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A multi-sector multi-region economic growth model of drought and the value of water: A case study in Pakistan

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ABSTRACT

This study integrates ecohydrological vegetation and multi-sector multi-region economic growth models to evaluate the impacts of drought on markets and value the economic value of water. The values of several parameters of the agricultural production function are identified by applying leaf area indices that are simulated by the ecohydrological model, AgriCLVDAS. The three-sector three-region closed-economy model with the agricultural production functions of both irrigable and rainfed farmland as well as the stochastic process of precipitation and availability of river water are formulated to analyze the water rent as well as GDP growth in Pakistan under drought stress. According to the characteristics of the closed-economy model, the crop price is increased during drought periods because of the price hike in water (i.e., an increase in the marginal productivity of water, which is double that in high-water periods in Pakistan). The study further presents a way of investigating water resource management policies by applying comparative dynamics.

1. Introduction

Clean and sufficient water supplies are vital for all communities, industries, and ecosystems for drinking, farming, sanitation, and energy production. Yet, the world's water systems face formidable threats. UNESCO [1] estimates that around 700 million people in 43 countries suffer from water scarcity and predict that "by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water stressed conditions."

As agriculture is the largest consumer of freshwater resources, it is the most directly and widely exposed to random fluctuations in precipitation, the negative side effect of which is drought. Drought transforms from "meteorological drought" to "hydrological drought" and "agricultural drought," which finally causes deficiency in the supply of drinking water and crops. Losses for humans usually emerge as the shortage of agricultural crops. However, while meteorological drought, hydrological drought, and agricultural drought are assessed quantitatively in meteorology, hydrology, and agriculture, respectively (e.g. Refs. [2,3]), quantitative evaluations of the economic impacts of drought are limited, resulting in a lack of understanding about investing in facilities to reduce drought risks. The evaluation of drought damage is difficult because of the indirectness of damage. In other words, unlike disasters such as floods, earthquakes, and volcanic eruptions that directly destroy household assets, production facilities, and infrastructure, drought damage is revealed in society only when individuals realize that the consumption bundle has been reduced because the decrease in the availability of water and crops has spread to other sectors and regions through the input/output structure of the economy. That is, impacts on final consumption depend on the market equilibrium, which includes the trade in intermediate goods. Hence, a market equilibrium model is required to evaluate drought damage likely to occur in the future. Moreover, developing agricultural countries must understand the impact of drought risk and effects of mitigation policies on economic

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growth. Against this background, the present study formulates a multi-sector multi-region economic growth model under drought stress and applies it to simulate economic growth in Pakistan.

The approach of this study is characterized by the following two processes. First, we utilize the simulation output data of leaf area index (LAI) generated by a state-of-the-art ecohydrological model to identify the values of parameters of the agricultural production function. LAI is defined by the one-sided area of green leaf per unit ground area. The indicator that is composed of the simulated LAI data can be seen as a good proxy of regional crop production. Second, we introduce the economic value of water for agricultural use in a three-sector three-region closed-economy model.

Recently, the number of trans-disciplinary projects in the natural and social sciences has risen (e.g. Refs. [4–6]). In economics, although environmental and agricultural economics have focused on water-related problems, water has not been treated explicitly as an independent factor, mainly because its use is not reported in national economic accounts. However, model formulations and calibration methods are being developed in parallel with the increasing availability of various types of data (e.g. Ref. [7]).

For computable equilibrium models analyzing the impacts of decreases in the availability of agricultural products, it is convenient to apply production functions that are homogeneous of degree one, specifically constant elasticity of substitution (CES) functions associated with nested structures, where the factors of production in each layer have the same constant elasticity level. Varieties of nested structures exist. For example, Decaluwé et al. [8] apply a framework where one of two nests at the lowest level is composed of capital and land, whereas the other comprises water and fertilizer. In Gómez et al. [9], a nest of agricultural water is composed of energy and groundwater, which is combined with a land–capital composite to create a land–capital–agricultural–water composite on the upper layer. In addition, numerous studies deal with irrigation water, such as van Heerden et al. [10]. For instance, the TERM-Water computable general equilibrium (CGE) model applied by Peterson et al. [11] introduces irrigation water at the top level of the nested CES structure, while the TERM-H2O model applied by Dixon et al. [12] introduces water resources at the bottom of the nested CES production structure.

Some models are applied to analyze the roles of adaptation in adjusting to new climate conditions, such as the Future Agricultural Resources model of Darwin et al. [13] and Darwin [14]. However, this model does not distinguish between rainfed and irrigated crops. Because large parts of agricultural land are not irrigated, the share of irrigated land ranges from 4% of the total cropped area in Africa to 42% in South Asia [15]. As such, it is indispensable to include rainfed agriculture in explicit ways to analyze the impacts of drought risk. Consequently, one version of the GTAP-W model (e.g. Refs. [16–18]) distinguishes between irrigated and rainfed agriculture and explicitly introduces irrigation water to compose an "irrigable land–water composite" in a nested structure of their production function.

We follow the above-mentioned version of GTAP-W to separate irrigable and rainfed land as well as formulate the land–water composite; we also deal with water brought directly as precipitation to both irrigable and rainfed land and introduce the stochastic fluctuation in the volume of precipitation that causes drought when small. Our approach is enabled by the quantitative identification of precipitation risk using observed data, through which we can better quantify the impact of drought, as well as the benefit of improving irrigation infrastructure.

The most significant methodological contribution of this study is applying the LAI data simulated by a well-validated vegetation model named AgriCLVDAS, which follows the Coupled Land and Vegetation Data Assimilation System.[1] In AgriCLVDAS, LAI is calculated by solving the coupled dynamics of water and biomass cycles. The present study incorporates the LAI data for several representative crops over several periods introduced by the AgriCLVDAS model to calibrate the parameters of the land–water composites of irrigable and rainfed land in the agricultural production function. Because we can calibrate the parameters of the land–water composite at the intermediate level of the nested structure of the production function rather than at the final level, equivalent to the vegetation level, we can better verify the relationship between water and land as well as the impact of water scarcity on vegetation.

Regarding trans-disciplinary research on water and agriculture, how to make a nested structure of the agricultural production function crucially depends on insights into the substitutability of the production factors as well as data availability. Hence, the formulation of models evolves in response to meteorological innovations; the method this study proposes is inspired by AgriCLVDAS, which is specially designed for agricultural vegetation, and it makes the best use of the LAI data AgriCLVDAS calculates. Although some projects have adopted LAI data (e.g. Refs. [5,6]), they are not concerned with methods such as the one developed in this study.

A further contribution of this study is to value water rent on the market, namely the economic value of water, which varies according to the exogenous environmental conditions of water availability based on the agricultural production function calibrated with LAI data. In agricultural economics, an increasing number of studies focus on the levels of production and trade of crops, which are minutely classified; some of these apply supply/demand functions to describe water demand (e.g. Refs. [21–23]). While they do cover a wide range of agricultural products and regions, they apply a partial equilibrium framework that ignores the linkages between agriculture and the rest of the economy.

On the contrary, a large number of general equilibrium models have also been developed (e.g. Ref. [24]), most of which are static models (e.g. Refs. [25–32]), while some are dynamic [33–35]. For example, Robinson and Gueneau [36] combine the regional water system model with a dynamic CGE one to develop the CGE-W model, which they use to investigate the dynamic impact of shocks on water resource changes such as drought. Fang et al. [37] apply a Ramsey-type economic growth model to a multi-sector multi-region problem to examine the effects of water allocation policies on GDP, consumption, income, the labor/capital ratio, and prices of China. This study also adopts a dynamic framework, because it does not suffice to discuss the issues of developing countries by using static models that restrict our view to the equilibrium around a steady state, thus not reflecting the current environment of those societies. Dynamic frameworks better suit analyzing the long-term impacts of drought and investment in infrastructure such as drought mitigation facilities. We are further concerned that those impacts are not uniform among sectors and regions. Moreover, although cross-section cascading effects are initially given as a flow, they could decrease the savings that finally result in the deceleration of economic growth, particularly for countries that depend on agriculture. Furthermore, the industrial structure could change with economic growth because of the intensiveness of each factor of the production function. This study thus decomposes the macroeconomy into three regions, all of which include three sectors, and focuses on the difference in growth under drought risk

[1] Sawada and Koike [19] and Sawada et al. [20] simulate the vegetation of agricultural plants. The authors simultaneously develop an open-economy version of the economic growth model where the methodology of identifying agricultural production functions with LAI data was shared, although the valuation of water rents based on those agricultural functions was unique to this study.

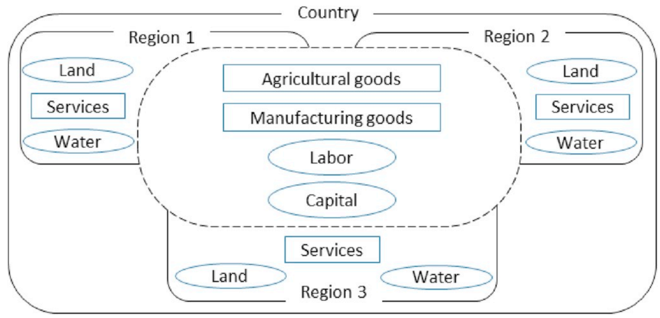


Fig. 1. Regions and markets in the model.

among sectors and regions.

Moreover, this study formulates a closed-economy model. By excluding international trade, the values of some variables cannot be identical to those in reality, while general equilibrium models, where all prices are determined endogenously, have inherent significance: they enable us to clearly analyze the structures of the impacts of drought on the marginal utilities of agricultural crops, marginal productivity of water, and other goods. While we do need to establish a way of pricing water, it is difficult to identify a specific method because of differences in data availability and practical experience [21]. This study therefore applies a general equilibrium framework and introduces the marginal value of water, which serves as a reference point for policy discussions on water resource management.

To summarize, this study is methodologically novel because it applies the simulation output LAI data, which are produced by the new ecohydrological model AgriCLVDAS, to identify the parameters of the agricultural production function, based on which the economic value of water is introduced in a perfectly competitive market in each stage of economic growth with stochastic precipitation. The framework is also used to analyze the impacts of drought and water resource management policies on economic growth by sector and region. The results will contribute to policy discussions on infrastructure planning such as investment in irrigation systems because, since those investments are costly, policies should be determined from a long-term perspective.

The remainder of the paper is organized as follows. In Section 2, we provide an outline of the model and present the formula of the land–-water composite. In Section 3, we apply the LAI data to calibrate the model and conduct a case study on Pakistan. In Section 4, we draw our conclusions and recommend further research topics.

2. Model

2.1. Environment

This section provides an outline of the model; full descriptions of formulas are given in Appendix A. The modelled economy is small, closed, and perfectly competitive, with three regions indexed by $i \in I = \{1, 2, 3\}$, where $i = 1$ will represent Punjab province, $i = 2$ Sindh province, and $i = 3$ the rest of Pakistan (ROP) in a case study in the next section. Each region produces three final goods/services indexed by $j \in J = \{a, m, s\}$, where a, m, and s represent agriculture, manufacturing, and services, respectively. Outputs are transacted in markets in the period in which they are produced. The agricultural and manufacturing goods produced in Region 1 are assumed to be perfect substitutes for the corresponding goods produced in Regions 2 and 3. As illustrated in Fig. 1, those two goods are mobile, and transportation is assumed to be

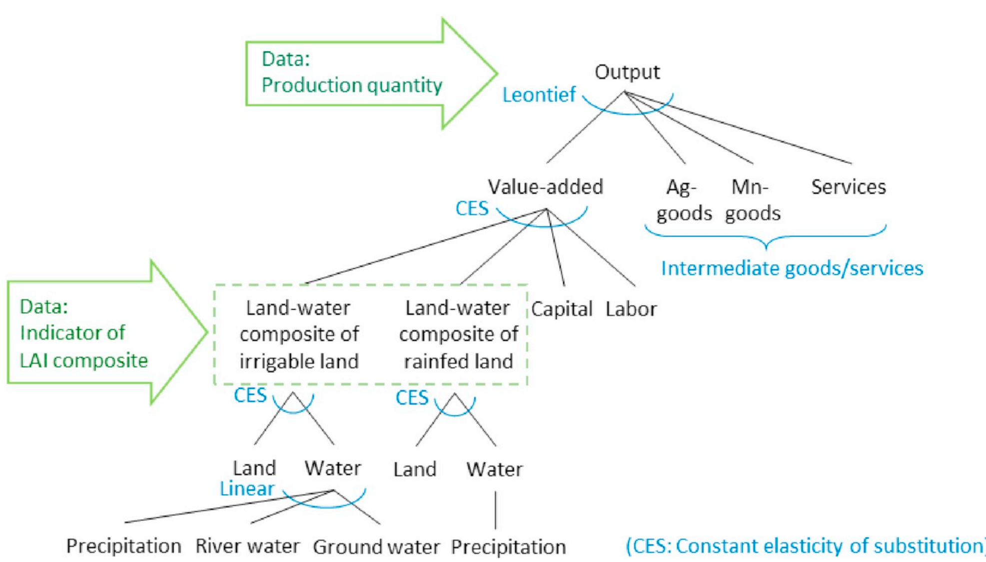
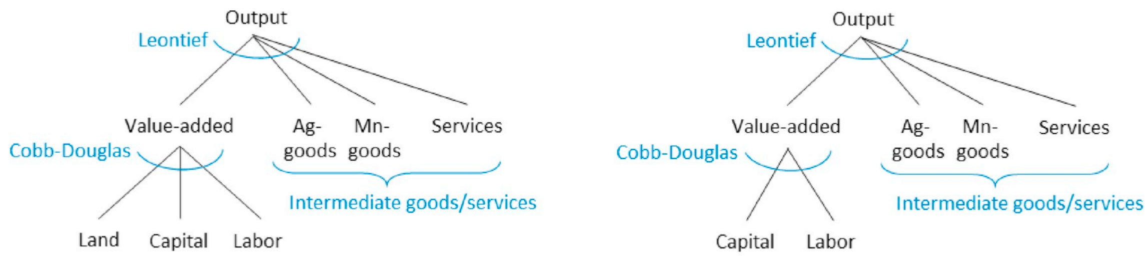


Fig. 2. Agricultural production technology.



(a) Manufacturing sector (b) Service sector

Fig. 3. Manufacturing and service production technologies.

costless, implying that the prices in all three regions are equal. On the contrary, the services produced in all three regions are immobile and not perfectly substitutable in the utility function, implying that each market is closed in each region and, generally, prices are different among regions. While agricultural goods and services are pure perishable consumption goods/services, manufacturing goods can be stocked and used for both consumption and capital accumulation.

Water resources are provided every period (year) as "manna" in the economy through precipitation, the amount of which is stochastic. For simplicity, we assume that the amount of available water in each period is exogenously given and cannot be stocked over periods as a basic setting. Later, we analyze the impacts of policies that improve the quality of irrigation systems, so that the agricultural sector can use larger amounts of water.

The labor and capital markets are open among the three regions, closed within a country, and perfectly competitive, with the wage rate and the interest rate determined endogenously. A representative adult person (worker) provides labor and capital and obtains wages and interest every period. Each worker provides one unit of labor inelastically in every period and population increases at a constant growth rate. Workers' savings are stored as capital to be rented by firms. Moreover, workers own land and water resources and obtain the rents generated by them.

2.2. Land–water composite

Production technologies of the three sectors are illustrated in Figs. 2 and 3; they are illustrated by nested tree structures of production functions of constant elasticity of substitution (CES), and therefore

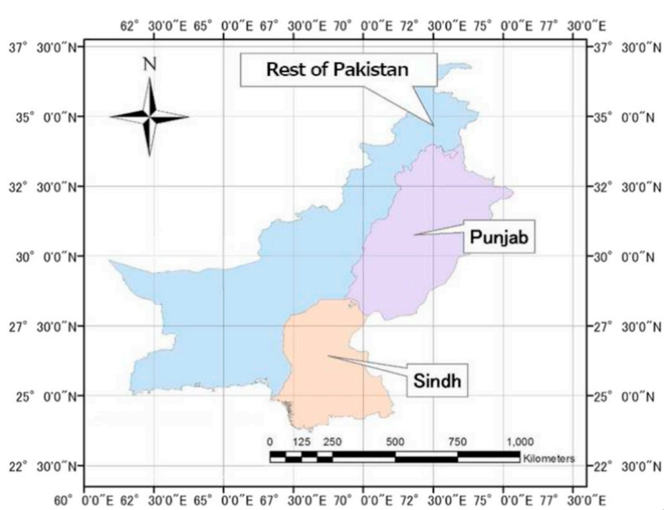


Fig. 4. Pakistan and three regions (Punjab, Sindh, and ROP).

exhibit constant-returns-to-scale.

The nested structure of the agricultural production function is the same as Calzadilla et al. [17] applied in their GTAP-W model. The agricultural sector inputs the land–water composite, $X_{hi}(t)$, in each period t, where we classify irrigable and rainfed land as indexed by $h \in H = \{1,2\}$, respectively. It is defined by a combination of land and water as follows:

$$X_{hi}(t) := \{\beta_{Thi} T_{hi}^{\alpha_{Xhi}} + \beta_{Zhi} Z_{hi}(t)^{\alpha_{Xhi}}\}^{\frac{1}{\alpha_{Xhi}}} \quad \text{for all } h, i, \tag{1}$$

where T_{hi} is crop acreage, given exogenously and held constant throughout the simulation. The amount of available water, $Z_{hi}(t)$, is given by

$$Z_{1i}(t) = Z_{1i}^{p}(t) + \Xi_i^s Z_{1i}^{s}(t) + \Xi_i^g Z_{1i}^{g}(t), \tag{2a}$$

$$Z_{2i}(t) = Z_{2i}^{p}(t) \quad \text{for all } i. \tag{2b}$$

In other words, the amount of available water for irrigable land, $Z_{1i}(t)$, is composed of three sources, namely water directly provided by precipitation, $Z_{1i}^{p}(t)$, water provided by river irrigation, $\Xi_i^s Z_{1i}^{s}(t)$, and water provided by groundwater irrigation, $\Xi_i^g Z_{1i}^{g}(t)$, where Ξ_i^s and Ξ_i^g are the performance levels of these irrigation systems, which are also treated as exogenous variables in the model. On rainfed land, water is supplied only by precipitation, $Z_{2i}^{p}(t)$. α_{Xhi}, β_{Thi}, and β_{Zhi} are parameters, and the elasticity of substitution between T_{hi} and $Z_{hi}(t)$ is given by $\sigma_{Xhi} := 1/(1 - \alpha_{Xhi})$.

Fig. 2 also indicates the two layers where we calibrate the model. While a conventional method only uses production quantity data, we also use the LAI composite data, which represents the level of $X_{hi}(t)$. Because we calibrate the parameters of the land–water composite at the layer in which it is defined, we can better specify the impacts of water on agricultural production. Further details are given in the next section.

We further assume the scale of precipitation and amount of available river water provided by canal irrigation in period t, $\psi(t)$ and $\psi^s(t)$ respectively, which are random variables that take a value out of the sets $\Psi = \{1, 2, \cdots, N\}$ and $\Psi^s = \{1, 2, \cdots, N\}$, respectively. $\psi(t)$ and $\psi^s(t)$ are positively correlated. The amounts of available water from precipitation in each respective region, $Z_{1i}^{p}(t)$ and $Z_{2i}^{p}(t)$ are determined as a function of the realized scale of precipitation, $\widehat{\psi}(t)$. Likewise, the amount of available river water, $Z_{1i}^{s}(t)$, is determined as a function of the realized scale of available river water, $\widehat{\psi}^s(t)$. "^" denotes the realized value of the random variables. In other words, $Z_{1i}^{p}(t)$ can take one value out of the set $\{Z_{1i1}^{p}, \cdots, Z_{1i\psi}^{p}, \cdots, Z_{1iN}^{p}\}$, which is identified by $\widehat{\psi}(t)$. $Z_{2i}^{p}(t)$ and $Z_{1i}^{s}(t)$ are similarly determined, while the available amount of groundwater, Z_{1i}^{g}, is assumed to be independent of precipitation and constant throughout. We assume that the stochastic paths of precipitation, $\{\psi(t)\}$ and available river water, $\{\psi^s(t)\}$, are stationary processes; in other words, the probability of each $\psi(t)$ and $\psi^s(t)$ are given by μ_ψ and μ_{ψ^s}, respectively, which are independent of period t. $\sum_{\psi=1}^{N} \mu_\psi = 1$ and $\sum_{\psi^s=1}^{N} \mu_{\psi^s} = 1$ hold.

Table 1
Precipitation scales and probabilities.

Scale of precipitation (ψ)	Probability of each scale (μ_ψ)	Precipitation (Z^p_{hi}) (km^3)					
		Irrigated land ($h = 1$)			Rainfed land ($h = 2$)		
		Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
1	5.26%	14.26	0.5004	0.6302	10.45	0.1798	4.437
2	22.8%	18.73	2.370	0.8186	13.73	0.8518	5.763
3	42.1%	23.20	4.240	1.007	17.00	1.524	7.089
4	28.1%	29.51	8.519	1.255	21.63	3.062	8.837
5	1.75%	35.82	12.80	1.503	26.26	4.599	10.58

2.3. Event sequence and market equilibrium

We apply the framework of the Solow model (e.g. Ref. [38]), where the savings rate is given exogenously and, therefore, a household's optimization is essentially static; this maximizes one-period utility by choosing the optimal consumption bundle in each period. Firms are also myopic, as they either maximize their one-period profits or minimize their one-period costs of production. The sequence of events in each period t is as follows:

1) The level of precipitation, $\widehat{\psi}(t)$, and available river water, $\widehat{\psi}^s(t)$, are determined, resulting in $\mathbf{Z}(t) := (\{Z^p_{1i}(t),\ Z^p_{2i}(t),\ Z^s_{1i}(t),\ Z^g_{1i}(t)\}_{i=1,2,3})$ being identified in each region, as well as the level of the land–water composite, $\mathbf{X}(t) := (\{X_{hi}(t)\}_{h=1,2,\ i=1,2,3})$. The economic environment in period t is given by the set of state variables, the total amounts of labor and capital in the economy and $\mathbf{X}(t)$.

2–1) Firms in the three sectors demand labor and capital, which are supplied by households via factor markets, and intermediate goods/services that are supplied by other firms in output markets, and provide the final goods/services. Those in the agricultural and manufacturing sectors maximize their one-period profits, while those in the service sector minimize their one-period costs of production.

2–2) Households allocate their labor and capital to the firms of the three sectors in factor markets, and purchase the bundle of final goods/services (agricultural goods, manufacturing goods, and a set of services) to maximize the one-period utility. The level of savings is determined as a fixed percentage of income.

2–3) All seven markets clear at the equilibrium; the wage rates, interest rates, prices of agricultural and manufacturing goods in the country, and prices of services in the three regions are determined.

3) The population increases and total capital changes because of savings. We move to the next period $(t+1)$, and the cycle restarts at 1).

This section introduced the key formulations and main structure of the model. Appendix A provides all details of the model setting, the optimization problems, and the equilibrium conditions.

Table 2
Scales of available amount of river water and ground water.

Scale of river water (ψ^s) and ground water	River water (Z^s_{hi}) (km^3)			Ground water (Z^g_{hi}) (km^3)		
	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
1	52.54	40.61	4.740	29.19	8.405	2.310
2	56.07	43.33	5.058	29.19	8.405	2.310
3	59.59	46.06	5.376	29.19	8.405	2.310
4	64.98	50.22	5.862	29.19	8.405	2.310
5	70.37	54.38	6.348	29.19	8.405	2.310

3. Case study

This section applies the model and simulates the growth process of Pakistan, as composed of three regions, which are defined as shown in Fig. 4. The base year is 2007, and the model proceeds in one year time steps.

3.1. Leaf area index and calibration

In this subsection, we calibrate the unknown parameters from Eq.(1), which illustrates the relationship between the amount of available water, $Z_{hi}(t)$, and the land-water composite, $X_{hi}(t)$, which is the amount of natural resources needed to obtain agricultural production. Since the ecohydrological model can simulate this relationship using physical principles, $Z_{hi}(t)$ and $X_{hi}(t)$ can be derived from the inputs and outputs of the ecohydrological model, respectively.

As mentioned in 2.2, the amount of available water is composed of precipitation, river water irrigation, and groundwater irrigation. Precipitation includes both rain and snow. Besides, agriculture in Pakistan highly depends on the irrigation water from Indus river. For precipitation, the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE; [39]) dataset is used for calibration.[2] By analyzing 57 years of precipitation data from APHRODITE, five scales of precipitation ($Z^p_{hi}(t)$) are set. Table 1 shows the scales of precipitation with respective probabilities in Punjab, Sindh, and the rest of Pakistan (ROP). The precipitation data are aggregated separately for irrigable and rainfed land. The distributions of irrigable land and rainfed land are obtained from the dataset provided by Cheema and Bastiaanssen [42]. River water irrigation data are provided by the Water and Power Development Authority (WAPDA). By analyzing the data from 2002 to 2010, five scales of river water irrigation ($Z^s_{hi}(t)$) are determined (Table 2). The ground water irrigation values used in this study was estimated by Cheema et al. [43]. Because a long-term record of ground water irrigation ($Z^g_{hi}(t)$) is not currently available, it is impossible to obtain the scales of this variable. Therefore, in this study $Z^g_{hi}(t)$ is assumed to be constant (see Table 2).

The ecohydrological model, AgriCLVDAS, can simulate both soil moisture and vegetation growth using meteorological data (e.g. precipitation). Sawada et al. [20] showed that the simulated LAI produced by the ecohydrological model was highly correlated with cereal crop production in Tunisia. The performance of this model is also validated in Pakistan using data from 2003 to 2010 [44]. The simulated LAI is well

[2] APHRODITE is one of the best choices for long-term gridded precipitation data in Asian countries since it was generated by integrating many in-situ observations and satellite precipitation retrievals. See Yatagai et al. [39] for the details of the APHRODITE's algorithm to retrieve precipitation. APHRODITE has been used in many previous studies on water resources in Asian countries including Pakistan (e.g. Refs. [40,41]).

Table 3
LAI-C by scales of precipitation and river water (Punjab, irrigated land).

LAI-C (X_{11}^{LAI}) of irrigated land ($h = 1$) in Punjab ($i = 1$)					
Scale of precipitation (ψ)	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.5603	0.5727	–	–	–
2	0.5620	0.5949	0.6140	–	–
3	–	0.6022	0.6293	0.6739	–
4	–	–	0.6521	0.6835	0.7335
5	–	–	–	0.6734	0.7097

correlated with the production of wheat (correlation coefficient = 0.757) and rice (correlation coefficient = 0.794) in Punjab. We define an indicator of LAI composite (LAI-C), $X_{hi}^{\mathrm{LAI}}(t)$ as follows:

$$X_{1i}^{\mathrm{LAI}}(t) = \sum_{w1,r,s} \frac{\mathrm{LAI}_{c,i}(t)}{\overline{\mathrm{LAI}_{c,i}}} \times \frac{\overline{P_{c,i}}}{\overline{P_c}} \times v_c, \tag{3a}$$

$$X_{2i}^{\mathrm{LAI}}(t) = \frac{\mathrm{LAI}_{w2,i}(t)}{\overline{\mathrm{LAI}_{w2,i}}} \times \frac{\overline{P_{w2,i}}}{\overline{P_{w2}}} \times v_{w2}, \tag{3b}$$

where, c is the crop type ($w1$: wheat in irrigated land, $w2$: wheat in rainfed land, r: rice, s: sugarcane), $\overline{P_{c,i}}$ and $\overline{P_c}$ are the mean annual total production in the region i and for Pakistan nationwide, respectively, and v_c is the market share of each crop type. $\mathrm{LAI}_{c,i}(t)$ is the yearly maximum of the simulated LAI and $\overline{\mathrm{LAI}_{c,i}(t)}$ is its mean from 2003 to 2010. Since $\overline{P_{c,i}}$, $\overline{P_c}$, and v_c are static variables, the temporal change in $X_{hi}^{\mathrm{LAI}}(t)$ is determined by variation of the simulated LAI.

AgriCLVDAS is driven by combinations of precipitation and river water irrigation, shown in Tables 1 and 2, to estimate LAI. Then, using Eqs.(3a) and (3b) and , the indicator of LAI composite (LAI-C), X_{hi}^{LAI}, is calculated from the simulated LAI. Tables 3 and 4 show the values of X_{h1}^{LAI} for several scales of precipitation and river water irrigation in Punjab. Values for the Sindh and ROP regions are provided in Appendix B. Note that several combinations of precipitation and river water irrigation are not used to drive AgriCLVDAS as river water is assumed to be somewhat correlated to precipitation and it is unrealistic to calculate results for scenarios with large (small) amounts of river water and small (large) amounts of precipitation. In addition, a simulation with a 10% increase of irrigation efficiency is implemented to obtain additional X_{hi}^{LAI} data (not shown). The baseline simulation from 2003 to 2010 to validate the performance of AgriCLVDAS is also included in the set of X_{hi}^{LAI}.

Tables 1–4 and Tables B.6–B.9 in Appendix B show the relationships between Z_{hi} and X_{hi}^{LAI}, which are simulated by AgriCLVDAS. Moreover, Table B.10 shows the time-invariant parameters of T_{hi} in Eq.(1).

Next, we assign values to the land–water composite, X_{hi}, using X_{hi}^{LAI} as shown in Tables 3 and 4 and Tables B.6–B.9, and identify the unknown parameters in Eq. (1) by calibration (with T_{hi} provided exogenously, and Z_{hi} provided by Eqs. (2a) and (2b), so that the land–water composite functions fit the relationship between the available amounts

Table 4
LAI-C by scales of precipitation and river water (Punjab, rainfed land).

LAI-C (X_{21}^{LAI}) of rainfed land ($h = 2$) in Punjab ($i = 1$)					
Scale of precipitation (ψ)	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.01117	0.01273	–	–	–
2	0.01117	0.01273	0.01448	–	–
3	–	0.01273	0.01448	0.01705	–
4	–	–	0.01448	0.01705	0.01961
5	–	–	–	0.01705	0.01961

Table 5
Calibration results of land-water composite function.

Classification of agricultural land	Scale parameter (β_{Zhi})			Scale parameter (β_{Thi})		
	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
Irrigated land ($h = 1$)	1383	3383	685.7	0.1273	0.3143	0.0342
Rainfed land ($h = 2$)	2318	608.7	25.54	4.392	4.185	0.1022

of water, the available areas of agricultural land, and the results of the AgriCLVDAS simulation. The Nelder-Mead method is used to optimize Eq. (1) minimizing the squared difference between X_{hi} calculated by Eq. (1) and X_{hi}^{LAI} calculated by AgriCLVDAS. The calibrated parameters are shown in Table 5. The complete description of the calibration method can be found in Suzuki [44].

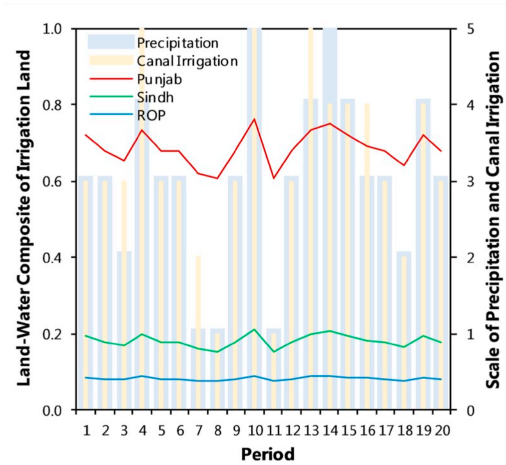
The required socio-economic parameters (a full table of parameters and values are listed in Appendix C) represent the 2007 macroeconomy of Pakistan. Data used for calibration are mainly extracted from the Social Accounting Matrix (SAM) of Pakistan [45] and the World Development Indicators issued by the World Bank. Some parameter values are assumed, due to the limited availability of data, and should be updated in the future by further data collection.

3.2. The value of water and economic growth

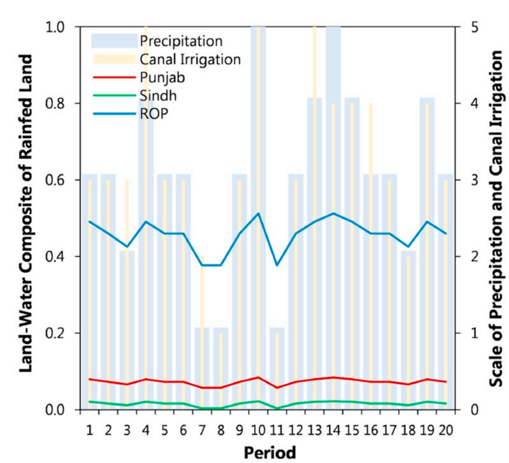
Analyses of the numerical simulation are associated with two focuses: the sample and mean path analyses. The former is based on one possible stream of the scale of precipitation and the available water provided by river irrigation, which is produced by the probability vector given in Table 1 and examines the relationships among the movements of the endogenous variables. The latter focuses on the expected dynamics based on a Monte Carlo simulation.

Horizontal axes of Figs. 5–8 represent time where one period of time in the simulation is given by a year. The bars in the background of Figs. 5 (a)–(l) represent one sample path of the scale of precipitation and the amount of water provided by river irrigation. This sample process brings about a scale-5 precipitation in Periods 10 and 14, a scale-5 river irrigation in Periods 3, 10, and 13, and a scale-1 precipitation in Periods 7, 8, and 11. Further, the available water provided by river irrigation is also at the minimum level in Periods 8 and 11, which are regarded as periods of drought.

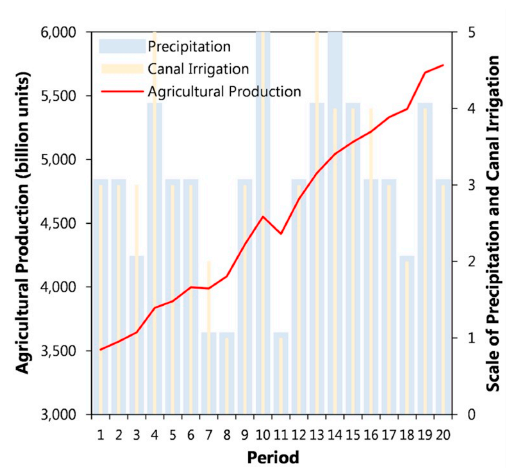
Figs. 5(a)–(l) illustrate the dynamic process of the endogenous variables in the model, such as the land–water composites, agricultural production, prices, sectoral and regional GDP, national GDP, and utility of a representative household. Note that the price of manufacturing goods, p_m, is standardized to unity. The values of the land–water composites of both irrigable and rainfed land for each region correlate with the total amount of water available for agriculture (Figs. 5(a) and (b)). Agricultural production clearly increases in Period 10 (i.e., the high-water period of scale-5 precipitation and the available water of river irrigation) and decreases in the next period (i.e., the drought period). On the contrary, other droughts do not cause large absolute decreases in agricultural production (Fig. 5(c)), whereas the following three facts should be noted. First, agricultural production per capita clearly decreases in periods with low precipitation and available river water (Fig. 5(d)), which implies that production growth partially depends on an increase in the labor population. Second, a decrease in production should be evaluated in terms of the level of deviation from the trend line. Finally, the price increase of agricultural goods in drought periods enhances the incentive of agricultural production (Fig. 5(e)), which is associated with increased demand for labor and capital, which partially replace water as factors of production, resulting in a modest change in



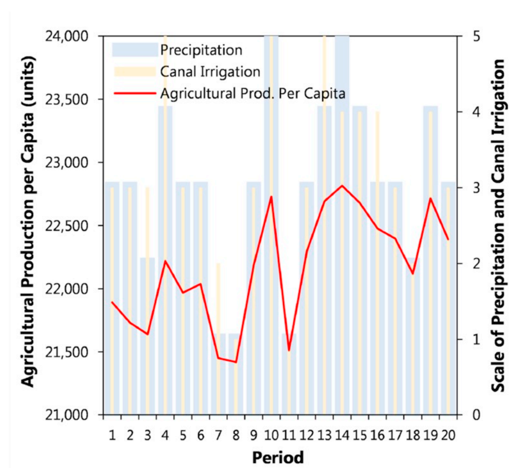
(a) Land-water composite of irrigated land



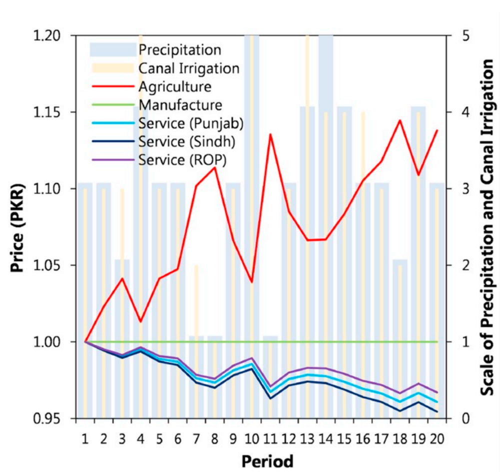
(b) Land-water composite of rainfed land



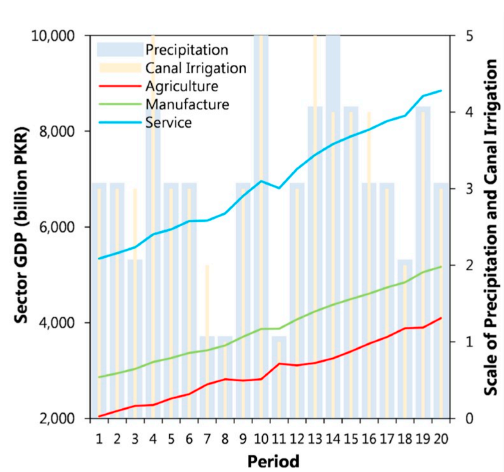
(c) Agricultural production



(d) Agricultural production per capita

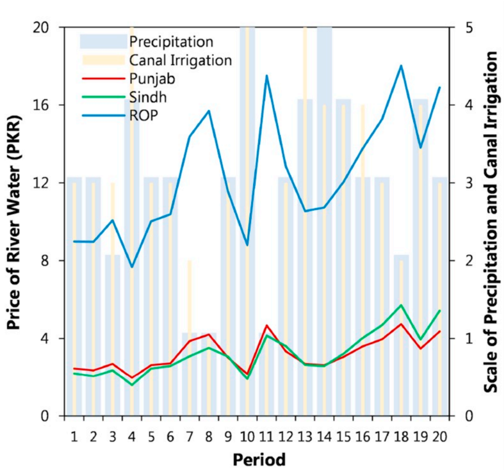


(e) Price

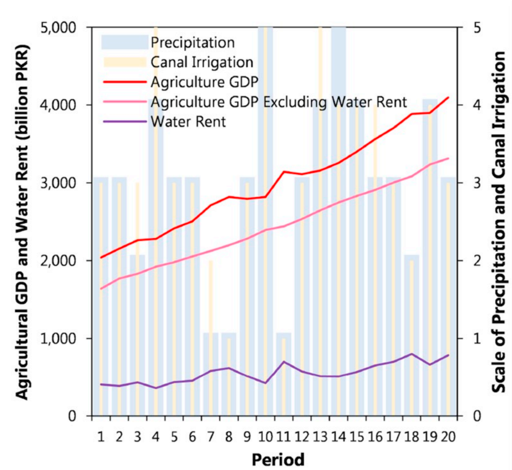


(f) Sector GDP

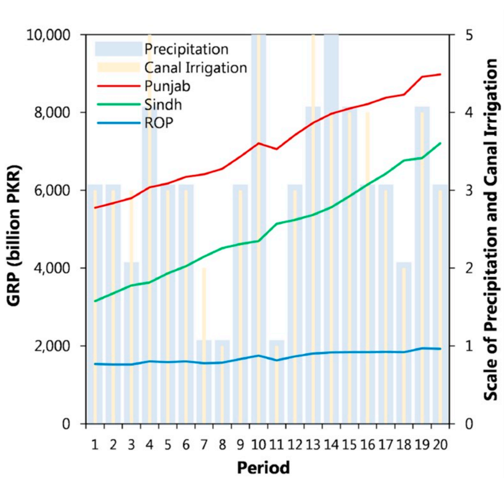
Fig. 5. Dynamic process of each variable (sample path).



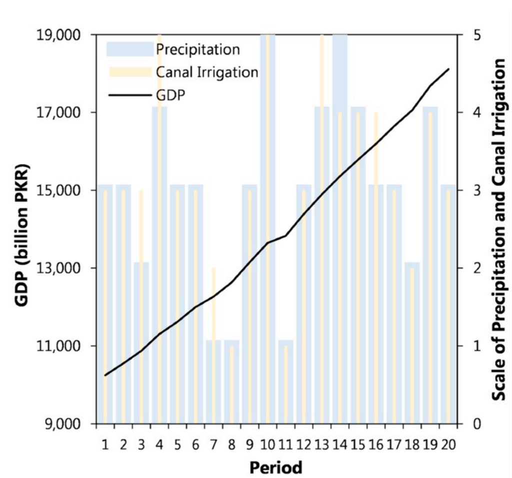
(g) Price of river water



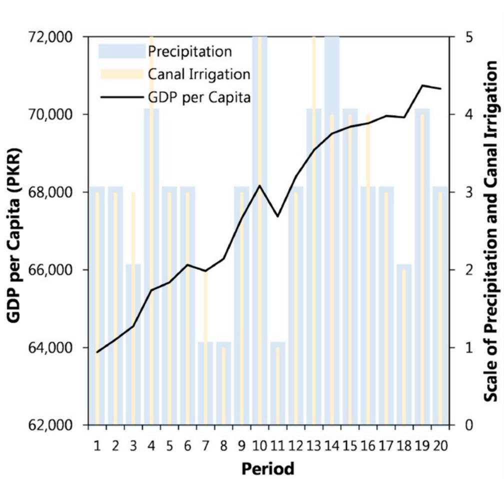
(h) Agricultural GDP and water rent



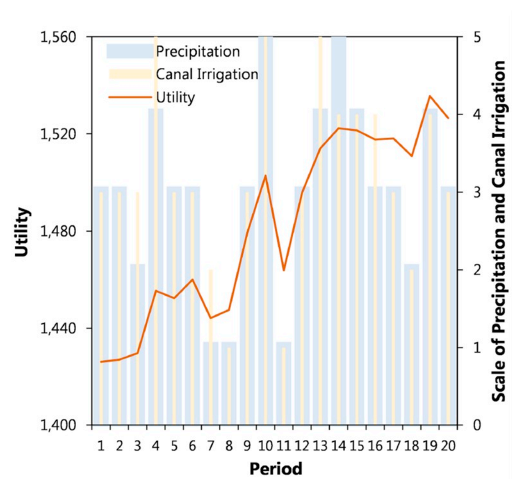
(i) Regional GDP (GRP)



(j) GDP

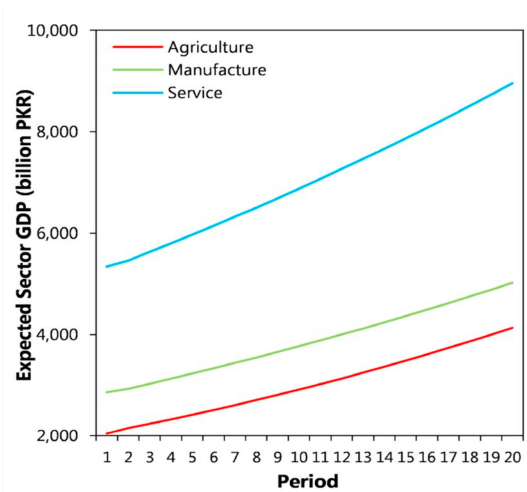


(k) GDP per capita

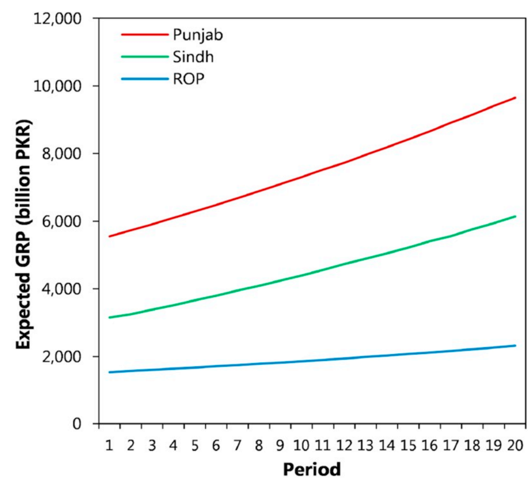


(l) Utility

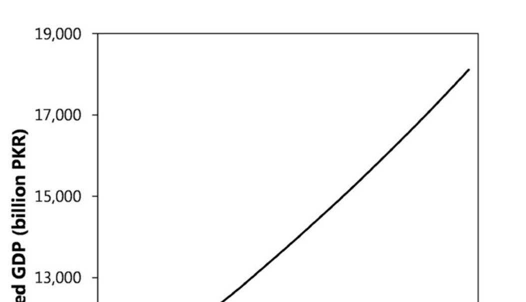
Fig. 5. (*continued*).



(a) Expected sector GDP



(b) Expected regional GDP (GRP)



(c) Expected GDP

Fig. 6. Dynamic process of value-added (mean path).

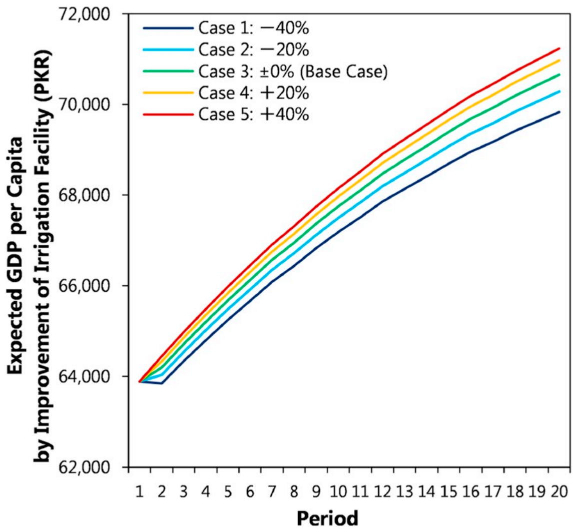


Fig. 7. Expected GDP per capita by improvement of irrigation facility (mean path).

total agricultural production. Owing to the price rise of agricultural goods in drought periods, which has a dominant impact compared with decreases in production, GDP in the agricultural sector increases during those periods and the opposite phenomena happen during high-water periods (Fig. 5(f)). These extreme results depend on the properties of the closed-economy model, where all prices are determined endogenously. In a model without international trade, food is obtained only domestically, resulting in an increase in the price of agricultural goods that attract factors of production, finally mitigating the large decrease in production. Moreover, the price rise of agricultural goods decreases the value-added of the other sectors, which discourages their production. The opposite impacts are witnessed during periods when large amounts of water are available. In other words, the price mechanism works to mitigate the impacts of extreme precipitation on agricultural production.

How the variation in prices is decomposed is worth noting. Fig. 5(g) shows the value of the marginal production of water in each region, which would represent the market price of water in a perfectly competitive water market. The price of water is higher for lower amounts of available water, especially in ROP, where the price is three to four times larger than those in the other two regions. Moreover, comparing Periods 8 and 10, where the levels of available water from canal irrigation are one and five, respectively, the water price of the former is approximately double in Period 8 in all regions.

Furthermore, Fig. 5(h) illustrates that most of the fluctuation in agricultural GDP stems from water rent fluctuations. Why GDP in the agricultural sector increases during drought periods is ascribed to the assumption of the model that it owns all water resources (note that all firms are finally owned by households) and monopolizes water rents. If firms in the agricultural sector have to buy water or bear the costs of leading water from rivers, they cannot make such profits during drought periods.

Figs. 6(a)–(c) illustrate the results of the Monte Carlo simulation. GDP is expected to grow by 77% over the 20 years, with the agricultural, manufacturing, and service sectors growing by 102%, 75%, and 68%, respectively. In other words, smaller sectors have larger growth rates, while the differences in the absolute values of sectoral GDP are expanding during these 20 years. On the contrary, the GDP of Punjab, Sindh, and ROP will grow by 74%, 95%, and 51% over the same 20 years.

The effects of water resource management policies are examined in Figs. 7 and 8. Fig. 7 shows the effects of changes in the performance of river irrigation facilities, represented by the level of Ξ_i^s, on expected GDP per capita growth, namely the values for the sensitivity of the parameters that serve the cost-benefit analysis.

Figs. 8(a)–(c) show the effect of reallocation for river water between Punjab and Sindh, which is implementable by dam control. Both regions increase their expected regional GDP by obtaining additional water from the other region, while the expected national GDP will be maximized by a strategy in which 20% of the water in Sindh is transferred to Punjab until Period 13 and no transfer is made from Periods 14 to 20. However, the difference is minimal between those two reallocations, which implies that the current policy of water allocation between Punjab and Sindh is close to the best in terms of national GDP, thus needing not be modified to a large extent.

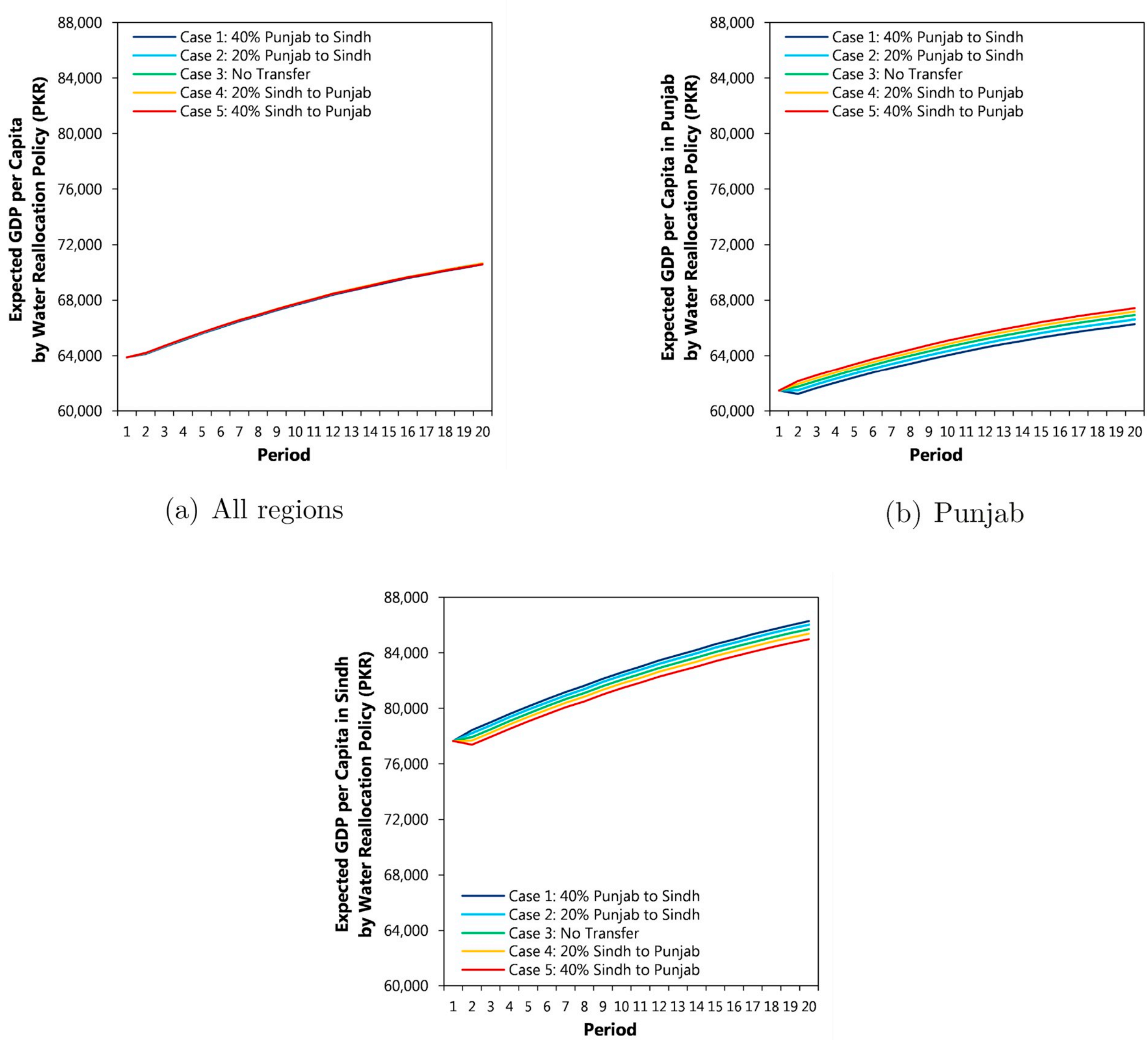
As described above, we obtained a salient result that larger amounts of variable factors of production are allocated to the agricultural sector during drought periods, which depends on the assumption of a closed economy. On the contrary, the authors developed a version of the model which assumed an open-economy, using the same data set. Numerical simulation of the open model illustrated that the variable factors of production moved to the manufacturing sector, which increased production, a part of which was exported and exchanged with agricultural goods. In other words, the country adopted the strategy of importing crops from overseas. Compared with the results obtained by such an open-economy model, the results of the closed-economy model in this study explain what could happen to resource allocation when a country is faced with difficulty in importing food.

In reality, the economies of many developing societies are somewhere between completely open and closed economies. Some rural areas are so remote from urban ones that imported crops do not easily reach their destination because of high transaction costs (e.g. transportation costs) as well as institutional barriers based on the cultural context. In other words, a market structure closer to closed-economy models exists, where local farmers and firms must strive to produce crops during drought periods by allocating larger amounts of labor, which finally results in increasing the value of water by 100% compared with periods of high precipitation. On the other hand, it is also a general fact that moving of workers from manufacture or service to agriculture is less easy than the opposite move that is frequently observed as seasonal migration of farmers. Asymmetric mobility of labor should also be considered in future research.

4. Conclusion

This study proposed a method of valuing the economic value of water under the stochastic arrival of drought stress by integrating the ecohydrological model, AgriCLVDAS, and a multi-sector multi-region economic growth model. AgriCLVDAS, whose performance was validated in Pakistan using data from 2003 to 2010, simulated LAI data which were closely correlated with the production of wheat and rice in Punjab. The methodological novelty of the study was, first, to define an indicator of the LAI composite by the weighted average of LAIs for representative crops of Pakistan, namely, wheat, rice, and sugarcane. Using this LAI composite, we calibrated the values of the land–water composite function and identified the parameters of the function that are a part of the agricultural production function. Hence, the parameters of the agricultural production function are identified by calibrations at two layers: that of the land–water composite, and of final output. Accordingly, although quantitative examination of an effect and validation with the use of various data of drought impacts is left for future research, it is theoretically ensured that an impact of the total amount of available water on quantity of the final output emerges more precisely in our new method than in conventional methods.

Subsequently, we formulated a multi-sector multi-region economic growth model, including the agricultural production function, and



(a) All regions

(b) Punjab

(c) Sindh

Fig. 8. Expected GDP per capita by water reallocation policy (mean path).

carried out a case study of Pakistan. In the closed-economy model, larger resources are allocated to the agricultural sector because of the price increase of agricultural goods, which in turn is determined by the price hike in water. In other words, an increase in the marginal productivity of water during drought periods is double that in high-water periods. The study further presented examples of policy analyses for water resource management by applying comparative dynamics. Although the formulated economic model is simple, with assumptions of a closed economy and the perfect mobility of labor and capital, it can contribute to policy discussions by providing a benchmark normative solution. Application of simulation of the model serves cost-benefit analysis of drought mitigation and water resource management policies.

We conclude by discussing some possible extensions and directions for future research. First, the open-economy version of the model is an extreme setting of assumptions for the international market, making it important to formulate a hybrid model, where urban areas are directly connected to international markets, while it is costly to send crops from overseas to rural areas, or a model with labor and capital mobility stickiness. Second, the savings rate, assumed to be constant in this model, should be endogenously determined in a framework of a dynamic optimization problem. Third, it is important to discuss intertemporal water resource allocation by dam control. Fourth, a natural expansion of the model would be to include a step-by-step construction of irrigation infrastructure in keeping with economic growth. Fifth, climate change that causes changes in scales and probabilities of precipitation should be incorporated into the model. Sixth, the impact of a drought that occurs two sequential years will be so severe that farmlands are destroyed by earth fissures, taking them a long time to recover. The recovery of land demands considerable labor, a serious problem in addition to planning to obtain food, which should be tackled by the trans-disciplinary collaboration of natural and social sciences as well as engineering. Finally, the model should be applied to the larger number of countries to carry out comparative studies, which will also contribute to enhancement of validity of the model.

Acknowledgement

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Appendix A. Model description

Appendix A.1. Environment

This appendix provides the full description of the model. To keep continuity of explanation, some parts of the description overlap with that of Section 2.

The economy is small, closed, and perfectly competitive, with three regions indexed by $i \in I = \{1, 2, 3\}$, where $i = 1$ will represent Punjab province, $i = 2$ Sindh province, and $i = 3$ the rest of Pakistan (ROP) in a case study in Section 3. Each region produces three final goods/services indexed by $j \in J = \{a, m, s\}$, where a, m, and s represent agriculture, manufacturing, and services, respectively. Each final good j produced in Region i in period t is traded at price $p_{ji}(t)$ in the same period. The agricultural and manufacturing goods produced in Region 1 are assumed to be perfect substitutes for the corresponding goods produced in Regions 2 and 3. Those two goods are mobile, and transportation is assumed to be cost free, implying that the prices in all three regions are equalized, namely $p_{a1}(t) = p_{a2}(t) = p_{a3}(t)$ and $p_{m1}(t) = p_{m2}(t) = p_{m3}(t)$. On the contrary, the services produced in all three regions are immobile and not perfectly substitutable in the utility function, implying that each market is closed in each region and, generally, $p_{s1}(t) \neq p_{s2}(t) \neq p_{s3}(t)$ holds. While agricultural goods and services are pure perishable consumption goods/services, manufacturing goods can be stocked and used for both consumption and capital accumulation.

The labor and capital markets are open among the three regions, closed in a country, and perfectly competitive, with the wage rate, $\omega(t)$, and the interest rate, $r(t)$, determined endogenously. A representative adult person (worker) provides labor and capital and obtains wages and interest every period. Each worker provides one unit of labor inelastically every period. Therefore, the total amount of labor in the economy, $L(t)$, is equalized to the population in the country, $L(0)\cdot(1+n)^t$, where $L(0)$ is the initial population and n is the population growth rate. Workers' savings are stocked as capital to be rented by firms. Moreover, workers own land and water resources and obtaining the rents generated by them.

Appendix A.2. Production technologies

Let $L_{ji}(t)$ and $K_{ji}(t)$ be the inputs of labor and capital, respectively, into the production of Sector j in Region i in period t. Moreover, the agricultural sector inputs the land–water composite, $X_{hi}(t)$, where we classify irrigable and rainfed land as indexed by $h \in H = \{1, 2\}$, respectively.

Let us further represent the intermediate goods/services produced in Sector j' and demanded by Sector j in Region i by $\mathscr{Y}_{j'ji}(t)$. All firms are assumed to have constant returns to scale technology. By omitting the notation of "(t)" hereafter for notational simplicity, aggregated production for the agricultural sector, Y_{ai}, and its technology for obtaining value-added, $F^{ai}(\cdot)$, in each region are given as follows:

$$Y_{ai} := \min\left[F^{ai}(AL_{ai}, K_{ai}, A_{X1}X_{1i}, A_{X2}X_{2i}), \frac{\mathscr{Y}_{aai}}{\varphi_{aai}}, \frac{\mathscr{Y}_{mai}}{\varphi_{mai}}, \frac{\mathscr{Y}_{sai}}{\varphi_{sai}}\right], \tag{A.1a}$$

$$F^{ai}(AL_{ai}, K_{ai}, A_{X1}X_{1i}, A_{X2}X_{2i}) := B_{ai}\left\{\beta_{Lai}(AL_{ai})^{\alpha_{ai}} + \beta_{Kai}K_{ai}^{\alpha_{ai}} + \beta_{X1i}(A_{X1}X_{1i})^{\alpha_{ai}} + \beta_{X2i}(A_{X2}X_{2i})^{\alpha_{ai}}\right\}^{\frac{1}{\alpha_{ai}}} \quad \text{for all } i, \tag{A.1b}$$

where A and A_{Xh} $(h = 1, 2)$ represent the exogenous levels of labor productivity and land–water composites, respectively. $\varphi_{j'ai}$ represents the input coefficient of intermediate goods/services. The elasticity of substitution is given by $\sigma_{ai} := 1/(1-\alpha_{ai})$. B_{ai} is the total factor productivity (TFP) of agricultural sector. β_{Lai}, β_{Kai}, and β_{Xhi} are the share parameters. $X_{hi}(t)$ is the land–water composite that is defined by Eq.(1). The amount of available water, $Z_{hi}(t)$, that is a constituent of $X_{hi}(t)$ is given by Eqs. (2a) and (2b) as the weighted sum of precipitation, water provided by river irrigation, and water provided by groundwater irrigation. The scale of precipitation and available amount of river water provided by the irrigation in period t, $\psi(t)$ and $\psi^s(t)$, are random variables, as described in 2.2.

We assume the production of manufacturing and service sectors, Y_{mi} and Y_{si}, respectively, and their technologies for obtaining value-added, $F^{mi}(\cdot)$ and $F^{si}(\cdot)$, as follows:

$$Y_{mi} := \min\left[F^{mi}(AL_{mi}, K_{mi}, A_{Tm}T_{mi}), \frac{\mathscr{Y}_{ami}}{\varphi_{ami}}, \frac{\mathscr{Y}_{mmi}}{\varphi_{mmi}}, \frac{\mathscr{Y}_{smi}}{\varphi_{smi}}\right], \tag{A.2a}$$

$$F^{mi}(AL_{mi}, K_{mi}, A_{Tm}T_{mi}) := B_{mi}(AL_{mi})^{\alpha_{Lmi}}K_{mi}^{\alpha_{Kmi}}(A_{Tm}T_{mi})^{\alpha_{Tmi}} \quad (\alpha_{Lmi} + \alpha_{Kmi} + \alpha_{Tmi} = 1) \quad \text{for all } i, \tag{A.2b}$$

$$Y_{si} := \min\left[F^{si}(AL_{si}, K_{si}), \frac{\mathscr{Y}_{asi}}{\varphi_{asi}}, \frac{\mathscr{Y}_{msi}}{\varphi_{msi}}, \frac{\mathscr{Y}_{ssi}}{\varphi_{ssi}}\right], \tag{A.2c}$$

$$F^{si}(AL_{si}, K_{si}) := B_{si}(AL_{si})^{\alpha_{Lsi}}K_{si}^{\alpha_{Ksi}} \quad (\alpha_{Lsi} + \alpha_{Ksi} = 1) \quad \text{for all } i, \tag{A.2d}$$

where T_{mi} is land for manufacturing production, which is a fixed factor and constant throughout. A_{Tm} represents the exogenous levels of land productivity. $\varphi_{j'ji}$ represents the input coefficient of intermediate goods/services. B_{ji} $(j = m, s)$ is the TFP of manufacturing and service sector. α_{Lji} $(j = m, s)$, α_{Kji} $(j = m, s)$, and α_{Tmi} are the share parameters.

Appendix A.3. Firm optimization

The sequence of events in each period t is identified in 2.3. As described, firms make decisions at step 2–1); in other words, decisions are made after the level of precipitation and vector of the state variables are given in each period.

Value-added prices are defined as follows:

$$p_{ji}^{v}(t) := p_{ji}(t) - \varphi_{aji}p_a(t) - \varphi_{mji}p_m(t) - \varphi_{sji}p_{si}(t) \quad \text{for all } j, i. \tag{A.3}$$

Since firms in the agricultural sector have fixed factors X_{1i} and X_{2i}, their problem is represented by profit maximization:

$$\Pi^{ai}\left(p_{ai}^{v}, \omega, r^k, \widehat{\mathbf{X}}_i\right) := \max_{L_{ai},K_{ai}}\left[p_{ai}^{v}F^{ai}(AL_{ai}, K_{ai}, A_{X1}\widehat{X}_{1i}, A_{X2}\widehat{X}_{2i}) - \omega L_{ai} - r^k K_{ai}\right] \text{ for all } i, \text{ where } \widehat{\mathbf{X}}_i := (\widehat{X}_{1i}, \widehat{X}_{2i}), \tag{A.4}$$

where $\omega(t)$ is the wage rate in period t and $r^k(t) := r(t) + \delta$ is the unit cost of capital, which is a sum of the interest rate, $r(t)$, and depreciation rate, δ. The optimal demand of labor, $L_{ai}^*(p_{ai}^v, \omega, r^k, \widehat{\mathbf{X}}_i)$, and of capital, $K_{ai}^*(p_{ai}^v, \omega, r^k, \widehat{\mathbf{X}}_i)$, is determined in the first-order conditions:

$$p_{ai}^{v}(t)A(t)\frac{\partial F^{ai}(\cdot)}{\partial\{AL_{ai}\}} = \omega(t), \quad p_{ai}^{v}(t)\frac{\partial F^{ai}(\cdot)}{\partial K_{ai}} = r^k(t). \tag{A.5}$$

Similarly, the problem of firms in the manufacturing sector is represented by

$$\Pi^{mi}\left(p_{mi}^{v}, \omega, r^k\right) := \max_{L_{mi},K_{mi}}\left[p_{mi}^{v}F^{mi}(AL_{mi}, K_{mi}, T_{mi}) - \omega L_{mi} - r^k K_{mi}\right] \quad \text{for all } i. \tag{A.6}$$

The demand functions of labor, $L_{mi}^*(p_{mi}^v, \omega, r^k)$, and of capital, $K_{mi}^*(p_{mi}^v, \omega, r^k)$, are introduced by the following conditions:

$$p_{mi}^{v}(t)A(t)\frac{\partial F^{mi}(\cdot)}{\partial\{AL_{mi}\}} = \omega(t), \quad p_{mi}^{v}(t)\frac{\partial F^{mi}(\cdot)}{\partial K_{mi}} = r^k(t). \tag{A.7}$$

On the contrary, a problem of the firms in the service sector is given by the cost minimization problem as follows:

$$C^{si}\left(\omega, r^k, Y_{si}\right) := \min_{L_{si},K_{si}}\left[\omega L_{si} + r^k K_{si}\right] \tag{A.8a}$$

$$\text{subject to } F^{si}(AL_{si}, K_{si}) = Y_{si} \text{ for all } i. \tag{A.8b}$$

The first-order conditions are given by

$$\lambda_{si}^*(t)A(t)\frac{\partial F^{si}(\cdot)}{\partial\{AL_{si}\}} = \omega(t), \quad \lambda_{si}^*(t)\frac{\partial F^{si}(\cdot)}{\partial K_{si}} = r^k(t), \tag{A.9}$$

where $\lambda_{si}^*(t)$ is the optimal value of the Lagrange multiplier that corresponds to constraint (A.8b). Considering that the production function is homogeneous of degree one in L_{si} and K_{si}, the demand function of labor, $L_{si}^*(\omega, r^k, Y_{si})$, the demand function of capital, $K_{si}^*(\omega, r^k, Y_{si})$, and the cost function, $C^{si}(\omega, r^k, Y_{si})$, are proportional to Y_{si}:

$$L_{si}^*\left(\omega, r^k, Y_{si}\right) = \tilde{L}_{si}^*\left(\omega, r^k\right) \cdot Y_{si}, \tag{A.10a}$$

$$K_{si}^*\left(\omega, r^k, Y_{si}\right) = \tilde{K}_{si}^*\left(\omega, r^k\right) \cdot Y_{si}, \tag{A.10b}$$

$$C_{si}^*\left(\omega, r^k, Y_{si}\right) = \tilde{C}_{si}^*\left(\omega, r^k\right) \cdot Y_{si}. \tag{A.10c}$$

Appendix A.4. Household optimization

Households make decisions at step 2–2) in the event sequence given in 2.3. Let $q_{ji}(t) := Q_{ji}(t)/L(t)$ represent the consumption of the j goods/services produced in Region i per adult person (worker). We assume that the agricultural goods produced in the three regions are perfectly substitutable, and total consumption is given by $q_a(t) := \sum_i q_{ai}(t)$. The same holds true for manufacturing goods; therefore, $q_m(t) := \sum_i q_{mi}(t)$.

The optimization problem of the representative household is represented by the one-period utility maximization problem as follows:

$$\max_{\mathbf{q}} u(\mathbf{q}) := \prod_j q_j^{\gamma_j}, \tag{A.11a}$$

$$\text{subject to } \mathbf{p}' \cdot \mathbf{q} \le \tilde{y}, \tag{A.11b}$$

where

$$\mathbf{q} := (q_a, q_m, q_{s1}, q_{s2}, q_{s3})' \tag{A.12}$$

is the consumption vector and

$$\mathbf{p} := (p_a, p_m, p_{s1}, p_{s2}, p_{s3})' \tag{A.13}$$

the price vector; the superscript " ' " means that the vector is transposed. Moreover, $\gamma_{\tilde{j}}$ $(\tilde{j} = a, m, s1, s2, s3)$ is the share parameter of the one-period utility function, $u(\mathbf{q})$, where $\gamma_{\tilde{j}} > 0$ and $\sum_{\tilde{j}} \gamma_{\tilde{j}} = 1$ hold. Furthermore, $\tilde{y}$ is the budget that the household spends on purchasing $\mathbf{q}$, which is defined by the fixed percentage of income in each period, namely

$$\tilde{y}(t) := (1-\sigma^{sr}) \cdot \left\{ \omega(t) + r(t)k(t) + \sum_{i}\sum_{j=a,m} \pi^{ji}(t) \right\}, \tag{A.14}$$

where the curly brackets represent the one-period income, composed of labor income, capital income, and a bundle of rents, while $(1-\sigma^{sr})$ is the consumption rate and σ^{sr} the savings rate, assumed to be constant throughout. $\omega(t)$ is the wage rate, $k(t) := K(t)/L(t)$, the capital stock per worker, $r(t) = r^k(t) - \delta$, the interest rate, and $\pi^{ji}(t) := \Pi^{ji}(t)/L(t)$, the rent per worker generated by the fixed factors in the agricultural and manufacturing sectors in each region. Since the capital market is closed, total household assets are equalized to the sum of capital that all industries demand: $K(t) := \sum_{j,i} K_{ji}(t)$.

Since the one-period utility function is given by a Cobb–Douglas form, Marshallian demand functions are introduced as

$$q^*_{\tilde{j}}(\mathbf{p}(t), \tilde{y}(t)) = \frac{\gamma_{\tilde{j}}}{p_{\tilde{j}}(t)} \tilde{y}(t) \quad (\tilde{j} = a, m, s1, s2, s3). \tag{A.15}$$

Finally, GDP is represented by

$$\mathrm{GDP} = \sum_{j,i} p^v_{ji}(t) Y_{ji}(t) = \left\{ \omega(t) + r^k(t)k(t) + \sum_{i}\sum_{j=a,m} \pi^{ji}(t) \right\} L(t), \tag{A.16}$$

where $Y_{ji}(t)$ is the production of Sector j in Region i. The capital accumulation process is represented as follows:

$$K(t+1) = (1-\delta)K(t) + \eta(t)L(t), \tag{A.17}$$

where $\eta(t)$ is investment per household given by

$$\eta(t) = \sigma^{sr} \cdot \left\{ \omega(t) + r(t)k(t) + \sum_{i}\sum_{j=a,m} \pi^{ji}(t) \right\} + \delta k(t). \tag{A.18}$$

Appendix A.5. Equilibrium conditions

Given the vector of the state variables, $\mathbf{S}(t) := (L(t), K(t), \mathbf{X}(t))$, the competitive equilibrium in period t is identified by a set $\{\omega(t), r^k(t), p_a(t), p_m(t), p_{s1}(t), p_{s2}(t), p_{s3}(t), Y_{s1}(t), Y_{s2}(t), Y_{s3}(t)\}$, which satisfies the following conditions. Although the values of all the endogenous variables above are specific in period t, we omit the notation of "(t)" below for notational simplicity.

The zero-profit conditions of the firms in the service sector in each region are represented by

$$\tilde{C}^*_{si}(\omega, r^k) = p^v_{si}(\mathbf{p}) \quad \text{for all } i, \tag{A.19}$$

where the value-added price, $p^v_{si}(\mathbf{p})$, is given by Eq.(A.3) and $\mathbf{p}$ is the price vector defined by Eq.(A.13).

The labor and capital market-clearing conditions are represented as follows:

$$\sum_{i}\sum_{j=a,m} L^*_{ji}\left(p^v_{ji}(\mathbf{p}), \omega, r^k\right) + \sum_{i} L^*_{si}(\omega, r^k, Y_{si}) = L(t), \tag{A.20a}$$

$$\sum_{i}\sum_{j=a,m} K^*_{ji}\left(p^v_{ji}(\mathbf{p}), \omega, r^k\right) + \sum_{i} K^*_{si}(\omega, r^k, Y_{si}) = K(t). \tag{A.20b}$$

The market-clearing conditions of agricultural goods are given as

$$q^*_a(\mathbf{p}, \tilde{y}(\mathbf{p}, \omega, r^k)) \cdot L(t) + \sum_{i}\sum_{j=a,m} \varphi_{aji} Y^*_{ji}\left(p^v_{ji}(\mathbf{p}), \omega, r^k\right) + \sum_{i} \varphi_{asi} Y_{si} = \sum_{i} Y^*_{ai}(p^v_{ai}(\mathbf{p}), \omega, r^k). \tag{A.21}$$

The left-hand-side of Eq.(A.21) represents demand for agricultural goods; the first term is the final demand of households, whereas the second and third terms are the intermediate demand of firms, while the right-hand-side represents supply. $\tilde{y}(\cdot)$ above is given by considering Eq.(A.14) and the fact that $\boldsymbol{\pi} := (\{\pi_{ji}(\cdot)\}_{j=a,m,\ i=1,2,3})$ is a function of $p^v_{ji}(\mathbf{p})$, ω and r^k.

Similarly, the market-clearing conditions of manufacturing goods and services are represented by

$$\left\{ q^*_m\left(\mathbf{p}, \tilde{y}(\mathbf{p}, \omega, r^k)\right) + \eta(\mathbf{p}, \omega, r^k) \right\} L(t) + \sum_{i}\sum_{j=a,m} \varphi_{mji} Y^*_{mji}\left(p^v_{ji}(\mathbf{p}), \omega, r^k\right) + \sum_{i} \varphi_{msi} Y_{si} = \sum_{i} Y^*_{mi}(p^v_{mi}(\mathbf{p}), \omega, r^k), \tag{A.22a}$$

$$q^*_{si}\left(\mathbf{p}, \tilde{y}\left(\mathbf{p}, \omega, r^k\right)\right)L(t) + \sum_{j=a,m} \varphi_{sji} Y^*_{sji}\left(p^v_{ji}(\mathbf{p}), \omega, r^k\right) + \varphi_{ssi} Y_{si} = \sum_i Y^*_{si}\left(p^v_{si}(\mathbf{p}), \omega, r^k\right) \quad \text{for all } i. \tag{A.22b}$$

The components of the investment function, $\eta(\cdot)$, are identified in the same way as those of $\tilde{y}(\cdot)$ are identified above. Note that while the manufacturing good market-clearing condition is unique in the country, the service market-clearing conditions are given separately for each region.

The equilibrium prices determine the level of investment, $\eta(\cdot)$, that results in the capital stock in the next period by following the process given by Eq.(A.17).

Appendix B. Values of the LAI composite and available agricultural land

Tables B.6–B.9 list the modelled values of LAI composite (LAI-C) in Sindh and the rest of Pakistan (ROP), and Table B.10, the available agricultural land for all regions. These values are used to identify values of parameters in Eq.(1).

Table B.6
LAI-C by scales of precipitation and river water (Sindh, irrigated land).

LAI-C (X^{LAI}_{12}) of irrigated land ($h = 1$) in Sindh ($i = 2$)					
Scale of precipitation (ψ)	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.1669	0.1731	–	–	–
2	0.1513	0.1583	0.1656	–	–
3	–	0.1829	0.1880	0.1952	–
4	–	–	0.1808	0.1859	0.1873
5	–	–	–	0.1976	0.2015

Table B.7
LAI-C by scales of precipitation and river water (Sindh, rainfed land).

LAI-C (X^{LAI}_{22}) of rainfed land ($h = 2$) in Sindh ($i = 2$)					
ψ	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.0002580	0.0002953	–	–	–
2	0.0002580	0.0002953	0.0004163	–	–
3	–	0.0002953	0.0004163	0.0007572	–
4	–	–	0.0004163	0.0007572	0.001032
5	–	–	–	0.0007572	0.001032

Table B.8
LAI-C by scales of precipitation and river water (ROP, irrigated land).

LAI-C (X^{LAI}_{13}) of irrigated land ($h = 1$) in ROP ($i = 3$)					
ψ	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.07339	0.07444	–	–	–
2	0.06656	0.06845	0.06772	–	–
3	–	0.07837	0.07060	0.06849	–
4	–	–	0.08020	0.06619	0.07510
5	–	–	–	0.07221	0.07234

Table B.9
LAI-C by scales of precipitation and river water (ROP, rainfed land).

LAI-C (X^{LAI}_{23}) of rainfed land ($h = 2$) in ROP ($i = 3$)					
ψ	Scale of river water (ψ^s)				
	1	2	3	4	5
1	0.008569	0.009189	–	–	–
2	0.008569	0.009189	0.009688	–	–
3	–	0.009189	0.009688	0.01025	–
4	–	–	0.009688	0.01025	0.01069
5	–	–	–	0.01025	0.01069

Table B.10
Available agricultural land.

T_{hi}	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
Irrigated land ($h = 1$)	0.3526	0.1676	0.0200
Rainfed land ($h = 2$)	0.2585	0.0602	0.1410

Appendix C. Socio-economic parameters

Tables C.11–C.15 list the necessary socio-economic parameters used to replicate the 2007 macroeconomy of Pakistan.

Table C.11
Intermediate input co-efficient (from the previous research [45]).

$\varphi_{j'ji}$	Agriculture ($j = a$)	Manufacture ($j = m$)	Service ($j = s$)
Agriculture ($j' = a$)	0.0927	0.1355	0.0092
Manufacture ($j' = m$)	0.1287	0.2953	0.1881
Service ($j' = s$)	0.1970	0.3676	0.4387

Table C.12
Total factor productivity (by the calibration [45,46]).

B_{ji}	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
Agriculture ($j = a$)	1.000	1.000	1.000
Manufacture ($j = m$)	52.68	18.96	59.14
Service ($j = s$)	11.40	7.699	21.25

Table C.13
Scale parameters of agricultural production function (by the calibration [45]).

	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
β_{Lai}	0.0209	0.0175	0.0257
β_{Kai}	0.5731	0.7344	0.5604
β_{X1i}	0.0534	0.0331	0.0423
β_{X2i}	0.0076	0.0041	0.0132

Table C.14
Share parameters of manufacturing and service production function (by the calibration [45]).

	Manufacture ($j = 2$)			Service ($j = 3$)		
	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)	Punjab ($i = 1$)	Sindh ($i = 2$)	ROP ($i = 3$)
α_{Lji}	0.2916	0.1880	0.3126	0.2640	0.2268	0.3246
α_{Kji}	0.6399	0.7334	0.6210	0.7360	0.7732	0.6754
α_{Tmi}	0.0686	0.0786	0.0664	–	–	–

Table C.15
Other socio-economic parameters.

Sign	Definition	Value
$L(0)$	Initial total population	160,332,974 (people) *From the statistical data [46]
n	Population growth rate	0.025 *From the annual average [46]
γ_j	Share parameter of the one-period utility function	$\{\gamma_a, \gamma_m, \gamma_{s1}, \gamma_{s2}, \gamma_{s3}\} = \{0.1864, 0.4294, 0.2664, 0.0650, 0.0529\}$ *By the calibration [45]
$K(0)$	Initial capital stock	36,489 (billion PKR) *From the statistical data [45]
σ^{sr}	Saving rate	0.2835 *From the estimation [45]
δ	Depreciation rate of capital stock	0.05 *By the assumption
T_{mi}	Land for manufacturing production	1 (for all i) *By the normalization

(continued on next page)

Table C.15 (*continued*)

Sign	Definition	Value
A	Exogenous level of productivity of labor	1 *By the assumption
A_{Xh}	Exogenous level of productivity of land-water composite	1 (for all h) *By the assumption
A_{Tm}	Exogenous level of land productivity	1 *By the assumption
α_{ai}	Substitution parameter between labor, capital, and land-water composite	-0.2 (for all i) *By the assumption
α_{Xhi}	Substitution parameter between agricultural land and available water	-1.584 (for all h, i) *By the calibration
Ξ_i^s	Performance level of the river irrigation facilities	0.56 (for all i) *From the previous research [44]
Ξ_i^g	Performance level of the ground irrigation facilities	1 (for all i) *By the assumption

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101368.

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