistan. Similarly, 2% and 5% variations in rice yields can be explained by temperature and precipitation variations respectively.

3.2. Crop Yield Sensitivity to Climate Variables at Higher Spatio-Temporal Scale (Simulated Data)

Crop yield sensitivity to climate during sensitive crop growth phases has been assessed through a literature review as summarized in Table 4.

Table 4. Wheat and rice crops sensitivity to heat and water stress during crop growth phases based on literature review. It is pertinent to mention here that booting, heading and anthesis/flowering are sub-stages of reproductive phase. Whereas, milky, dough and grain filling are sub-stages of ripening phase.

Crop	Sensitive Crop Growth Phase	Climate Variable	Potential Reasons and Threats to Crop Yields	Region	References
Wheat	Flowering and grain-filling	Temperature	Considerable loss in grain yield	Global	[81]
Wheat	Reproductive	Temperature	Higher temperatures during reproductive stage leads to crop yield loss	India, China	[82]
Wheat	Reproductive	Temperature	High temperatures during reproductive phases result in a significant acceleration of leaf senescence due to oxidative damage induction in plants	Global	[83,84]
Wheat	Booting and grain-filling	Temperature and water stress	Heat stress experienced around flowering can have large negative impacts on cereal grain yields. Water stress cause decrease in leaf area index, crop growth rates and dry matter accumulation	Pakistan	[85]
Wheat	Anthesis/flowering and milky seed	Heat stress (temperature)	Wheat crops exposure to 35–40 °C during anthesis stage reduced yield up to 75%.	Pakistan	[86]
Wheat	Grain filling	Temperature	Wheat crop yield is highly sensitive to higher temperature during grain filling stage i.e., every 1 degree rise in temperature can reduce 7–8% of crop yield	South Asia	[87]
Wheat	Growing season	Temperature	Every 1 °C rise of temperature can reduce 4–5 million tons yield	India (Indo Gangetic Plane)	[88,89]
Wheat, rice	Anthesis and grain filling	Temperature	Heat stress during anthesis results in floret abortion and pollen sterility during the reproductive phase. Indeed, at the reproductive and grain- filling stages, an increase in temperature will reduce the time required for assimilate translocation, which reduces grain yield	South Asia	[90]
Wheat, rice	Flowering	Temperature	Extreme heat stress during flowering stage caused decreased pollen viability and stigma deposition, leading to increased grain sterility.	Pakistan	[91]
Wheat, rice	Reproductive	Temperature	Crop exposure to extreme temperatures (both hot and cold) particularly during sensitive stages of the crop cycle (e.g., the flowering or reproductive stage) can cause physiological damage and lead to crop failure	Global	[43]
Rice	Flowering	Heat stress	Higher night time temperatures (beyond 22 °C) negatively affect grain yield due to altered pollen germination and enhanced spikelet fertility	India, South Asia	[92,93]
Rice	Flowering	Temperature	Yield reduction, Season-long heat stress can reduce photosynthesis and accelerate senescence	IGB	[47]
Rice	Flowering, booting and grain filling	Water Stress	Soil water deficit during flowering and grain filling reduces yield and quality	Global	[94]

Table 4. *Cont.*

Crop	Sensitive Crop Growth Phase	Climate Variable	Potential Reasons and Threats to Crop Yields	Region	References
Rice	Vegetative, flowering and grain filling	Water stress	Water deficit during vegetative, flowering and grain filling stages reduced yield. Water stress at vegetative stage effectively reduced total biomass due to decrease of photosynthesis rate and dry matter accumulation.	Iran	[46]
Rice	Growing season	Temperature and water stress	Temperature and water availability above or below optimal threshold ranges for longer duration cause a huge yield	India	[95]
Rice	Reproductive and grain-filling	Temperature	Higher temperatures at anthesis and grain formation cause poor anther dehiscence and panicle sterility can substantially reduce grain yields	South Asia	[90]
Rice	Gametogenesis/ flowering	Heat stress	Heat stress during flowering stage affects the pollen viability and hence affects the yields	South Asia	[93]
Rice	Reproductive and ripening	Heat and water stress	Extremely high temperatures and lack of water can cause complete sterility, while high temperatures during ripening can lead to reduced grain filling and poor milling quality (i.e., more broken grains) and can have reduced rice yields—by as much as 10% for every 1 degree increase in minimum temperature.	Asia	[96]
Rice	Vegetative and reproductive	Heat stress	Heat stress affects the overall crop development and growth process by accelerating the crop maturity	Bangladesh	[39]
Rice	Anthesis and grain filling	Temperature	Combination of high temperature and low light may seriously affect grain weight and percentage of filled spikelet.	Global	[41]

From Table 4, it is evident that the flowering and grain-filling phases are considered as the most vulnerable phenological phases to temperature thresholds (which remain conservative over phases and location) [41,84] and water stress during rice and wheat cropping periods [97]. Heat stress reduces pollen viability and stigma deposition during flowering and leads to increased grain sterility and hence reduces yield. Droughts or water shortage cause stomatal closure which affects the carbon dioxide and oxygen ratio in the leaves and consequently reduces the photosynthesis process, which is a major factor responsible for net yield losses in plants [98].

The crop yields sensitivity to climate variables at higher spatial (grid cell level aggregated for study sites) and temporal (intra and crop growth phases) scales has been assessed using simulated gridded crop yields (cultivated over irrigated areas) and climate data. Season (i.e., rabi and kharif) and location-specific simulated wheat and rice crop yields in tons per hectare (T ha^{-1}) under the two irrigation options, i.e., IPOT and INO, have been used to correlate with the seasonal (sowing to harvest) temperature and precipitation (see Table 5).

Table 5. Crop yield sensitivity to climate variables using LPJmL model simulated data over six study sites in the IGB river basins during the period 1981–2010. Bold numbers show the strong correlation, i.e., more than 0.30 between wheat and rice crop yields with climate variables and star shows the statistically significance level.

States	Wheat Yield (Rabi Season)				Rice Yield (Kharif Season)			
	Temperature		Precipitation		Temperature		Precipitation	
	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)	Corr (r)	R^2 (%)
Punjab Pakistan	**−0.63** ***	40.0	**0.34**	11.0	**−0.74** ***	55.0	**0.82** ***	67.0
Punjab India	**−0.52** **	27.0	−0.18	0.0	**−0.68** ***	47.0	**0.81** ***	65.0
Haryana	**−0.56** ***	32.0	0.0	0.0	**−0.51** **	26.0	**0.87** ***	75.0
Uttar Pradesh	**−0.67** ***	45.0	0.14	0.0	**−0.72** ***	52.0	**0.43** ***	18.0
Nepal	**−0.85** ***	72.0	**0.57** ***	33.0	**−0.41** *	17.0	−0.25	0.1
Bangladesh	**−0.72** ***	52.0	**0.62** ***	39.0	**−0.73** ***	54.0	0.02	0.0

*, ** and *** signs indicate significant at 0.05, 0.01 and 0.001 level of significance, respectively.

To estimate the crop yield sensitivity to temperature, simulated yields from IPOT run has been used. Whereas, to estimate the crop yield variations associated with precipitation variations, yields from INO run has been used. Under IPOT run, the impacts of precipitation variations on crop yields are compensated by supplying an unlimited amount of water as irrigation. Consequently, the temperature is the main driver to explain variations in both wheat and rice crops yields under IPOT run. Both wheat and rice crop yields show strong negative and statistically significant ($p < 0.05$, bold values) correlations with temperatures (Table 5). These correlations are relatively higher for rice crop during kharif season in all study sites except in Nepal where rabi temperature shows a stronger negative correlation with wheat crop i.e., Pearson correlation coefficient (r) of values −0.85 with 99.9% confidence interval. The negative correlation supports the results in literature stating that crop exposure to long term extreme temperatures (both hot and cold) particularly during sensitive crop growth phases (e.g., the flowering or reproductive phases) can cause physiological damage and lead to crop failure [85,88,89]. In our study area, the degree of relationship strength varies for different study sites (i.e., −0.41 to −0.74 for rice in kharif season and from −0.52 to −0.85 for wheat in rabi season). R^2 explains that 17 to 55% variations in rice crop yields are linked with kharif temperatures, whereas, 27 to 72% variations in wheat crop yields are associated with rabi temperatures. These estimates reveal that wheat crop yields are more sensitive to temperature variations than rice crop yields. Precipitation variations also play a vital role in crop yield variations between the seasons and location. Precipitation variations in rabi show low to medium level correlation (i.e., r from 0 to 0.62) with wheat yield. However, for rice in kharif, precipitation shows a strong positive correlation that ranges from 0 to 0.87. Kharif precipitation shows strong positive and significant relationship with rice crop ($p < 0.001$) for most of the selected study sites. Table 5 shows that 65 to 75% variations in rice crop yields of Eastern study sites of Indus river basins i.e., PunjabP, PunjabI and Haryana could be attributed to precipitation variations in kharif.

Crop yield sensitivity to climate variables at higher temporal scale (crop growth phases) has also been estimated over six study sites using simulated data (i.e., crop yields and climate variables). Table 6 shows wheat and rice yields relationship with temperature and precipitation for climate-sensitive crop growth phases (i.e., vegetative, reproductive and ripening phases).

Crop phase-specific temperatures show a strong but negative correlation with both wheat and rice yields. Both wheat and rice yields show a stronger relationship ($p < 0.05$) with reproductive phase temperatures i.e., r from −0.33 to −0.86 and −0.33 to −0.71 respectively. The degree of relationship strength varies for each location in both cropping seasons but with the higher and consistent crop yield sensitivity to the reproductive phase temperatures. Wheat yield shows large sensitivity ($p < 0.001$) to reproductive phase temperature variations as compared to rice almost for all sites. After reproductive phase, vegetative phase stands the second most sensitive crop growth phase for both wheat and rice crop. Similarly, both wheat and rice yields show higher sensitivity to the precipitation variations during the reproductive phase followed by vegetative phase particularly for rice. Crop yields sensitivity to phase-specific precipitation variations vary largely for each study site in the IGB river basins.

Table 6. Time series Correlation and Coefficient of Determination (R^2 in %) of simulated wheat (**a**) and rice (**b**) crop yields with crop phase-specific temperatures and precipitation over six study sites in the IGB river basins during the period 1981–2010. Bold numbers show the strong correlation, i.e., more than 0.40 between wheat and rice crop yields with crop phase-specific climate variables and star shows the statistically significance level.

(a)	**Correlation (R^2 in %) of Wheat Yield (Rabi Season)**					
States	**Phase-Specific Temperature**			**Phase-Specific Precipitation**		
	Vegetative	**Reproductive**	**Ripening**	**Vegetative**	**Reproductive**	**Ripening**
Punjab Pakistan	**−0.42** (17.0) *	**−0.79** (63.0) ***	−0.02 (0.0)	**0.66** (43.0)	**0.51** (26.0)	**0.53** (28.0)
Punjab India	−0.26 (07.0)	**−0.61** (37.0) ***	−0.02 (0.0)	0.27 (7.0)	**0.66** (43.0)	0.18 (03.0)
Haryana	**−0.43** (18.0) **	**−0.75** (56.0) ***	0.02 (04.0)	0.26 (7.0)	**0.66** (44.0)	0.01 (0.0)
Uttar Pradesh	**−0.52** (28.0) **	**−0.85** (72.0) ***	−0.13 (0.01)	**0.46** (21.0)	**0.75** (56.0)	−0.04 (0.0)
Nepal	−0.72 (52.0) ***	**−0.86** (73.0) ***	−0.01 (03.0)	**0.43** (18.0)	**0.49** (24.0)	0.35 (12.0)
Bangladesh	−0.32 (10.0) *	−0.33 (11.0) *	−0.26 (0.0)	0.34 (11.0)	−0.12 (01.0)	−0.35 (12.0)*
(b)	**Correlation (R^2) of Rice Yield (Kharif Season)**					
States	**Phase-Specific Temperature**			**Phase-Specific Precipitation**		
	Vegetative	**Reproductive**	**Ripening**	**Vegetative**	**Reproductive**	**Ripening**
Punjab Pakistan	**−0.59** (35.0) ***	**−0.61** (38.0) ***	−0.38 (14.0) *	**0.45** (20.0)	**0.77** (59.0)	0.19 (04.0)
Punjab India	**−0.57** (32.0) ***	**−0.54** (30.0) ***	**−0.48** (23.0) **	**0.45** (21.0)	**0.72** (52.0)	**0.41** (16.0)
Haryana	**−0.43** (18.0) **	−0.39 (15.0) *	−0.33 (11.0) *	**0.58** (33.0)	**0.71** (50.0)	**−0.53** (28.0) **
Uttar Pradesh	**−0.61** (37.0) ***	**−0.71** (50.0) ***	0.04 (0.0)	**0.68** (46.0)	0.39 (15.0)	**−0.52** (27.0) **
Nepal	−0.08 (01.0)	−0.33 (11.0) *	−0.31 (09.0) *	−0.20 (04.0)	−0.18 (03.0)	−0.15 (02.0)
Bangladesh	**−0.54** (29.0) **	**−0.66** (44.0) ***	**−0.62** (39.0) ***	**0.50** (25.0)	**0.58** (34.0)	−0.03 (0.0)

*, ** and *** signs indicate significant at 0.05, 0.01 and 0.001 level of significance, respectively.

3.3. Impacts of Climate Variables on Irrigation Water Demand

The impacts of int(e)r(a)-annual variations of climate variables on crop-specific irrigation water demand have also been investigated over seasons (Figure 3) and during sensitive crop growth phases (Figure 4). Figure 3 shows the crop-specific seasonal irrigation water demand by wheat and rice crops and their relationship with seasonal (sowing to harvest) temperature and precipitation over six study sites for the period 1981–2010.

LPJmL model output of the potential irrigation run is used to estimate the crop-specific irrigation water demand by wheat and rice for all study sites. Irrigation water demand by rice is large as compare to the wheat water demand for all study sites (Figure 3a,b). Spatial and quantitative distribution of irrigation water demand by crops is dependent on water availability from precipitation in the region [4]. Figure 3c,d show the relationship of crop-specific seasonal irrigation water demand with temperature and precipitation over the entire growing season length. Figure 3c reveals that both temperature and precipitation are mainly negatively correlated with the wheat irrigation water demand i.e., higher temperature and precipitation will lead to lower irrigation water demand. Therefore, any rise of temperature and precipitation during the rabi season will lead to a decreased irrigation water demand by wheat. It is evident that an increase in precipitation will reduce the requirement for irrigation. Less evident is the negative relationship of temperature with water demand. Two processes may cause this negative relationship. First with temperatures well above optimal temperatures, the early crop maturing and speedy growth and by that the evaporation will reduce [39]. Secondly a decrease in water demand maybe caused by the beneficial effects of CO_2 on plants, shortening the growing season length [99]. Our results also describe shortening of the growing season length with temperature increase and hence reduced seasonal irrigation water requirements. Furthermore, we found that increased precipitation reduces water demand from irrigation. The decrease in crop water demand from irrigation in response of increased precipitation is also reported by Konzmann et al. [99]. However, climate variables show a mixed behaviour with rice irrigation water demand for the study sites. Higher temperatures during the kharif season lead towards higher irrigation water demand due to higher atmospheric water demand and thus evaporation [39]. Whereas, more water availability from precipitation reduces the water required from irrigation.

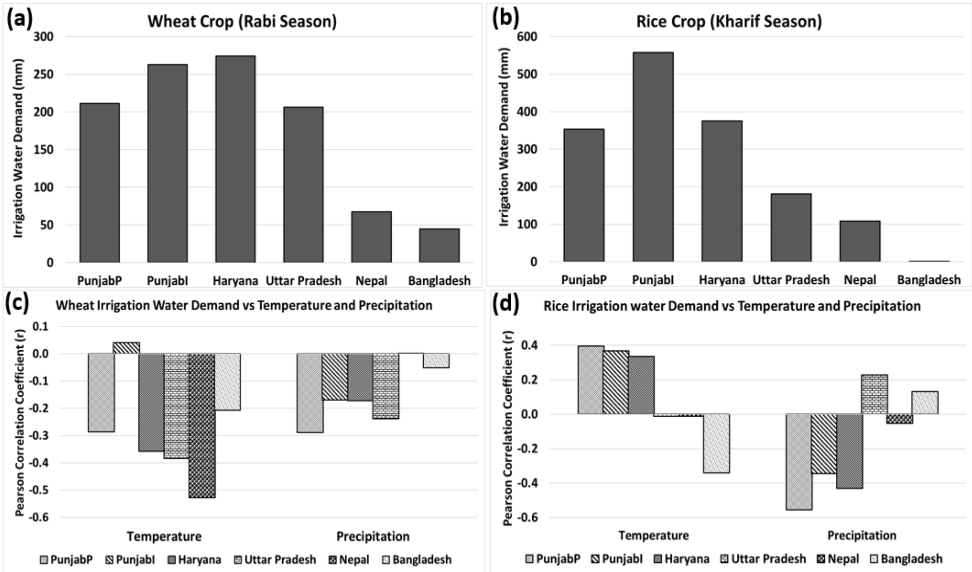

Figure 3. Crop−specific seasonal irrigation water demand (mm) by wheat (**a**) and rice (**b**) crops and their relationship with temperature and precipitation (**c**,**d**) estimated over six study sites in the IGB river basins during period 1981–2010.

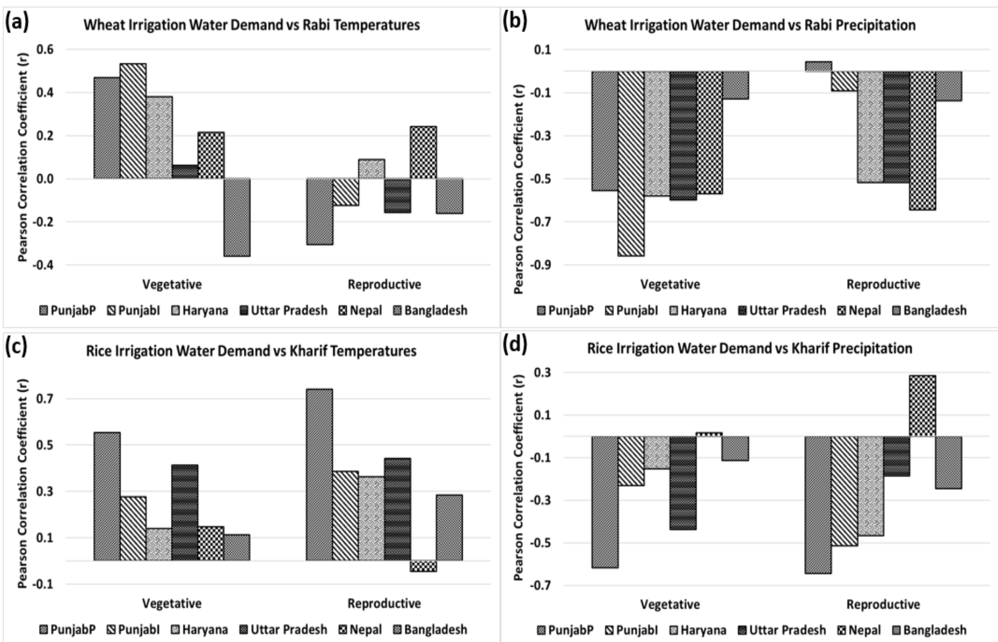

Figure 4. Time series correlation of phenological phase specific irrigation water demand with temperature and precipitation in all selected study sites during period 1981–2010. The upper panels (**a**,**b**) show the correlation bars of irrigation water demand with temperature (**a**) and precipitation (**b**) during the vegetative and reproductive phase of wheat crop in rabi season. Panels (**c**,**d**) show the correlation bars of irrigation water demand with temperature (**c**) and precipitation (**d**) during the vegetative and reproductive phase of rice crop in kharif season.

Impacts of climate variables on irrigation water demand by crops have also been assessed at higher temporal scale (i.e., during sensitive crop growth phases). Pearson correlation coefficient (r) between phenological phase-specific irrigation water demand by both wheat and rice crops and temperature and precipitation has been calculated for all study sites during period 1981–2010.

The irrigation water demand is mainly positively correlated with temperatures by both crops in both phases i.e., vegetative and reproductive except during reproductive phase of the wheat crop where it shows a mixed relationship (*r* between −0.3 and 0.3) (Figure 4a,c). Results also show that impacts of crop phase-specific temperatures on irrigation water demand are stronger in most cases during the reproductive phase of rice in the kharif season (up to 0.74 correlation coefficient value) varying largely from East to West in the IGB river basin. During the reproductive phase of rice in the kharif season, up to 55% variation (R^2) in irrigation water demand is linked with the reproductive phase temperature in Punjab Pakistan, however, in Nepal and Bangladesh temperature variations do not affect rice crop water demand too much. Figure 4b,d show that crop phase-specific precipitation is negatively (−0.13 to −0.86 and 0 to −0.62 during the vegetative phase of wheat and rice, respectively) correlated with the irrigation water demand of both crops in all study sites. Negative relationships show that higher precipitation will lead to less crop water requirements from irrigation. The strength of the crop phase-specific relationship is different for all study sites which is explained by the geographical hydro-climatic heterogeneity.

4. Discussion

The climatic variations play a vital role in crop development and growth but show a varying degree of relationship strength by season and location. A number of theoretical, modelling and empirical studies have already estimated the impacts of climate variability on crop yield fluctuation using different methodology and datasets at annual, seasonal and regional to national scales [39,98,100]. These studies suggested a range of climate variability impacts on crop production. For example, a recent study reported that approximately 33% variations in observed global yields are caused by inter-annual climate variability. Whereas, in some agriculture intensive worldwide areas at national scale, >60% yield variability is linked with temperature and precipitation variations [80]. Estimation of crop yield sensitivity to climate variability depends on several factors i.e., spatial and temporal scale, data length for analysis, methods used etc. It should be noted that crop yield variations can also be caused by other non-climatic parameters i.e., irrigation scheduling, land-use conditions, edaphic variables (e.g., soil characteristics), crop varieties, pests etc. [101,102]. The impact of these variations are not taking into account in our simulations with the LPJmL model, but are inherent part of the observed yield data and should have been consider to compensate the negative impacts of climatic conditions [103]. Integrated crop water assessments at different spatial scales are crucial to guide farmers, researchers, stakeholders and policy maker to understand, investigate and plan sustainable strategies of crop production in climate hotspot countries [104]. In our study, we analyzed the crop yield relationships with climate variables at low spatial and temporal resolution often used by policy makers. By using a higher resolution both in space and time we demonstrated the impact of climate variability during sensitive crop growth phases on yield. These higher resolution results may better prepare framers and water managers for increased climate variability than the coarser resolution impact assessments for policy makers. In the next sections we discuss the sensitive crop growth phases and the impact of climate variability on yield and water demand. The last section discusses the limitations of our study.

4.1. Crop Yield Sensitivity at Different Spatial Scales

Our results of reported yield's sensitivity to climate variables revealed that temperature and precipitation are not the only drivers to cause any substantial change in crop yield production. At larger spatial scale (i.e., province and states), both observed wheat and rice reported yields show a weak relationship (up to 21%) with seasonal precipitation and even weaker links with temperature (Table 2). At coarser spatial scale i.e., province and states, weak correlations between crop yields and climate variables may be linked with averaging out of the climatic variations. Crop yield variations showed relatively stronger relationships (up to 30%) with climate variables when investigated at a smaller spatial scale i.e., districts in Punjab province Pakistan (Table 3). At district scale, both crops, particularly wheat, show strong association with temperature variations. The low correlations and flat slopes of the observed data at province level clearly show the influence of other non-climatic factors and the averaging out effect of variations as to be expected at this coarse resolution (see Table 2). Although, the correlations are low, the direction of the slopes of observed data and simulated data are in the same direction at the province level.

Santiago et al. [103] also reported crop yield fluctuations are responding stronger to temperature trends i.e., up to 12%, than precipitation trends i.e., up to 2% (in case of wheat crop yields, see Figure 2 of [103]. In this study, the authors used panel models to evaluate the impact of growing season precipitation (P), average temperature (T) and diurnal temperature range (DTR) on historical period yield trends in wheat, maize and soy crops from 33 counties of the Argentine Pampas region in South America. The stronger impacts of temperature variations on rice yield variation, as compared to precipitation, has also been reported in Bangladesh. The limited impact of precipitation variations are caused by the already high water availability and irrigation use [80]. The variations in the strength of the correlations between yield and climate variables varies between regions (i.e., districts, province and states). This variation may be associated with local climate conditions (thresholds and patterns), crop variety used and size of the area under consideration for analysis. Poor correlation values −0.14 to 0.13 (Table 2) could also be caused by averaging out location and time specific variations.

Our modelling results show that crop yield variations are strongly associated with climatic variations with a statistically strong relationship ($p < 0.001$) when estimated at grid cell (aggregated over the study sites) scale (Table 5). Strong correlations of modelled yield and climate variables at province and state level are associated with the fact that temperature and precipitation are the main drivers in our modelling setup to cause any change in crop production. In our modelling setup, the irrigation system (i.e., surface irrigation), crop sowing dates and any management and adaptation options (irrigation efficiency, crop variety, pesticides etc.) remained constant. Hence, a statistically relatively strong relationship of simulated wheat and rice yields is observed with both temperature and precipitation. Our results indicate that 27–72% variations in wheat yields and 17–55% variations in rice yields are linked with temperature variations. The correlation strength varies from one location to another which might be associated with the size of the irrigated land in the selected study sites.

Continuous higher temperatures and precipitation variability throughout the wheat and rice crop growing seasons can negatively affect crop production [82]. Studies estimate that 3–10% (4–5 million tons) wheat yield loss in the Southern and Eastern parts of Asia are linked with 1 °C rise in temperature [87,103]. Similarly, increasingly higher temperatures caused a huge loss in rice crop production in the Indo Gangetic Planes and Sri Lanka [95,105].

The impacts of precipitation variations on crop yields are generally compensated by supplying water as irrigation [4]. In our modelling results, up to 39% variations in wheat and up to 75% variation in rice yields in six study sites are linked with precipitation variations in the absence of additional water supply. Relatively weak correlations of wheat (PunjabP, PunjabI and Haryana in Indus) and rice (Uttar Pradesh, Nepal and Bangladesh in Ganges and Brahmaputra river basins) yields with precipitation variations results from the yield dependency on irrigation application. Wheat crop production in the IGB river basins is mainly irrigated, and therefore, shows a weak non-significant relationship with precipitation in most of our study sites. However, for rice crop, during the kharif season, an ample amount of water is available from precipitation in the IGB river basins. This seasonal precipitation pattern leads to a relatively strong and significant ($p < 0.001$) relationship of rice yield with precipitation in our study sites. The strength of these correlations depends largely on the local climatic and soil conditions which varies with location from East to West and between seasons.

Our statistical analysis results revealed that the crop yield variations are associated with climate variables with much stronger correlations at higher spatial scales i.e., at grid cell level. This is depicted by the high correlation values up to 72% variations in wheat yield and up to 55% variations in rice yields influenced by temperature and up to 39% variations in wheat and up to 75% variations in rice yields by precipitation in the selected study sites. Our modelling analysis results also revealed that temperature is the stronger driver to cause changes in both wheat and rice yields variations in the IGB region.

4.2. Climate Sensitive Crop Growth Phases

Increased climate variability particularly higher temperatures during sensitive crop growth phases can affect net crop production negatively by influencing biochemical and metabolic processes [37,106]. Also, water shortage during the flowering phase causes severe damages to rice yield by affecting the dry matter allocation to the harvestable storage organs [71,107,108]. Our literature-based analysis identifies that both wheat and rice yields are most sensitive to temperature and precipitation during the vegetative and reproductive crop growth phases (Table 4). Wheat yields show more sensitivity to temperature variations during both phases. Whereas, rice crop yields show stronger sensitivity to water stress during reproductive crop growth phase.

Studies revealed that crop exposure to heat and or water stress during the vegetative phase can lead to reduced crop production and poor grain quality. The reproductive phase including flowering/anthesis sub-stage is generally known as the more sensitive phase to temperature stress and can lead to irreversible loss in crop production [50,91,108–112]. Any extreme event (heat and or water stress) duirng these sesnsitive crop growth phases can have major implication on net crop production [82,89,113].

Our modelling results are generally in line with the published studies given in Table 2, where both wheat and rice crops show strong correspondence with the vegetative and reproductive phase climate variables. Further, our analysis revealed that both crops show a stronger relationship with temperature and precipitation during the reproductive phase. We also observed that other than vegetative and reproductive phases, both wheat and rice crops show significant, but fluctuating relationships (i.e., r from −0.35 to +0.53 for wheat and r from −0.53 to +0.41 for rice) with ripening phase precipitation for some states. These fluctuations could be associated with location and season specific climate and crop conditions. Similarly, Vijay et al. [114] also found the milk stage in the ripening phase as the more sensitive crop growth phase in wheat which can lead to reduced crop production. Our modelling results of crop yield sensitivity to phase-specific climate variables (based on Pearson correlation coefficient) suggest the need for time and location specific adaptation and management to cope with the uncertain climate variations. The sensitivity of crop yields with crop phase-specific temperature and precipitation varies differently in all study sites and seasons. The ranges of these variations correspond to the region-specific temperature and precipitation conditions that vary geographically [43].

4.3. Impacts of Climate Variables on Irrigation Water Demand during Sensitive Crop Growth Phases

Interannual climate variability is evident and its impacts on water availability in soil and plants are obvious globally with a substantial influences on irrigation water demand and supply in arid and semi-arid areas of South Asian countries [67,115–117]. Irrigation also plays a major role in cooling soil temperatures during crop's exposure to high temperatures [118]. The crop development and climate conditions determine the irrigation water demand in certain crop growth phases.

Our results of crop phase-specific (vegetative and reproductive) irrigation water demand by both wheat and rice show a strong and a varying relationship with phenological phase-wise temperature and precipitation (Figure 4). Irrigation water demand by wheat crop show mixed (mainly positive correlations during the vegetative phase and both positive and negative correlations during the reproductive phase) relationship with temperature (Figure 4a). Whereas, irrigation demand by rice crop mainly present a positive correlation with temperature in all study sites during both vegetative and reproductive phases (Figure 4c). The strong positive correlations during both vegetative and reproductive phases of rice crop during kharif season could be associated with the higher seasonal temperatures (Figure 4c). An increase in temperature causes a rise in evapotranspiration which will require higher irrigation water demand during different developmental phases. Crop phase-specific irrigation requirements depend on the length of crop growth stages which are ultimately related to temperature conditions [38,39]. However, irrigation water demand is generally negatively correlated with precipitation during both vegetative and reproductive phases of wheat and rice crop in all study sites (Figure 4b,d). An increase in precipitation reduces the crop water requirement from irrigation. A substantive decrease of 17 % in global irrigation water demand is reported due to the beneficial effects of CO_2 on plants, shortening of growing season length linked with climate change (warming) and regional precipitation increases [99]. The crop phase-specific correlations of climate variables with irrigation water demand by crops vary largely from East to West in seasons. For example, during vegetative phase of wheat crop, temperature is positively correlated with irrigation water demand in Punjab Pakistan. However, vegetative phase temperature show negative relationship with irrigation water demand by wheat crop in Bangladeshi districts. Similarly, precipitation during reproductive phase of rice crop show large range of correlation with irrigation water demand. Large range of correlation values of irrigation water demand with temperatures and precipitation are the result of the large-scale spatial distribution of monsoon precipitation patterns in the region [119]. Temperatures show strong impacts on irrigation water demand by rice crop during the kharif season with stronger and direct relationship during the reproductive phase (Figure 4c). Whereas, precipitation shows strong impacts on wheat crop irrigation demand (Figure 4b). During the crop growth period, when temperatures are well above optimal temperatures, it accelerates the crop maturity process and reduces net irrigation water demand [39].

To understand the impacts of intra-annual climate variability on crop yields, a good insight into the crop growth phase specific irrigation water demand and supply by different water sources will help in determining the potential adaptation options for sustained future food security.

4.4. Limitations of the Study

A number of uncertainties in our results (different correlations strengths of crop yields and climate variables using observed and modelled data at province level) can be associated with the model, data and methodology used. The model simulation are reasonably good on average [4,120], however, year- to year variability needs further improvement. Considering observed climate and yield data unavailability at higher spatial and temporal scales, we have used LPJmL model simulated data to estimate the relationships of climate variables with yield and water demand at higher spatio-temporal scale (i.e., grid-cell and crop growth phases). In the current simulations, climate variables are the main drivers to cause year to year yield variations with fixed land-use information, standard field/crop management practices, irrigation system (i.e., surface) and a single sowing date, i.e., 1 November for wheat in the rabi season and zone-specific monsoon dependent sowing dates for rice in the kharif season. In reality, climate variables are not the only driver to cause major changes to yield. Next to the uncertainties in the climate data [55,57] a number of uncertainties in our results could be associated with the model limitations i.e., use of constant crop varieties, year-wise management decisions, and impacts of diseases and pests [121,122]. Model skills can be improved by validating simulated results with observations at local scale. Uncertainties in the yields statistics and observed climate data analysis (FAO and PBS crop yields data) can also be attributed to the expected human errors involved in reported low-quality agricultural data sets and use of station data to represent the whole district's climate respectively [122]. Assessments of crop yield responses to climate using models such as LPJmL, maybe further improved by implementing changing land-use scenarios, year wise changing sowing dates, and irrigation systems with changing irrigation efficiencies.

5. Conclusions

The objective of this study is to improve understanding of the impact of int(e)r(a)-annual climate variability on crop yields and crop water demand from irrigation in selected study sites of the IGB river basins in South Asia during the historical period 1981–2010.

Our results confirm the importance of climate-related assessments in crop yields and irrigation water demand at higher spatial (grid cell aggregated over study sites area) and temporal (crop phenological phases) scales. The results confirm that climate variables (i.e., temperature and precipitation) play a major role in crop development and growth. However, the degree of crop yield relationship strength with climate variables varies largely between seasons and among locations. Crop yields (i.e., wheat and rice) show very low sensitivity to climate variables (i.e., up to 4% to temperatures and up to 21% to precipitation) when assessed at the province and state level using observed yield and climatic data. However, crop yield showed a little higher sensitivity to temperature (up to 32%) and precipitation (up to 20%) variations at higher spatial scale i.e., districts level in Punjab Pakistan.

Simulated wheat and rice yields at 5 arc-min spatial resolution aggregated over selected study sites show that 27–72% variations in wheat and 17–55% variations in rice yields are linked with temperature variations in the rabi and kharif cropping seasons, respectively. In the absence of irrigation application, precipitation variations also play a major role, i.e., up to 39% variations in wheat yield and up to 75% variations in rice yield are directly linked with precipitation changes in the IGB river basins. Statistically significant and strong negative correlations between temperature and wheat yield indicate that wheat crop is quite vulnerable to heat stress. Kharif precipitation shows a statistically strong and positive relationship with rice yield production, indicating that a change in monsoon onset and uncertain climate extremes can impact the rice yield productivity.

Estimation of crop yield sensitivity to temperature and precipitation at high temporal scale, i.e., crop phase-specific, reveals that both wheat and rice crop yields are highly sensitive to reproductive phase temperatures (i.e., Pearson correlation of r from −0.33 to −0.86 for wheat and −0.33 to −0.71 for rice respectively). We conclude that wheat yields are most vulnerable to increasing winter temperatures in the reproductive phase. In the absence of irrigation application, both wheat and rice crop yields show mainly a significant positive relationship with crop phase-specific precipitation for all study sites with the strongest correlation, however with a large range, during the reproductive phase −0.12 to 0.75 for wheat and −0.18 to 0.77 for rice. Our analysis confirms that the crop yield sensitivity to climate variables depends on time and space specific climatic conditions.

Timing and quantity of irrigation water demand are also strongly associated with the variations in temperature and precipitation. We observed that irrigation water demand by both wheat and rice are generally positively correlated with temperature in both climate-sensitive crop phases with an exception during the reproductive phase of wheat where it shows a mixture (both positive and negative) of correlations for different locations. Whereas, crop phase-specific irrigation water demand by both crops show a negative relationship with precipitation i.e., under increased precipitation scenarios, decreased irrigation projections are expected. This study shows that crop phase specific climate variables play a major role in crop yield fluctuations within and between the years and also drive irrigation water demand in quantity and time. Therefore, improved knowledge on the shifts in irrigation water availability and demand based on local soil and climate conditions during sensitive crop growth phases and possible impacts on crop yields of rice and wheat in the IGB river basin will support adaptation strategies to cope with projected climate change and socio-economic scenarios.

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