https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

CHANS-SD-YRB V1.0: A System Dynamics model of the coupled human-natural systems for the Yellow River Basin

Shan Sang[1,2], Yan Li[1,2*], Shuang Zong[1,2], Lu Yu[1,2], Shuai Wang[1,2], Yanxu Liu[1,2], Xutong Wu[1,2], Shuang Song[1,2], Wenwu Zhao[1,2], Xuhui Wang[3], Bojie Fu[4]

[1]State Key Laboratory of Earth Surface Processes and Hazards Risk Governance (ESPHR), Beijing Normal University, Beijing, China

[2]Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing, China

[3]Institute of Carbon Neutrality, Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

[4]State Key Laboratory of Regional and Urban Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

Corresponding Author:

Yan Li, Ph.D.

Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China

Email: yanli.geo@gmail.com

Abstract: Modeling the coupled human–natural systems (CHANS) is vital for understanding human–natural interactions and achieving regional sustainability, offering a powerful tool to alleviating human–water conflicts, ensuring food security, thereby supporting the region's pathway toward sustainable development. However, the scarcity of regional-scale CHANS models constrains progress in practical applications for regional sustainability. The Yellow River basin (YRB) is an ideal region

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

for modeling regional CHANS due to its closely coupled human and natural systems, which are stressed by water and ecosystem fragility. Here, we developed the CHANS-SD-YRB model using the System Dynamics approach, integrating 10 sectors essential for modeling human-water interactions of the basin, including five human sectors (Population, Economy, Energy, Food, and Water Demand) and five natural sectors (Water Supply, Sediment, Land, Carbon, and Climate). The model can simulate evolution and feedbacks of the YRB CHANS annually at provincial and sub-basin scales, while conserving hydrological connectivity between sub-basins. The model can accurately reproduce historical CHANS dynamics, achieving strong quantitative agreement with historical data ($R > 0.95$ for human sectors and $R > 0.7$ for natural sectors), which supports its applicability for scenario analyses and future projections. We applied the model to explore human–natural system dynamics under a future baseline scenario, assuming the continuation of existing policies and climate projection under middle of the road scenario (SSP–RCP 2-4.5). The future projections (2021-2100) indicate that achieving sustainable development in the YRB will remain challenging, though economic growth and food security are expected to improve. Emerging issues, such as ecological–human water trade-offs, labor shortages, reduced sediment load, and limited carbon absorption capacity, may hinder regional long-term sustainability.

Keywords: coupled human-natural systems, regional modeling, system dynamics, the Yellow River Basin

1 Introduction

Coupled human and natural systems (CHANS) emphasize the reciprocal feedback and co-evolution between human and natural systems, offering an integrated framework for diagnosing complex problems and guiding sustainable development (Fu and Li, 2016). While global-scale CHANS research has deepened our knowledge of dynamic feedbacks among Earth's spheres and system evolution under climate change, sustainability challenges often manifest at regional scales, where social and ecological dynamics are more intricately intertwined (Liu et al., 2007). Compared to global

CHANS, regional CHANS are open systems that continuously exchange energy and materials with other regions and the global system, e.g., water resources and electricity transfers (Dobbs et al., 2023; Zhang et al., 2022a) and trade (Ristaino et al., 2021), resulting in pericoupling and telecoupling of different systems (Liu, 2017). Besides, regional CHANS are shaped by more immediate and complex human influences and stressors, such as urban expansion (van Vliet, 2019), ecological protection (Xu et al., 2017; Yang et al., 2022), and water resource regulation policies (diversion and allocation) (Song et al., 2024), which alter regional CHANS dynamics. Moreover, due to their diverse ecological and socioeconomic resilience, regional CHANS exhibit heterogeneous responses to external weather events and climate change, as evidenced by differing responses in crop yield (Hasegawa et al., 2021) and economic production to extreme heat and warming (Waidelich et al., 2024). By capturing dynamic interactions of interconnected components, CHANS theories and models enable more effective policies and interventions that align ecological integrity with socioeconomic progress (Motesharrei et al., 2016; Verburg et al., 2016). As such, advancing CHANS research is essential for informing adaptive strategies in the face of regional growing environmental and societal pressures.

Modeling of CHANS is a frontier area of geographical science and has become a key approach in resources, environment, and climate research. CHANS models serve as essential tools for analyzing the complex dynamics of human–natural interactions and guiding pathways toward sustainability. Numerous modeling approaches have been developed to simulate human–natural interactions at global scale, including system dynamics (SD) models (e.g., ANEMI (Breach and Simonovic, 2021), FeliX (Rydzak et al., 2013; Ye et al., 2024), and FRIDA (Rajah et al., 2025)), integrated assessment models (IAMs) (Vaidyanathan, 2021), integrated Earth system model (iESM) (Jain et al., 2022) and synchronously coupled human component in the earth system model (E3SM-GCAM) (Di Vittorio et al., 2025). These models effectively characterize human–natural interactions at the global scale, and have been applied to assess the

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

impacts of climate change on human society (e.g., agriculture (Monier et al., 2018), economic damage (Wang et al., 2020b), fatalities increase and welfare loss (Dottori et al., 2018)), and humans' feedback on the Earth system, such as those from climate mitigation on water and food security (Cheng et al., 2022; Fujimori et al., 2022). However, global models cannot represent the complex dynamics of human–natural interactions at the regional level, due to the openness of regional CHANS (Verburg et al., 2016), diversified regional human and natural processes (Clark et al., 2015), with locally heterogeneous responses to disturbances (Baldos et al., 2023). Moreover, the coarse spatiotemporal resolution of global models limits their capacity to support effective decision-making for regional development (X. Li et al., 2018).

To address this limitation, many regional CHANS models have been developed at various regional scales (e.g., national, basin, and urban) using System Dynamics (SD) and agent-based modeling (ABMs) techniques. Notable examples include the ANIME-Yangtze model (Jiang et al., 2022), the T21-China (Qu et al., 2020), and the iSDG-Australia model (Allen et al., 2019), all based on SD, the Jordan Water Model (Yoon et al., 2021) based on ABM, as well as integrated models in the San Juan River Basin (Hyun et al., 2019) and the Heihe River Basin (Li et al., 2021). These models are designed to capture finer-scale dynamics and region-specific human–natural interactions, since they embed localized characteristics (e.g., fishing ban, reservoir operation strategies, demographic policies, transboundary flows) and account for heterogeneity overlooked by global models. As a result, regional CHANS models offer stronger policy relevance, providing actionable insights for national, basin, and urban decision-making, and advancing CHANS research across multiple scales.

The Yellow River Basin (YRB) in China is one of the regions where conflicts between human and natural systems are most acute and complex, particularly in terms of human–water relations, due to the severe imbalance between socioeconomic development and natural hydrological, ecosystem processes. The YRB faces severe water stress, with the water resource utilization rate exceeding 80% (Feng and Zhu,

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

2022; Zhang et al., 2022b). Intensive water extraction has triggered a series of ecological and environmental issues, including flow interruptions, water pollution, and declining groundwater levels, all of which in turn constrain socioeconomic development. The Yellow River traverses the Loess Plateau (Zhu et al., 2019), where severe soil erosion makes the Yellow River one of the most sediment-laden rivers globally (Fu et al., 2011; Yin et al., 2021). The pronounced spatial and temporal variability in streamflow and sediment load leads to significant riverbed aggradation, frequent flooding, and disruption of agricultural production and other livelihood activities (Miao et al., 2016). Due to internal hydrological connectivity, sub-basins are highly interconnected and are susceptible to upstream influences. Upstream water overuse diminishes downstream availability (Wei et al., 2023), a factor that played a major role in flow interruptions during the 1990s (Changming and Shifeng, 2002; Wang et al., 2019). Ecological challenges differ across the subbasin, with the upstream facing ecosystem degradation and limited water retention (Ning et al., 2022), the midstream characterized by soil erosion and large-scale ecological restoration (Fu et al., 2011), and the downstream focusing on wetland conservation (Fu et al., 2023). Policy measures aimed at ecological restoration, such as afforestation and cropland conversion, have increased vegetation cover, reduced sediment loads but also decreased runoff, exacerbating water scarcity (Feng et al., 2016; Wang et al., 2016). These interlinked dynamics underscore the YRB as a complex coupled human–natural system, where addressing environmental challenges requires an integrated, systems-oriented approach.

The existing models for the YRB are typically designed for specific problems with a narrow application focus and only represent a limited set of human and natural components within the CHANS. These include limited nature-to-human impact pathways, e.g., low flows threatening farmers' livelihoods (Liu et al., 2008), the damage of floods and droughts on agriculture (Zhang et al., 2015), as well as human-to-nature impact pathways, e.g., effects of ecological restoration policy on hydropower and water–sediment–carbon dynamics (Wu et al., 2025; Yan et al., 2024), and the impacts

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

of irrigation water-saving and salinity-control practices on crop yield and water productivity (Wu et al., 2023). These models focus on isolated components of CHANS, with limited consideration of fully coupled human–natural interactions, which limits their capacity to represent full human–natural interactions and support regional decision-making.

To address the gap in CHANS modeling for the YRB, following our previously proposed CHANS modeling framework for the basin (Sang et al., 2025), we implemented the framework to develop the coupled human and natural systems model for the YRB (CHANS-SD-YRB) using the System Dynamics approach. Through dynamic interaction with policies, climate change, human activities, and environmental feedbacks, the CHANS-SD-YRB model provides a platform for predicting system dynamics, conducting scenario analyses, evaluating policies, and optimizing water-food-carbon synergies. This study offers both theoretical and practical insights for advancing regional CHANS modeling and promoting sustainable development in the YRB.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

2 Description of the CHANS-SD-YRB

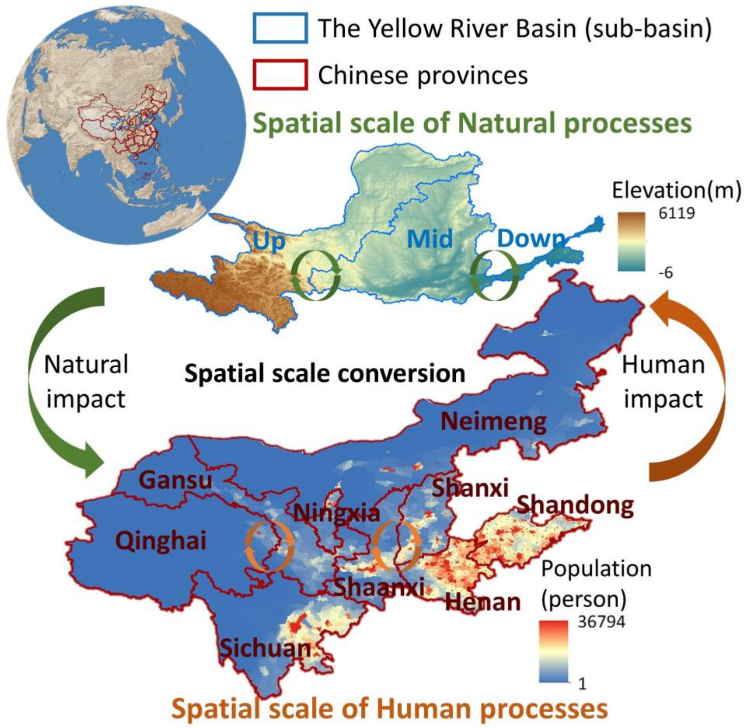


Fig.1 Geolocation of the Yellow River Basin and boundary of the natural and human processes in the CHANS-SD-YRB model. Natural processes are simulated at the sub-basin scale (base map: elevation), and human processes at the provincial scale across nine provinces (base map: population density in 2020).

We developed the CHANS-SD-YRB based on system dynamics, a method well-suited for capturing complex system behaviors characterized by nonlinearity, multi-level structures, and feedback loops (Akhtar et al., 2013). The model was constructed and implemented using the VENSIM DSS (Ventana Systems, 2023) software platform, operating on an annual time step. The CHANS-SD-YRB simulates both human and natural processes for historical simulations (1981–2020) and future projections (2021–2100). Human processes are simulated at the provincial scale, covering the nine provinces along the Yellow River (Qinghai, Sichuan, Gansu, Ningxia, Neimeng,

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Shaanxi, Shanxi, Henan, and Shandong), while natural processes are simulated at the sub-basin scale (up-, mid-, and downstream) (Fig.1). The model is designed to capture the various interactions within and between different components of human system and natural system across administrative and hydrological units. The spatial scale conversion between provincial and sub-basin levels relies on weights (e.g., the proportion of sub-basin-level values to provincial total values) derived from historical high-resolution gridded datasets of human-related variables. These weights enable disaggregation of provincial outputs to the sub-basin level (see Supporting Information S4 for details). Given the availability of gridded data for human processes and the strong correlations among relevant variables, gridded population and GDP data were used as proxies to disaggregate provincial-level outputs to the sub-basin scale (Table S3).

2.1 Model structure

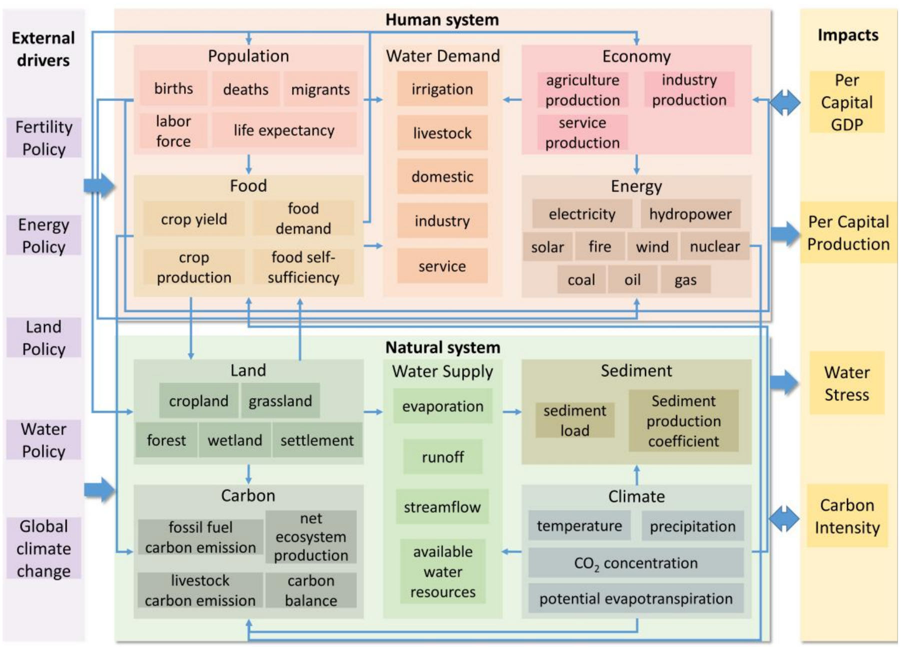


Fig.2 Structure of the CHANS-SD-YRB, which shows sectors of human and natural systems, their key processes and interactions.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Drawing on the modeling framework of CHANS in the YRB (Sang et al., 2025), we designed the CHANS-SD-YRB structure (Fig. 2), including five sectors related to human society (*Population*, *Economy*, *Energy*, *Food*, and *Water Demand*), and five sectors related to natural ecosystem (*Water Supply*, *Sediment*, *Land*, *Carbon,* and *Climate*).

These sectors are interconnected to represent various human-natural interactions as summarized below. Key interactions among human system modules are summarized below. The *Population* sector affects food demand (*Food*), residential water use (*Water Demand*), household electricity and gas consumption (*Energy*), and settlement land area (*Land*). The sector also interacts dynamically with the *Economy* sector, where economic output influences deaths and migrants, while the labor force, in turn, drives economic production. The *Economy* sector drives energy uses (electricity, coal, oil, and gas use) from *Energy*, as well as industrial and service water withdrawal from *Water Demand.* The gross agricultural production in the *Economy* is made up of crop and livestock production (*Food*). The *Energy* sector produces fossil fuel emissions in the *Carbon* sector. The *Food* sector is affected by the *Land* and *Climate* sector, and it also determines irrigation water withdrawal (*Water Demand*) and livestock-related emissions (*Carbon*). Additionally, the *Food* sector interacts closely with the *Land* sector, where crop production depends on cropland area, which, in turn, is influenced by food self-sufficiency. The *Water Demand* sector affects streamflow in the *Water Supply* sector through consumptive water use.

The key interactions among natural system modules are listed below. The *Land* sector influences evapotranspiration in the *Water Supply* sector through vegetation coverage, and it influences carbon absorption in *Carbon* sector through land use area. The carbon absorption is also affected by climatic variables including temperature, precipitation, and CO_2 concentration. Similarly, runoff in the *Water Supply* sector is affected by precipitation, precipitation intensity (mm/h, the rate of rainfall within one hour calculated from daily data), and potential evapotranspiration. Streamflow

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

influences sediment dynamics in the *Sediment* sector together with the *Climate* sector.

In addition, the CHANS dynamics in the YRB are modulated by external drivers, including policies and global climate change that affect various modeled processes (e.g., fertility, energy, land use, and water). With comprehensive representation of CHANS processes and their interactions, the CHANS-SD-YRB model is capable of generating integrated indicators to assess the state of the coupled system, such as per capita GDP, per capita food production, water stress, and carbon intensity. These indicators not only serve as evaluation metrics but also feed back to influence the internal dynamics of the human–natural system in the YRB.

2.2 Sector description

The CHANS-SD-YRB model focuses on the essential human–natural processes in the YRB, with a particular emphasis on human–water interactions. To this end, it has a comprehensive representation of the full range of natural and human processes that influence water use and supply. Formulation of each sector aims to explicitly account for cross-sectoral interactions as fully as possible while remaining sufficiently simple to be implemented within the SD software. Considering data availability and the spatial scales of process, human sectors (*Population*, *Economy*, *Energy*, *Food*, and *Water Demand*) are simulated at the provincial level, while natural sectors (*Water Supply*, *Sediment*, *Land*, *Carbon*, and *Climate*) are simulated at the sub-basin level within the YRB. Next, we describe each sector and its key formulation and provide full details in Supporting Information S2.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

2.2.1 Population

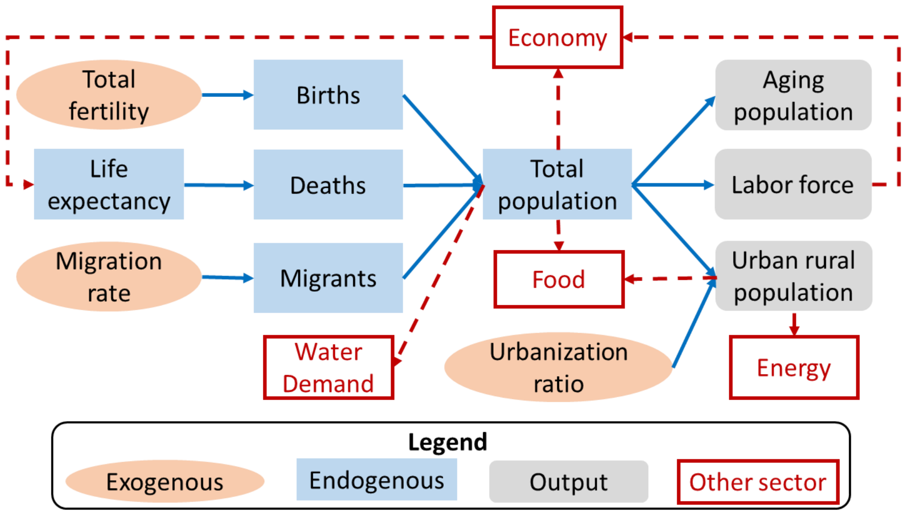


Fig.3 Structure of the *Population* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

Population dynamics are represented by birth, death, and migrants, which are determined by a series of social and economic factors. The total population is characterized by age and gender with exogenous urbanization ratios. The output of *Population* sector drives *Economy*, *Energy*, *Food*, and *Water Demand* sectors through labor force, urban and rural populations.

The key variable, total population, is modeled using the age-structured mathematical method (Kemei et al., 2024), which categorizes individuals by one-year age group and gender (Equation 1),

$$Pop_{g,a} = \ IniPop_{g,a} + \begin{cases} \int (B_{g,a} + NM_{g,a} - D_{g,a})dt, & a = 0 \\ \int (Pop_{g,a} + NM_{g,a} - D_{g,a})dt, & 1 \leq a \leq 99, a = 100 \ \ and \ \ over \end{cases} \tag{1}$$

where *Pop* is population, subscript *g* and *a* are gender (g = M is male, g = F is female) and age (a = 0-100 and over); $IniPop_{g,a}$ is the population in the initial year, $B_{g,a}$ is the births (Equation S2), $D_{g,a}$ is the deaths (Equations S3-S6), and $NM_{g,a}$ is the net migrants (i.e., immigrants – emigrations, Equations S7-S8).

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

2.2.2 Economy

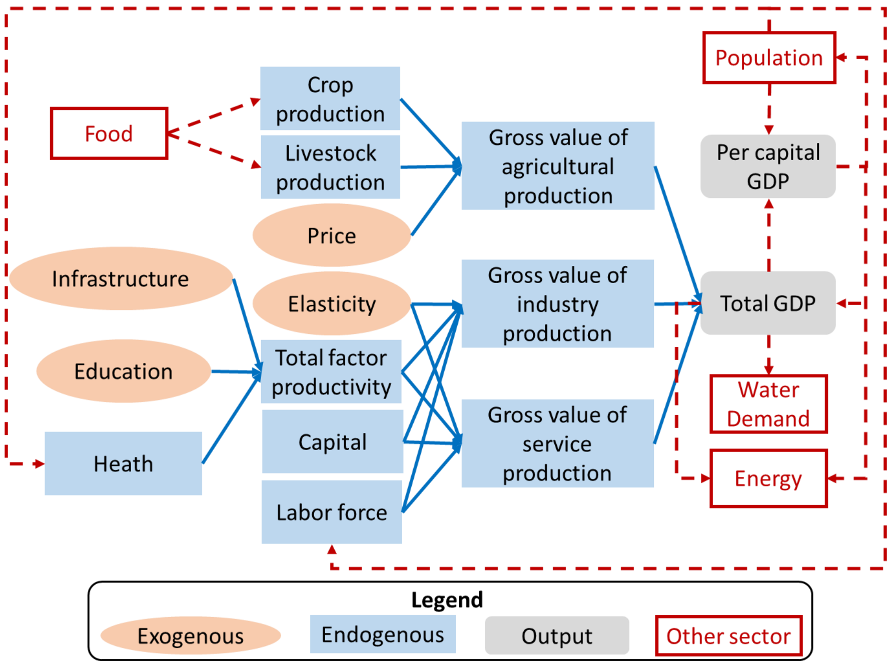


Fig.4 Structure of the *Economy* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Economy* sector simulates production activities in agriculture, industry, and services, which in turn drive changes in the *Population*, *Energy*, and *Water Demand* sectors.

The gross product of industry and services is calculated using the Cobb-Douglas production function (Cobb and Douglas, 1928) to account for multiple factors in the economy (Equation 2). Exogenous variables (infrastructure, education, and elasticity), and endogenous variables (health and labor force) from the *Population* sector (Equations S10-S17) all affect the gross domestic product in industry and service (GDP_s),

$$GDP_s = IniGDP_s \times TFP_s \times \left(\frac{L_s}{IniL_s}\right)^{1-\alpha_s} \times \left(\frac{K_s}{IniK_s}\right)^{\alpha_s} \quad (2)$$

where subscript s represents industry and service, $IniGDP_s$ is the initial GDP; TFP_s is the total factor productivity; L_s represents the labor force and $IniL_s$ is its initial value

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

(from *Population* sector); α_s is capital and $1-\alpha_s$ is labor elasticities, from T21-China (Qu et al., 2020); K_s and $IniK_s$ refer to the capital stock and its initial level.

Gross agricultural production includes crop and livestock production from *Food* sector, calculated by their respective prices (Equations S18-S19).

2.2.3 Energy

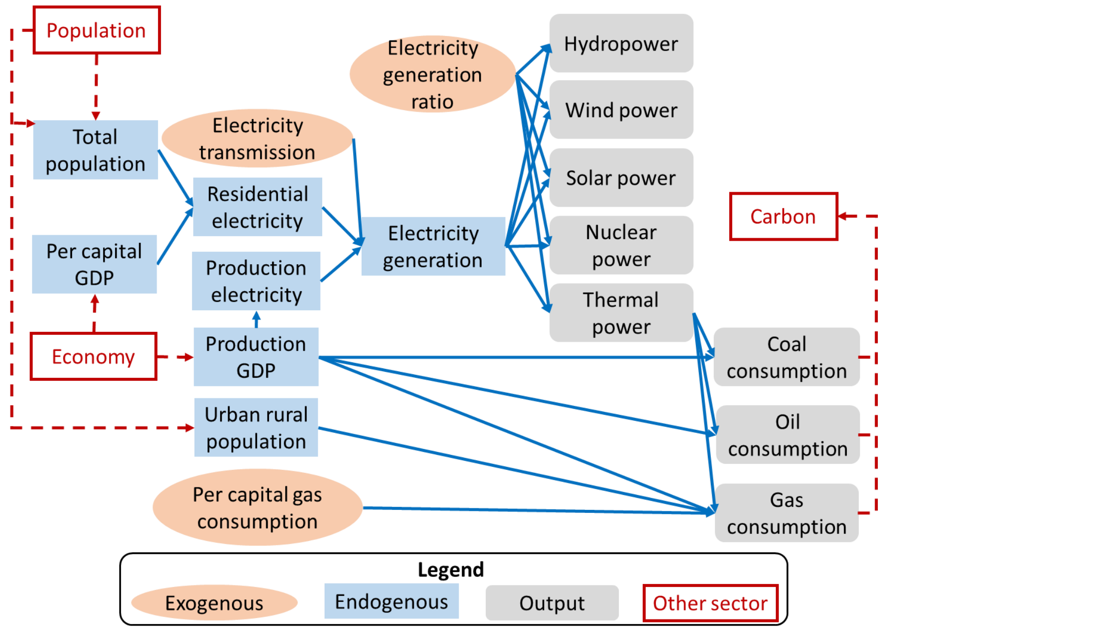


Fig.5 Structure of the *Energy* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Energy* sector simulates production, consumption, and the structure of energy, encompassing coal, oil, gas, and electricity. Coal, oil, and gas consumption are derived from linear relationships between historical sectoral GDP and corresponding consumption (Equations S22-S24). Electricity generation is divided into residential and industrial uses, the former is estimated from the linear fit of historical per capita GDP and residential demand, and the latter is calculated using electricity intensity data from the China Energy Statistical Yearbook (NBSC, 2020a) (Equations S20-S21). Cross-provincial electricity transmission is also incorporated according to the same yearbook. The shares of electricity generated from thermal, hydro, wind, solar, and nuclear

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

sources are determined by exogenously specified ratios, as reported in the China Energy Statistical Yearbook (NBSC, 2020a). Fossil fuel consumption drives carbon emissions in the *Carbon* sector.

2.2.4 Food

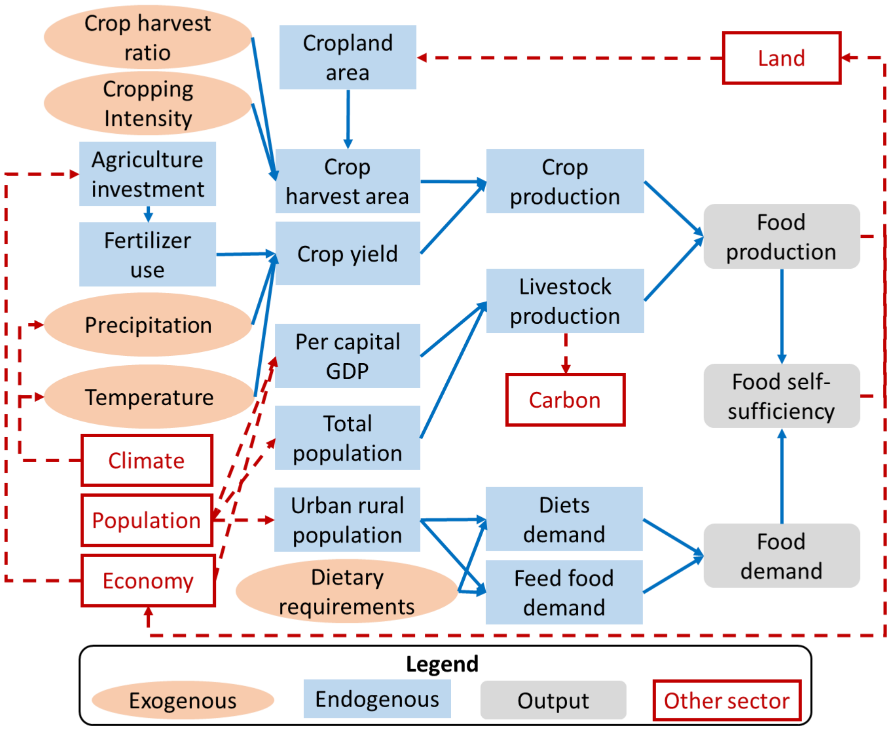


Fig.6 Structure of the *Food* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Food* sector simulates the production of livestock and crops, and food demand, and these productions directly affect gross agricultural production in the *Economy* sector. Livestock production ($Livestock_{pro}$) is calculated by an empirical function, driven by economic development and population growth (Equation 3),

$$Livestock_{pro} = Pop \times \left(Para_{GL1} + (Para_{GL2} - Para_{GL1}) \times \frac{PC_{GDP}}{PC_{GDP} + Const_{GL}}\right) \quad (3)$$

where $Para_{GL1}$、 $Para_{GL2}$ and $Const_{GL}$ are parameters obtained by fitting the historical per capita meat production and per capita GDP (PC_{GDP}) data.

Crop production ($Crop_{pro}$) is determined by the yield ($Yield_c$) and harvest area (PA_c)

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

of seven major crop types (subscript *c*): rice, wheat, corn, soybeans, cotton, potatoes, and oil crops (Equation 4). The harvest area is influenced by cropland area from the *Land* sector, exogenous cropping intensity and crop harvest ratio. Crop yields are positively affected by agricultural investment from the *Economy* sector, along with effects of precipitation, temperature, and CO_2 concentration from the *Climate* sector (Equations S26-S31).

$$Crop_{pro} = \sum_{c=1}^{7} Yield_c \times PA_c \tag{4}$$

Food demand encompasses both staple and feed grain demand, which are determined by population size from *Population* sector and dietary patterns (Equations S33-S36).

2.2.5 Water Demand

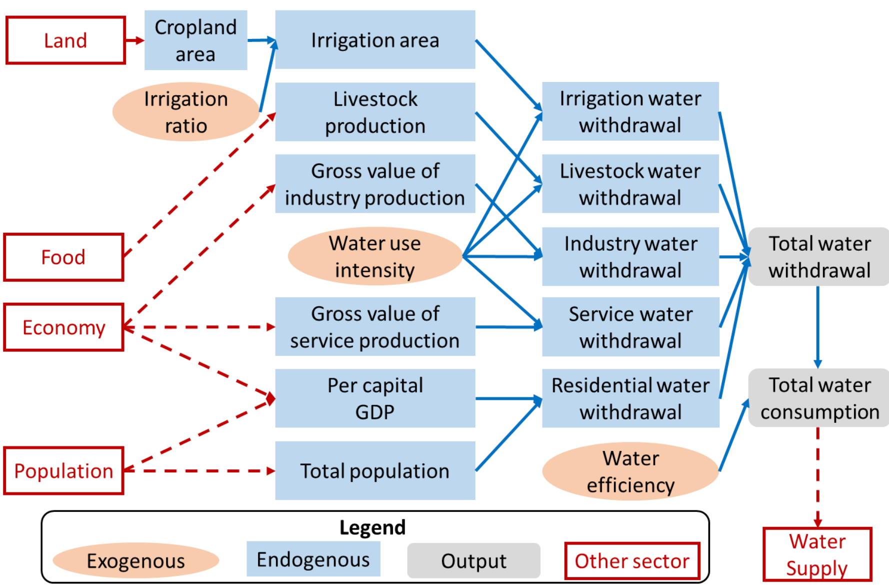


Fig.7 Structure of the *Water Demand* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Water Demand* sector simulates water withdrawal (*WW*) and consumption (*WC*) across multiple uses—irrigation, livestock, industry, services, and residential—in the nine provinces of the YRB. Water consumption is derived as the product of water

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

withdrawal and water use efficiency reported in the Water Resources Bulletin (YRCCMWR, 2020) (Equations S37-S38), which affects the *Water Supply* sector.

Irrigation water withdrawal (WW_{irr}) is estimated based on exogenous irrigation water use intensity (WWI_{irr}), and irrigation cropland ratios (IR) from the China Agricultural Yearbook (MAARA, 2020), and cropland area ($Area_{Cropland}$) provided by the *Land* sector (Equation 5).

$$WW_{irr} = WWI_{irr} \times Area_{Cropland} \times IR \tag{5}$$

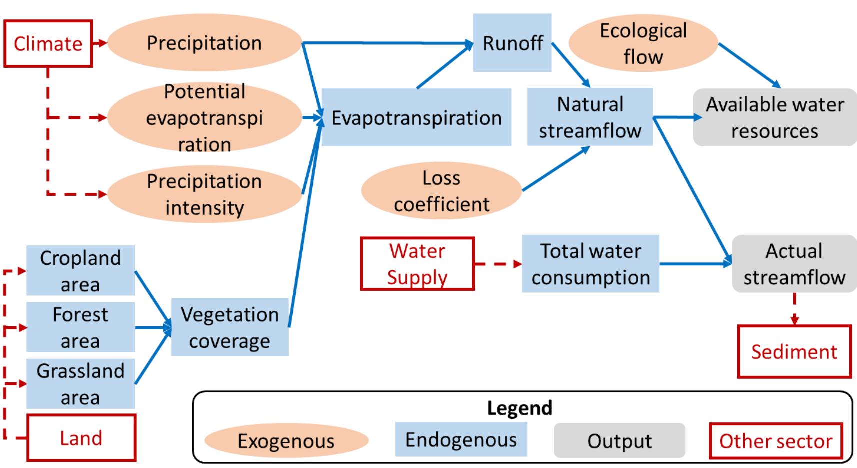
The water withdrawal for livestock, industry, and services is also driven by exogenous sectoral water use intensities collected from the China Statistical Yearbook and National Long-term Water Use Dataset of China (Zhou et al., 2020), in combination with livestock production from the *Food* sector, economic output from the *Economy* sector (Equations S40-S43).

Residential water withdrawal (WW_{res}) is obtained from the empirical function, driven by economic development and population growth (Equation 6),

$$WW_{res} = Pop \times \left(Para_{GD1} + (Para_{GD2} - Para_{GD1}) \times \frac{PC_{GDP}}{PC_{GDP}+Const_{GD}}\right) \tag{6}$$

where $Para_{GD1}$, $Para_{GD2}$, and $Const_{GD}$ are parameters obtained by fitting the historical per capita domestic water use with per capita GDP (PC_{GDP}).

2.2.6 Water Supply



https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Fig.8 Structure of the *Water Supply* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Water Supply* sector simulates runoff, discharge, and their changes in each sub-basin. Runoff (R) is determined by precipitation (Pre) and evapotranspiration (ET) based on the water balance principle derived from the Budyko equation, which is suitable for non-humid regions of China (Yang et al., 2009) (Equation 7).

$$R = Pre - ET \tag{7}$$

The ET is calculated by various exogenous climate variables from the *Climate* sector, and vegetation coverage from the *Land* sector (Equations 8-9, S46-S48),

$$ET = \frac{PET \times Pre}{(Pre^n + EP^n)^{\frac{1}{n}}} \tag{8}$$

$$n = Para_{E1} \times \left(\frac{Ks}{PI}\right)^{Para_{E2}} \times FVC^{Para_{E3}} \times e^{Para_{E4} tan\beta} \tag{9}$$

where PET is potential evapotranspiration at sub-basin, from the *Climate* sector; n is a parameter reflecting the basin landscape characteristics, related to saturated hydraulic conductivity (Ks), precipitation intensity (PI), average slope (β), and fraction of vegetation coverage (FVC); $Para_{E1}$, $Para_{E2}$, $Para_{E3}$, and $Para_{E4}$ are parameters fitted from historical data.

Runoff and the loss coefficient (defined by the ratio of natural streamflow to runoff) determine the natural streamflow due to the water loss during the confluence process (Equation S49). Natural streamflow and ecological flow constraints define the upper limit of available water resources. By integrating human water consumption from the *Water Demand* sector across sub-basins, the model calculates the actual streamflow (Equations S50-S52). Actual streamflow is transferred through hydrological connectivity from upstream to midstream and then to downstream, ultimately reaching the sea, which governs sediment transport processes within the *Sediment* sector.

2.2.7 Sediment

The *Sediment* sector estimates sediment load (Sed) for each sub-basin using an empirical model in the literature (Yin et al., 2023b), which links actual streamflow from

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

the *Water Supply* sector to sediment transport,

$$Sed = Para_{SS} \times AS + Const_{SS} \tag{10}$$

where $Para_{SS}$ and $Const_{SS}$ are derived from linear fitting of historical hydrological station data on actual streamflow and sediment load.

2.2.8 Land

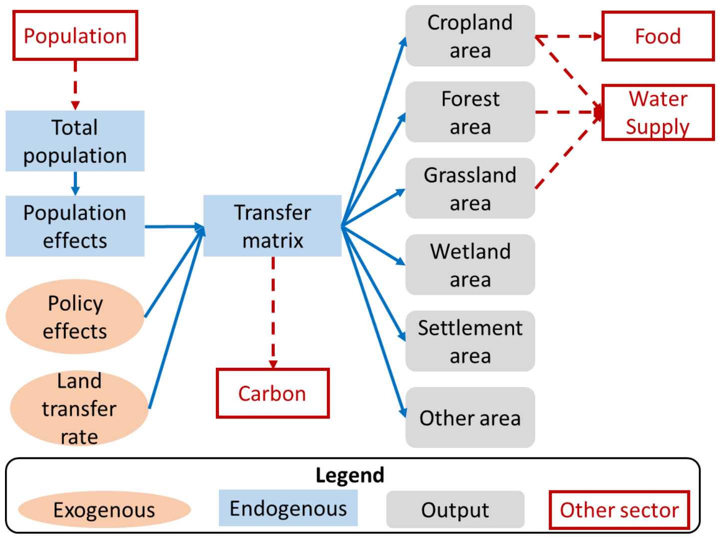


Fig.9 Structure of the *Land* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Land* sector simulates the area changes of six land use types (cropland, forest, grassland, wetland, settlement, and others) based on the land transfer matrix obtained from historical remote sensing data (Xu et al., 2018). The land transfer matrix calculates the inflow and outflow of each land category and can be configured to represent the influence of future land use drivers. This sector outputs vegetation area (including forest, grassland, and cropland), which influences the *Water Supply* sector. Cropland area changes impact the *Food* sector, while land use conversion also plays a role in the *Carbon* sector.

Based on the initial land use area ($IniArea_i$), the transfer matrix determines the area ($Area_i$) allocated to each land use type (Equations 11, S55-S61),

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

$$Area_i = IniArea_i + \int \left(\sum_{i=1}^{6} FTM_{i,j} - \sum_{j=1}^{6} FTM_{i,j}\right)dt \qquad (11)$$

where $FTM_{i,j}$ is the finial land use transfer matrix, indicating the area of land use i transferred to land use j, i and j represent six land use type.

2.2.9 Carbon

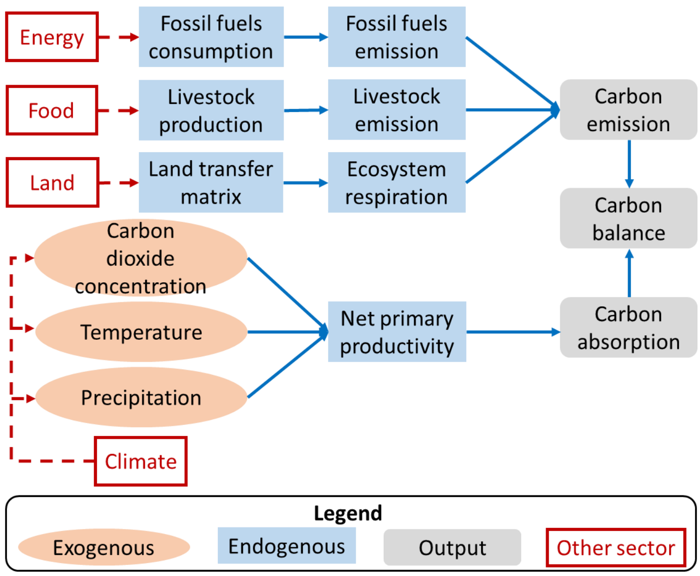


Fig.10 Structure of the *Carbon* sector. Blue lines indicate connections inside the sector, red dotted lines indicate connections with other sectors.

The *Carbon* sector simulates the basin's carbon balance processes, including carbon emission and absorption, adapted from the carbon cycle of ANEMI (Davies and Simonovic, 2011). Carbon emissions (*CE*) encompass fossil fuel emissions, and livestock emission, and ecosystem respiration, which are influenced by outputs from the *Energy*, *Food*, and *Land* sectors.

Fossil fuel and livestock emissions are calculated based on fossil fuel consumption, livestock production, and their respective emission coefficients. Ecosystem emissions include carbon released from burning as well as from the decomposition of biomass, litter, humus, and charcoal, which are determined by carbon pools' lifespans, decomposition factor, and respiration coefficients (Equations S64-S88).

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Carbon absorption (*CA*) is determined by net primary productivity (*NPP*) and land use area. NPP is influenced by climate factors, including CO_2 concentration, temperature, and precipitation (Equations 12, S63),

$$CA = \sum_{i=1}^{6} NPP_i \times Area_i \tag{12}$$

where i represent land use type, land use area ($Area_i$) from the *Land* sector.

2.2.10 Climate

The *Climate* sector supplies both historical and projected climate data essential for the *Water Supply*, *Food*, and *Carbon* sectors. The key climate variables comprise temperature and precipitation (at the sub-basin and provincial levels), as well as potential evapotranspiration, precipitation intensity, and CO_2 concentration (at the sub-basin level). These variables are treated as exogenous inputs, without accounting for potential feedbacks from human activities or natural system responses on regional climate patterns.

2.3 Data sources

In the model, there are more than 100 exogenous variables, some of which are initial variables that drive the simulation. These exogenous variables are derived either from historical statistical data or from fitted results based on historical data (Table S2). All data sources required for the model simulation are listed in Table 1.

Table 1. Summary of data sources for the YRB model. Updated from Sang et al. (2025).

Sector	Variables*	Data sources	Spatial and temporal scale	Time range
Population	age-specific population, births, deaths, migrants	• China Statistical Yearbook (NBSC, 2020c), • China Population Census Yearbook (NBSC, 2020b)	• provincial, annual	• 1981–2023
Economy	GDP, investment, employment	• China Agricultural Yearbook (MAARA, 2020), • China Statistical	• provincial, annual	• 1981–2023

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

		Yearbook (NBSC, 2020c)		
Energy	electricity, coal, oil, gas consumption	• China Energy Statistical Yearbook (NBSC, 2020a)	• provincial, annual	• 1981–2023
Food	crop production, fertilizer, irrigated area	• China Agricultural Yearbook (MAARA, 2020)	• provincial, annual	• 1981–2023
Water demand	Industrial, domestic, irrigation water withdrawal	• National Long-term Water Use Dataset of China (NLWUD) (Zhou et al., 2020) • China Statistical Yearbook (NBSC, 2020c)	• prefectural, annual	• 1965–2013 • 1981–2023
Water supply	runoff, streamflow, water stress	• China Natural Runoff Dataset (CNRD) (Gou et al., 2021), • Gauge-based Natural Streamflow Dataset (Miao et al., 2022) • Yellow River Water Resources Bulletin (YRCCMWR, 2020)	• 0.25° grid, Monthly • 0.25° grid, annual • provincial, annual	• 1961–2018 • 1961–2018 • 1998–2022
Sediment	sediment load	• Yellow River Water Resources Bulletin (YRCCMWR, 2020)	• provincial, annual	• 1998–2022
Land	cropland, forest, grassland, wetland, settlement	• China land use remote sensing monitoring dataset (CNLUCC) (Xu et al., 2018) • Long-term global land surface satellite fractional vegetation cover product (Jia et al., 2015, 2019)	• 1 km grid, annual	• 1980, 1990, 1995, 2000, 2005, 2010, 2015, 2020
Carbon	fossil fuel carbon emissions, net primary productivity	• Carbon Emission Accounts and Datasets (Shan et al., 2018), • Global Vegetation	• Provincial, annual • 5 km grid, 8 day	• 1997–2021 • 1981–2018

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

		Productivity Products (GVPP) (Cui et al., 2016; Wang et al., 2020a; Yu et al., 2018)		
Climate	temperature, precipitation, CO_2 concentration, potential evapotranspiration and precipitation intensity	• Gridded daily observation dataset over China region (Wu and Gao, 2013), • European Environment Agency (EEA, 2019), • China Meteorological Data Service Center (https://data.cma.cn/)	• 0.25° grid, Annual • Global, Annual • Meteorological stations, Monthly	• 1961–2020 • 1800-2020 • 1956-2018

* Listed are some typical variables of each sector

3 Model validation and application

3.1 Historical model validation

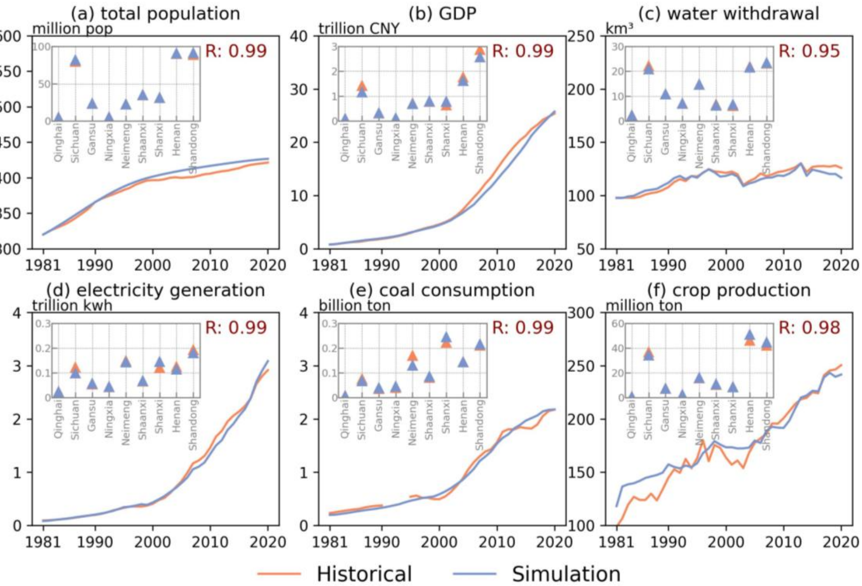


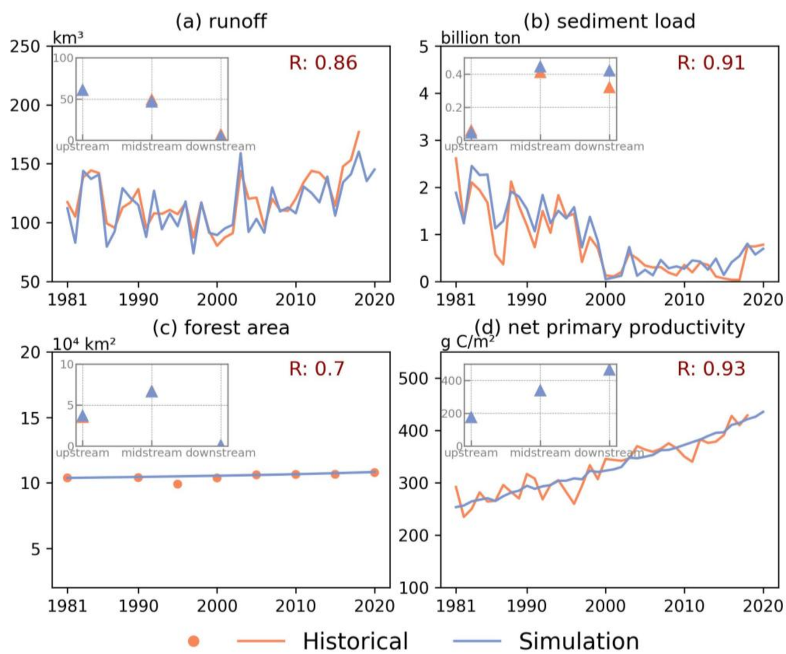
Fig.11 Validation of human system processes during historical period of 1981-2020. (a) total population in *Population* sector; (b) GDP in *Economy* sector; (c) water withdrawal in *Water Demand* sector; (d) electricity generation and (e) coal consumption in *Energy* sector; (f) crop production in *Food* sector. Pink triangles in the upper left sub-image represents the average of historical and simulation value in

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

1981-2020 of each province in the YRB.

We compared model performance during the historical period (1981–2020) against historical data. These data are sourced from multiple channels, including statistical yearbooks, hydrological stations, remote sensing observations, and outputs from other models (Table S3).

For human sectors, the simulation accuracy of selected key variables from each sector is consistently high (R > 0.95), including total population, gross domestic product (GDP), water withdrawal, electricity generation, coal consumption, and crop production across the nine provinces. However, the accuracy varies among provinces, particularly for GDP, electricity generation, coal consumption, and crop production. In general, Shanxi exhibits lower simulation accuracy compared to the others. Among all sectors, the greatest uncertainty arises in simulating coal consumption, because the absence of a clear historical trend results in poor fitting performance. Nevertheless, the model performs reasonably well in the human sectors, effectively capturing the historical dynamics of human systems in the YRB.



https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Fig.12 Validation of the natural system processes during historical period of 1981-2020. (a) runoff in *Water Supply* sector; (b) sediment load in *Sediment* sector; (c) forest area in *Land* sector, and the historical dataset is discontinuous; (d) net primary productivity in *Carbon* sector. Pink triangles in the upper left sub-image represents the average of historical and simulation value in 1981-2020 of each sub-basin in the YRB.

For natural sectors, the simulation accuracy for runoff, sediment load, forest area, and NPP in the YRB is relatively high ($R > 0.7$). At the sub-basin level, the overall performance is satisfactory; however, the model shows lower accuracy in simulating sediment transport in the mid- and downstream. Compared to the human sectors, the natural sectors generally exhibit lower correlations with historical data, largely due to the simplifications required when modeling physically complex natural processes. Nevertheless, the model is still capable of capturing the historical dynamics of natural processes in the YRB.

3.2 Model application for future projection

3.2.1 Future baseline scenario

The future baseline scenario represents a trajectory in which existing plans and policies continue to operate without substantial changes in external environments. The development of the baseline scenario primarily relies on variables from the *Population*, *Economy*, *Water Demand*, and *Land* sector based on available government planning documents, historical trends, and other projections (Table 2). Future climate data (2015-2100) are from the ensemble mean of 11 CMIP6 models (ACCESS-CM2, CESM2, CMCC-ESM2, GFDL-ESM4, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, UKESM1-0-LL, and HadGEM-GC31-LL) (available at https://cds.climate.copernicus.eu/datasets/projections-cmip6?tab=download) for the SSP 2-4.5 because this scenario aligns more closely with the climate trends in the YRB. To ensure temporal consistency, CMIP6 historical climate data (1981–2014) were used instead of observed historical records. We run the model under the future baseline

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

scenario to project the evolution of CHANS in the basin from 2021 to 2100 (see Supporting Information S5 for details of scenario design).

Table 2 Settings of key variables in the future baseline scenario

Sector	**Variables**	**Future baseline**
Population	• Total fertility • Gender ratio • Average years of schooling • Urban and rural population ratio • Labor force	• 2024 United Nations Population Projections • 2024 United Nations Population Projections • The national maximum in 2023 (Germany) as the upper limit • Analysis and Forecast of Urbanization Trends in China's Modernization by 2020 • Delay retirement age
Energy	• Electricity generation sources ratio • Irrigation intensity	• Projected provincial-level energy structure meeting China's carbon peaking and carbon neutrality goals (Li et al., 2024) • Irrigation water use intensity declines linearly (1%/yr) to its minimum value.
Water Demand	• Industry, service, livestock water use intensity	• Industry, service and livestock water use intensity declines linearly (1%/yr) to its minimum value.
Land	• Land use area	• Minimum cropland area above the red line for cropland protection. • Other lands are allowed to be fully converted into other categories.
Climate	• Temperature, Precipitation, Potential evapotranspiration, precipitation intensity,	• SSP 2-4.5 —— CMIP 6

	CO_2 concentration,

3.2.2 Projection of CHANS dynamics in future baseline scenario

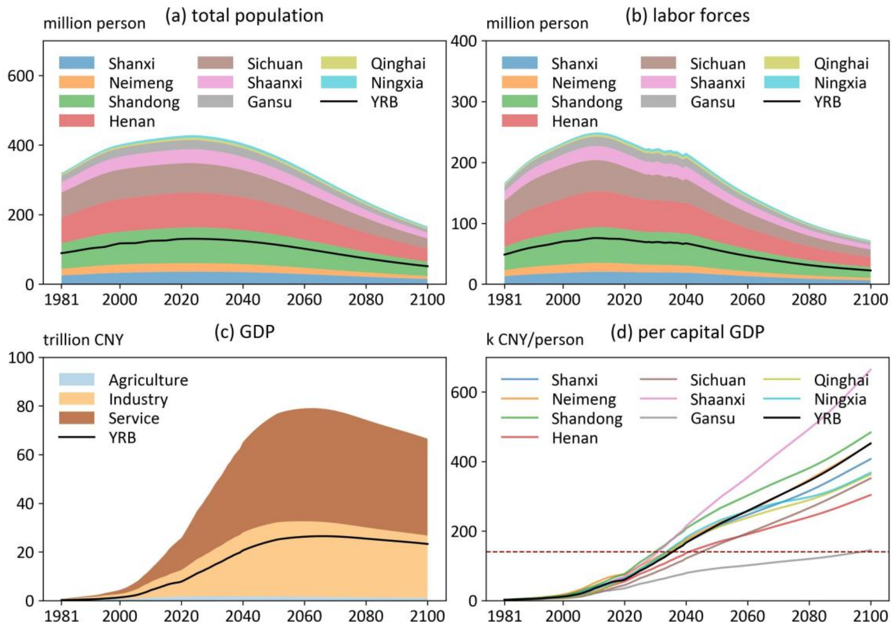


Fig.13 Changes in key variables of the *Population* and *Economy* sector in the future baseline scenario: (a) the total population, (b) the total labor forces, (c) the gross output of agriculture, industry, and service, and the total gross domestic output, (d) the per capital GDP in nine provinces and YRB.

The model simulates human and natural system dynamics under the future baseline scenario and produces outputs for nine provinces and their corresponding areas within the YRB. The simulation results are reported either at the provincial level (nine provinces) for human system sectors or at the basin level (basin boundary) for natural system sectors. The total population in the nine provinces and the YRB is projected to peak in 2023 and 2024, at 428 million and 131 million, respectively, driven by declining fertility rates. The labor force peaks earlier, reaching 249 million in the nine provinces in 2011 and 76 million in the YRB in 2010. After 2025, the labor force is projected to increase again due to the delayed retirement policy. GDP in the nine provinces is

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

expected to increase until a peak in 2062, at 79 trillion CNY (three times the 2020 level, in 2020 constant prices), under the influence of a labor force decline, with the YRB reaching its peak four years later. In contrast to total GDP, per capita GDP in all regions is projected to continue rising throughout the future period. Although all provinces demonstrate improvements in economic status and living standards, considerable regional disparities persist. Among the nine provinces, Shaanxi demonstrates the largest growth in average per capita GDP from 2021 to 2100 relative to the historical period (1981-2020), with a more than sixteenfold increase, while the YRB as a whole shows an over twelvefold increase.

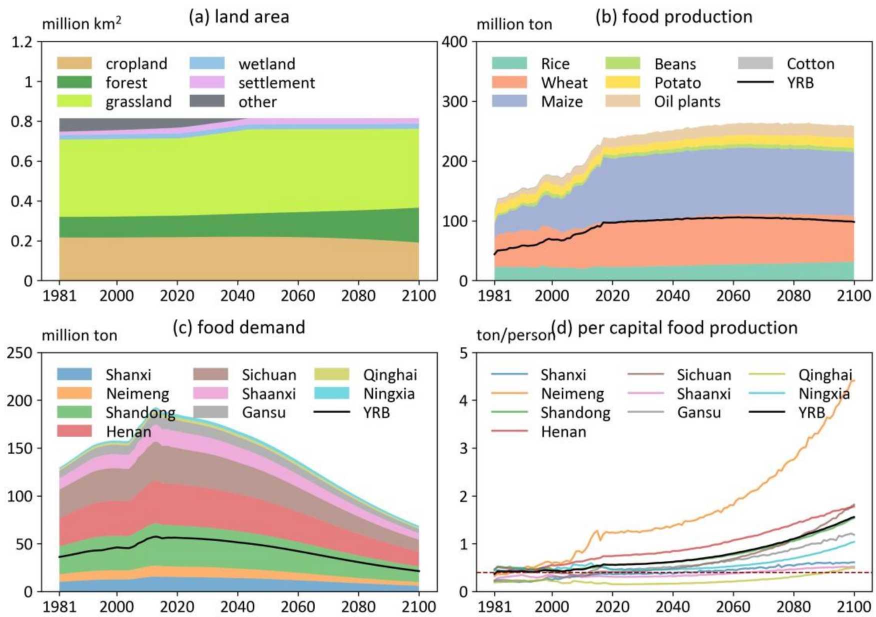


Fig.14 Land and food in the future baseline scenario. (a) land area in the YRB; (b-d) food production of seven crop types, food demand and per capital food production in nine provinces and the YRB, red dotted line represents the 0.4 tons international food security threshold.

Under the future baseline scenario, land use patterns remain relatively stable based on historical trends, as no new land policies are introduced and cropland area needs to stay above the red line. The forest area is projected to increase gradually, reaching 62%

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

above the 2021 level by 2100, while the cropland area is expected continue declining, falling 12% below the 2021 level. Total crop production in nine provinces and YRB is projected to peak in 2079 and 2062, respectively, driven by the combined effects of declining cropland area and increasing crop yields. Food demand in both the nine provinces and the YRB as a whole peaked in 2013 (192 million tons and 57 million tons, respectively), largely driven by population dynamics. In the future, per capita food production in the YRB is projected to consistently exceed the international food security threshold of 0.4 tons per person. However, in certain years, provinces such as Qinghai and Shaanxi could fall below this standard.

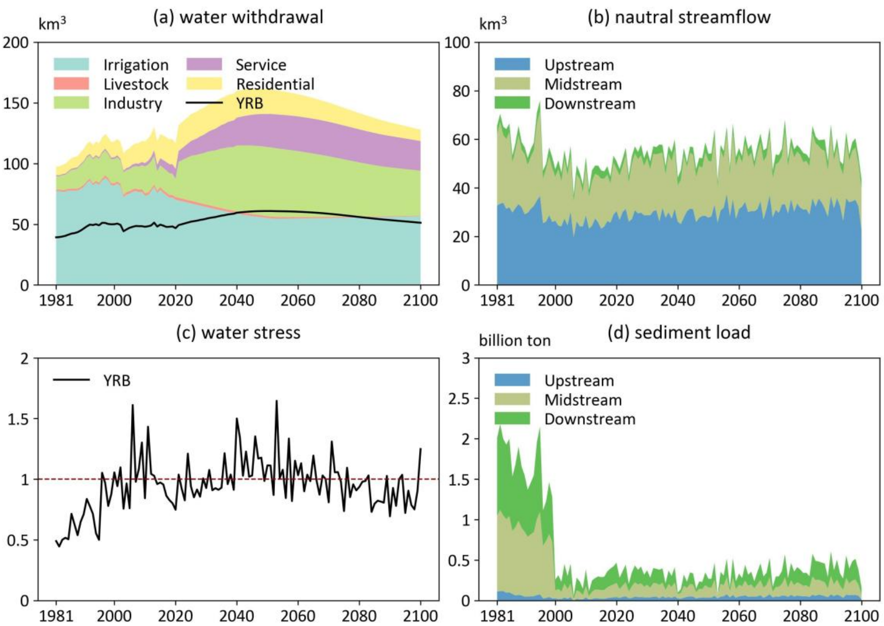


Fig.15 Water demand and supply in the future baseline scenario. (a) water withdrawal across five water-use sectors in nine provinces and the YRB; (b) natural streamflow in up-, mid- and downstream; (c) water stress in the YRB, red dotted line represents the water security threshold; (d) sediment load in the up-, mid- and downstream.

Total water withdrawal in the nine provinces and the YRB is projected to peak in 2047 and 2051, reaching 162 km³ and 61 km³, respectively. Irrigation water withdrawal is expected to decline, driven by reductions in cropland area and irrigation intensity, the

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

latter resulting from improvements in irrigation efficiency assumed in the scenario. Peaks in residential, industrial, service, and livestock water withdrawals are primarily associated with projected peaks in population and GDP. Natural streamflow is projected to follow a fluctuating upward trend, with the future annual mean nearly identical to the historical average (a 0.7% increase), and the largest increase occurring in the upstream region (8%). Considering the ecological flow requirement of 18.7 km^3 (YRCCMWR, 2015), water stress (calculated as water consumption divided by (natural discharge - ecological flow)) is expected to decline in the latter half of the century, largely due to the peak and subsequent reduction in water withdrawal. However, overall water stress is projected to exceed historical levels in 2041 and will fall below 1 in 54% of the years, reflecting mitigation of persistent human–water tensions and future trade-offs between ecological and human water use. As a result of reduced actual streamflow, sediment transport in the Yellow River is projected to decline sharply, with a 63% decrease in sediment load relative to the historical period.

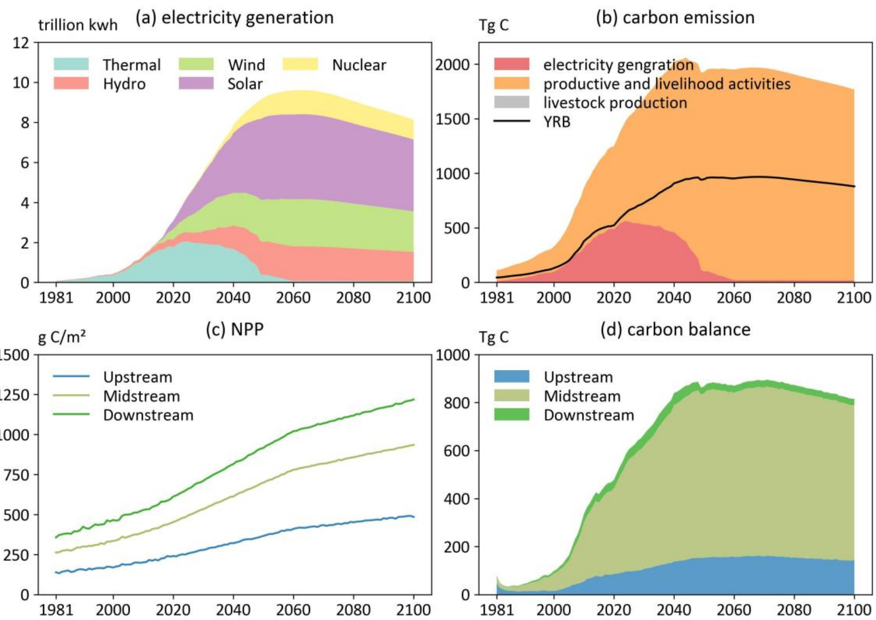


Fig.16 Electricity and carbon in the future baseline scenario. (a) the electricity generation from five sources in nine provinces; (b) carbon emission from three

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

sources in nine provinces and the YRB; (c-d) the net primary productivity and carbon balance in the up-, mid-, and downstream.

Since the energy system is transitioning to carbon neutrality goals under the future baseline scenario, thermal power generation is projected to decline sharply, while clean energy (hydropower, wind, solar, and nuclear) will become the dominant source for electricity generation. The large-scale adoption of clean energy will lead to a peak in carbon emissions from electricity generation in 2024. In contrast, emissions from productive and livelihood activities are projected to rise substantially over time, with total human emissions in the YRB reaching a peak in 2044. NPP is anticipated to increase markedly in response to CO_2 concentration increase. Although the carbon balance of the YRB has remained positive (net carbon source), it is expected to gradually decline after 2071, indicating that the basin's ecosystems alone cannot fully offset human-induced carbon emissions.

The above projections of future baseline scenarios highlight persistent challenges to achieving sustainable development in the YRB, underscoring the need for integrated policy responses to address these challenges. Priority should be given to enhancing water-use efficiency and establishing adaptive water resource allocation mechanisms that balance ecological and human water needs. Sediment management strategies, which combine ecological restoration with hydraulic regulation, are necessary to maintain river stability and delta health. To counter the decline in labor force, policies should promote industrial upgrading and technological innovation. Strengthening the basin's carbon mitigation capacity requires accelerating the clean energy transition and expanding ecological restoration to enhance carbon sequestration. Finally, a multi-sectoral, CHANS-based governance framework should be established to coordinate water, land, energy, and carbon management, enabling evidence-based scenario analysis and adaptive policy design for long-term sustainability.

4 Discussion and conclusions

The development of the CHANS-SD-YRB model involves a series of key

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

considerations in translating a conceptual framework into a functioning model. The framework focuses on human–water interactions in the YRB, integrating bidirectional feedback between human and natural processes. SD was chosen to implement the framework, as it effectively captures feedback, non-linear relationships, and cross-sectoral linkages within complex human–natural systems, while remaining practical and straightforward to use. For quantitative representation of human–natural processes, we prefer theoretical methods that incorporate key interactions within the system suitable for implementation using SD. For example, the Budyko framework connects the *Land*, *Climate*, *Water Demand*, and *Water Supply* sectors. Relative to distributed hydrological models, it offers lower computational complexity and reduced data requirements. The Cobb–Douglas production function links the *Population* and *Economy* sectors. Compared with Computable General Equilibrium models (Fujimori et al., 2014), it is simpler to construct and requires fewer parameters and data inputs. When no suitable theoretical framework/method is available to describe a process, we rely on empirical relationships derived from historical data. For example, crop yields are estimated using fitted relationships between climate variables, fertilizer application, and historical yields. For processes that cannot be represented through empirical functions, we apply literature-based estimates to obtain approximate quantitative relationships, such as fossil fuel emission factors. For processes influenced by external drivers that cannot be endogenously expressed within the model, we quantify them using exogenous parameters derived from historical statistics, such as water intensity. Given the heterogeneous human–natural interactions in the YRB, we represent all processes at the provincial and sub-basin scales using scale-specific parameters, except where parameters or data at these levels are unavailable.

The CHANS-SD-YRB model explicitly couples multiple human and natural sectors, enabling a more integrated representation of feedbacks across population, economy, energy, food, water, sediment, land, carbon, and climate. Unlike models that focus on specific sectors or isolated subsystems—such as eco-hydrological models and

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

sediment transport models, which may well capture individual processes but cannot represent the complex human–nature interactions driving system dynamics. Our model's comprehensive coupling broadens its scope of application to address complex regional CHANS challenges and provides practical guidance for sustainable development. The CHANS-SD-YRB model serves as a comprehensive platform for conducting system dynamics prediction, scenario analysis, policy evaluation, and optimization, to alleviate human–water conflicts, ensure food security, and achieve long-term sustainability. For example, analysis of the impacts of the 1987 Yellow River water allocation policy (Song et al., 2024) offer valuable insights for adjusting interprovincial water distribution to promote sustainable water governance; assessment of ecological restoration policies (Li et al., 2015) can guide future ecological engineering; spatiotemporal dynamics of future water gaps can serve as a valuable reference for planning inter-basin water transfers. The model's flexibility also allows for the incorporation of additional feedback, for example, linking water scarcity to industrial output or climate warming to agricultural productivity. These could include the effects of global warming on human health (Yin et al., 2023a) and economic activities (Nordhaus, 2017), water constraints on production, dietary shifts influencing carbon emissions and land use (Ren et al., 2023), and the trade-offs between carbon mitigation and food security (Xu et al., 2022).

Nevertheless, the model remains subject to further refinement. The current simplifications of natural processes could be replaced with more sophisticated models to enhance simulation accuracy. For instance, the YRB hydrological processes involve highly complex human interventions, including reservoir, conservation, and revegetation projects (Wang et al., 2025). The refined runoff simulations by distributed hydrological models improve water supply assessments through their better characterization of spatial heterogeneity in soil, precipitation, and snowmelt (Cong et al., 2009). The model's spatial and temporal resolutions are relatively coarse due to the inherent mismatch in spatiotemporal scales between human and natural processes. The scale at which we make the model represents a practical compromise, constrained by data availability and aligned with the study's objectives. Simulations at finer scales (e.g., monthly, daily, or gridded) would enhance the representation of natural processes (e.g., hydrological processes, land use changes, and food production) and the associated spatiotemporal heterogeneity (e.g., daily simulations can assess the impacts of extreme weather). However, it may also exacerbate the scale mismatch with socioeconomic processes, making it challenging to analyze cross-sectoral dynamics. Technically, the inherent limitations of the SD software restrict the model's ability to represent temporal fluctuations and spatial variations. To overcome this, transitioning from the VENSIM platform to a code-based implementation will be necessary, which would also facilitate coupling with other models. Future research should prioritize these improvements to strengthen both the performance and applicability of the model.

Overall, the CHANS-SD-YRB model fills the gap in CHANS modeling for the YRB. It integrates the dynamics of ten interconnected sectors: *Population*, *Economy*, *Energy*, *Food*, *Water Demand*, *Water Supply*, *Sand*, *Land*, *Carbon*, and *Climate*, achieving reciprocal feedback between human and natural systems. This model can serve as a robust tool to inform policy decisions that influence the evolution of coupled human–natural systems and to explore pathways for optimizing these systems toward sustainability. Furthermore, the modeling process provides valuable experience for regional CHANS modeling and contributes to advancing the broader development of CHANS models at the regional scale.

Code and data availability

The CHANS-SD-YRB V1.0 model (Vensim DSS format), along with the input data and simulation outputs used in this study, are openly accessible at https://doi.org/10.5281/zenodo.17568963 (Sang, 2025).

Author contributions

Conceptualization: YL, SS[1], BF. Data curation: SS[1]. Formal analysis: SS[1]. Funding acquisition: BF, YL. Investigation: YL, SS[1]. Methodology: SS[1], YL, BF.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Project administration: YL. Resources: YL. Software: SS[1], SZ, LY. Supervision: YL, BF. Validation: SS[1], SZ, LY. Visualization: SS[1]. Writing – original draft: SS[1]. Writing – review and editing: SS[1], YL, SW, YXL, XTW, SS[2], WZ, XHW. (Note: SS[1] refers to Shan Sang, and SS[2] refers to Shuang Song, to distinguish between authors with identical initials.)

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Dr. Weishuang Qu for developing the Threshold 21 model in the Millennium Institute that inspired this study, and also for his and Dr. Haiyan Jiang's generous help with the CHANS-SD-YRB modeling. We also thank the data support from National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn).

Financial support

This study is supported by the National Natural Science Foundation of China (Grant No. 42041007), and the Fundamental Research Funds for the Central Universities.

References:

Akhtar, M. K., Wibe, J., Simonovic, S. P., and MacGee, J.: Integrated assessment model of society-biosphere-climate-economy-energy system, Environmental Modelling & Software, 49, 1–21, https://doi.org/10.1016/j.envsoft.2013.07.006, 2013.

Allen, C., Metternicht, G., Wiedmann, T., and Pedercini, M.: Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging, Nat Sustain, 2, 1041–1050, https://doi.org/10.1038/s41893-019-0409-9, 2019.

Baldos, U. L. C., Chepeliev, M., Cultice, B., Huber, M., Meng, S., Ruane, A. C., Suttles, S., and van der Mensbrugghe, D.: Global-to-local-to-global interactions and climate change, Environ. Res. Lett., 18, 053002, https://doi.org/10.1088/1748-9326/acc95c, 2023.

Breach, P. A. and Simonovic, S. P.: ANEMI3: An updated tool for global change analysis, PLoS ONE, 16, e0251489, https://doi.org/10.1371/journal.pone.0251489, 2021.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Changming, L. and Shifeng, Z.: Drying up of the yellow river: its impacts and counter-measures, Mitigation and Adaptation Strategies for Global Change, 7, 203–214, https://doi.org/10.1023/A:1024408310869, 2002.

Cheng, Y., Huang, M., Lawrence, D. M., Calvin, K., Lombardozzi, D. L., Sinha, E., Pan, M., and He, X.: Future bioenergy expansion could alter carbon sequestration potential and exacerbate water stress in the United States, Science Advances, 8, eabm8237, https://doi.org/10.1126/sciadv.abm8237, 2022.

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C., and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models, Water Resources Research, 51, 5929–5956, https://doi.org/10.1002/2015WR017096, 2015.

Cobb, C. W. and Douglas, P. H.: A theory of production, The American Economic Review, 18, 139–165, 1928.

Cong, Z., Yang, D., Gao, B., Yang, H., and Hu, H.: Hydrological trend analysis in the Yellow River basin using a distributed hydrological model, Water Resources Research, 45, 2008WR006852, https://doi.org/10.1029/2008WR006852, 2009.

Cui, T., Wang, Y., Sun, R., Qiao, C., Fan, W., Jiang, G., Hao, L., and Zhang, L.: Estimating Vegetation Primary Production in the Heihe River Basin of China with Multi-Source and Multi-Scale Data, PLOS ONE, 11, e0153971, https://doi.org/10.1371/journal.pone.0153971, 2016.

Davies, E. G. R. and Simonovic, S. P.: ANEMI: a new model for integrated assessment of global change, Interdisciplinary Environmental Review, 2011.

Di Vittorio, A. V., Sinha, E., Hao, D., Singh, B., Calvin, K. V., Shippert, T., Patel, P., and Bond-Lamberty, B.: E3SM-GCAM: A Synchronously Coupled Human Component in the E3SM Earth System Model Enables Novel Human-Earth Feedback Research, Journal of Advances in Modeling Earth Systems, 17, e2024MS004806, https://doi.org/10.1029/2024MS004806, 2025.

Dobbs, G. R., Liu, N., Caldwell, P. V., Miniat, C. F., Sun, G., Duan, K., and Bolstad, P. V.: Inter-basin surface water transfers database for public water supplies in conterminous United States, 1986–2015, Sci Data, 10, 255, https://doi.org/10.1038/s41597-023-02148-5, 2023.

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R. A., and Feyen, L.: Increased human and economic losses from river flooding with anthropogenic warming, Nature Clim Change, 8, 781–

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

786, https://doi.org/10.1038/s41558-018-0257-z, 2018.

EEA: Trends in atmospheric concentrations of CO2 (ppm), CH4 (ppb) and N2O (ppb), between 1800 and 2017, 2019.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., and Wu, B.: Revegetation in China's Loess Plateau is approaching sustainable water resource limits, Nature Clim Change, 6, 1019–1022, https://doi.org/10.1038/nclimate3092, 2016.

Feng, Y. and Zhu, A.: Spatiotemporal differentiation and driving patterns of water utilization intensity in Yellow River Basin of China: Comprehensive perspective on the water quantity and quality, Journal of Cleaner Production, 369, 133395, https://doi.org/10.1016/j.jclepro.2022.133395, 2022.

Fu, B. and Li, Y.: Bidirectional coupling between the Earth and human systems is essential for modeling sustainability, National Science Review, 3, 397–398, https://doi.org/10.1093/nsr/nww094, 2016.

Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y., and Wu, B.: Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China, Ecological Complexity, 8, 284–293, https://doi.org/10.1016/j.ecocom.2011.07.003, 2011.

Fu, B., Liu, Y., and Meadows, M. E.: Ecological restoration for sustainable development in China, National Science Review, 10, nwad033, https://doi.org/10.1093/nsr/nwad033, 2023.

Fujimori, S., Masui, T., and Matsuoka, Y.: Development of a global computable general equilibrium model coupled with detailed energy end-use technology, Applied Energy, 128, 296–306, https://doi.org/10.1016/j.apenergy.2014.04.074, 2014.

Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., Sands, R., van Zeist, W.-J., Havlik, P., Domínguez, I. P., Sahoo, A., Stehfest, E., Tabeau, A., Valin, H., van Meijl, H., Hasegawa, T., and Takahashi, K.: Land-based climate change mitigation measures can affect agricultural markets and food security, Nat Food, 3, 110–121, https://doi.org/10.1038/s43016-022-00464-4, 2022.

Gou, J., Miao, C., Samaniego, L., Xiao, M., Wu, J., and Guo, X.: CNRD v1.0: A High-Quality Natural Runoff Dataset for Hydrological and Climate Studies in China, Bulletin of the American Meteorological Society, 102, E929–E947, https://doi.org/10.1175/BAMS-D-20-0094.1, 2021.

Hasegawa, T., Sakurai, G., Fujimori, S., Takahashi, K., Hijioka, Y., and Masui, T.: Extreme climate events increase risk of global food insecurity and adaptation needs, Nat Food, 2, 587–595, https://doi.org/10.1038/s43016-021-00335-4, 2021.

Hyun, J.-Y., Huang, S.-Y., Yang, Y.-C. E., Tidwell, V., and Macknick, J.: Using a coupled agent-based modeling approach to analyze the role of risk perception in water management decisions, Hydrology and Earth System Sciences, 23, 2261–2278, https://doi.org/10.5194/hess-23-2261-2019, 2019.

Jain, S., Mindlin, J., Koren, G., Gulizia, C., Steadman, C., Langendijk, G. S., Osman, M., Abid, M. A., Rao, Y., and Rabanal, V.: Are We at Risk of Losing the Current Generation of Climate Researchers to Data Science?, AGU Advances, 3, e2022AV000676, https://doi.org/10.1029/2022AV000676, 2022.

Jia, K., Liang, S., Liu, S., Li, Y., Xiao, Z., Yao, Y., Jiang, B., Zhao, X., Wang, X., Xu, S., and Cui, J.: Global Land Surface Fractional Vegetation Cover Estimation Using General Regression Neural Networks From MODIS Surface Reflectance, IEEE Transactions on Geoscience and Remote Sensing, 53, 4787–4796, https://doi.org/10.1109/TGRS.2015.2409563, 2015.

Jia, K., Yang, L., Liang, S., Xiao, Z., Zhao, X., Yao, Y., Zhang, X., Jiang, B., and Liu, D.: Long-Term Global Land Surface Satellite (GLASS) Fractional Vegetation Cover Product Derived From MODIS and AVHRR Data, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12, 508–518, https://doi.org/10.1109/JSTARS.2018.2854293, 2019.

Jiang, H., Simonovic, S. P., and Yu, Z.: ANEMI_Yangtze v1.0: a coupled human–natural systems model for the Yangtze Economic Belt – model description, Geosci. Model Dev., 26, 2022.

Kemei, Z., Rotich, T., and Bitok, J.: Modelling population dynamics using age-structured system of partial differential equations, IJAMR, 13, 110–116, https://doi.org/10.14419/m81azj37, 2024.

Li, M., Shan, R., Abdulla, A., Virguez, E., and Gao, S.: The role of dispatchability in China's power system decarbonization, Energy Environ. Sci., 17, 2193–2205, https://doi.org/10.1039/D3EE04293F, 2024.

Li, X., Cheng, G., Lin, H., Cai, X., Fang, M., Ge, Y., Hu, X., Chen, M., and Li, W.: Watershed System Model: The Essentials to Model Complex Human-Nature System at the River Basin Scale, Journal of Geophysical Research: Atmospheres, 123, 3019–3034, https://doi.org/10.1002/2017JD028154, 2018.

Li, X., Zhang, L., Zheng, Y., Yang, D., Wu, F., Tian, Y., Han, F., Gao, B., Li, H., Zhang, Y., Ge, Y., Cheng, G., Fu, B., Xia, J., Song, C., and Zheng, C.: Novel hybrid coupling of ecohydrology and socioeconomy at river basin scale: A watershed system model for the Heihe River basin, Environmental Modelling & Software, 141, 105058, https://doi.org/10.1016/j.envsoft.2021.105058, 2021.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Li, Y., Sang, S., Mote, S., Rivas, J., and Kalnay, E.: Challenges and opportunities for modeling coupled human and natural systems, National Science Review, 10, nwad054, https://doi.org/10.1093/nsr/nwad054, 2023.

Li, Z., Liu, X., Niu, T., Kejia, D., Zhou, Q., Ma, T., and Gao, Y.: Ecological Restoration and Its Effects on a Regional Climate: The Source Region of the Yellow River, China, Environ. Sci. Technol., 49, 5897–5904, https://doi.org/10.1021/es505985q, 2015.

Liu, C., Golding, D., and Gong, G.: Farmers' coping response to the low flows in the lower Yellow River: A case study of temporal dimensions of vulnerability, Global Environmental Change, 18, 543–553, https://doi.org/10.1016/j.gloenvcha.2008.09.002, 2008.

Liu, J.: Integration across a metacoupled world, E&S, 22, art29, https://doi.org/10.5751/ES-09830-220429, 2017.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., and Taylor, W. W.: Complexity of Coupled Human and Natural Systems, Science, 317, 1513–1516, https://doi.org/10.1126/science.1144004, 2007.

MAARA: China Agriculture Yearbook, https://data.cnki.net/yearBook?type=type&code=A, 2020.

Miao, C., Kong, D., Wu, J., and Duan, Q.: Functional degradation of the water–sediment regulation scheme in the lower Yellow River: Spatial and temporal analyses, Science of The Total Environment, 551–552, 16–22, https://doi.org/10.1016/j.scitotenv.2016.02.006, 2016.

Miao, C., Gou, J., Fu, B., Tang, Q., Duan, Q., Chen, Z., Lei, H., Chen, J., Guo, J., Borthwick, A. G. L., Ding, W., Duan, X., Li, Y., Kong, D., Guo, X., and Wu, J.: High-quality reconstruction of China's natural streamflow, Science Bulletin, 67, 547–556, https://doi.org/10.1016/j.scib.2021.09.022, 2022.

Monier, E., Paltsev, S., Sokolov, A., Chen, Y.-H. H., Gao, X., Ejaz, Q., Couzo, E., Schlosser, C. A., Dutkiewicz, S., Fant, C., Scott, J., Kicklighter, D., Morris, J., Jacoby, H., Prinn, R., and Haigh, M.: Toward a consistent modeling framework to assess multi-sectoral climate impacts, Nat Commun, 9, 1–8, https://doi.org/10.1038/s41467-018-02984-9, 2018.

Motesharrei, S., Rivas, J., Kalnay, E., Asrar, G. R., Busalacchi, A. J., Cahalan, R. F., Cane, M. A., Colwell, R. R., Feng, K., Franklin, R. S., Hubacek, K., Miralles-Wilhelm, F., Miyoshi, T., Ruth, M., Sagdeev, R., Shirmohammadi, A., Shukla, J., Srebric, J., Yakovenko, V. M., and Zeng, N.: Modeling sustainability: population, inequality, consumption, and bidirectional coupling of the Earth and Human Systems, National Science Review, 3, 470–494, https://doi.org/10.1093/nsr/nww081, 2016.

NBSC: China Energy Statistical Yearbook, https://data.cnki.net/yearBook?type=type&code=A, 2020a.

NBSC: China Population Census Yearbook, https://data.cnki.net/yearBook?type=type&code=A, 2020b.

NBSC: China Statistical Yearbooks, https://www.stats.gov.cn/english/, 2020c.

Ning, X., Zhu, N., Liu, Y., and Wang, H.: Quantifying impacts of climate and human activities on the grassland in the Three-River Headwater Region after two phases of Ecological Project, Geography and Sustainability, 3, 164–176, https://doi.org/10.1016/j.geosus.2022.05.003, 2022.

Nordhaus, W. D.: Revisiting the social cost of carbon, Proceedings of the National Academy of Sciences, 114, 1518–1523, https://doi.org/10.1073/pnas.1609244114, 2017.

Qu, W., Shi, W., Zhang, J., and Liu, T.: T21 China 2050: A Tool for National Sustainable Development Planning, Geography and Sustainability, 1, 33–46, https://doi.org/10.1016/j.geosus.2020.03.004, 2020.

Rajah, J. K., Blanz, B., Kopainsky, B., and Schoenberg, W.: An endogenous modelling framework of dietary behavioural change in the fully coupled human-climate FRIDA v2.1 model, Geoscientific Model Development, 18, 5997–6022, https://doi.org/10.5194/gmd-18-5997-2025, 2025.

Ren, M., Huang, C., Wu, Y., Deppermann, A., Frank, S., Havlík, P., Zhu, Y., Fang, C., Ma, X., Liu, Y., Zhao, H., Chang, J., Ma, L., Bai, Z., Xu, S., and Dai, H.: Enhanced food system efficiency is the key to China's 2060 carbon neutrality target, Nat Food, 4, 552–564, https://doi.org/10.1038/s43016-023-00790-1, 2023.

Ristaino, J. B., Anderson, P. K., Bebber, D. P., Brauman, K. A., Cunniffe, N. J., Fedoroff, N. V., Finegold, C., Garrett, K. A., Gilligan, C. A., Jones, C. M., Martin, M. D., MacDonald, G. K., Neenan, P., Records, A., Schmale, D. G., Tateosian, L., and Wei, Q.: The persistent threat of emerging plant disease pandemics to global food security, Proceedings of the National Academy of Sciences, 118, e2022239118, https://doi.org/10.1073/pnas.2022239118, 2021.

Rydzak, F., Obersteiner, M., Kraxner, F., Fritz, S., and McCallum, I.: FeliX3–Impact Assessment Model: Systemic View across Societal Benefit Areas beyond Global Earth Observation, Laxenburg: International Institute for Applied Systems Analysis (IIASA),

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

2013.

Sang, S.: CHANS-SD-YRB V1.0: A System Dynamics model of the coupled human-natural systems for the Yellow River Basin (1.0.0), Zenodo, https://doi.org/10.5281/zenodo.17568963, 2025.

Sang, S., Li, Y., Zong, S., Yu, L., Wang, S., Liu, Y., Wu, X., Song, S., Wang, X., and Fu, B.: The modeling framework of the coupled human and natural systems in the Yellow River Basin, Geography and Sustainability, 6, 100294, https://doi.org/10.1016/j.geosus.2025.100294, 2025.

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., and Zhang, Q.: China CO2 emission accounts 1997–2015, Sci Data, 5, 170201, https://doi.org/10.1038/sdata.2017.201, 2018.

Song, S., Wen, H., Wang, S., Wu, X., Cumming, G. S., and Fu, B.: Quantifying the effects of institutional shifts on water governance in the Yellow River Basin: A social-ecological system perspective, Journal of Hydrology, 629, 130638, https://doi.org/10.1016/j.jhydrol.2024.130638, 2024.

Vaidyanathan, G.: Integrated assessment climate policy models have proven useful, with caveats, Proc. Natl. Acad. Sci. U.S.A., 118, e2101899118, https://doi.org/10.1073/pnas.2101899118, 2021.

Ventana Systems, Inc.: Vensim DSS (version 9.3), 2023.

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. van der, Seitzinger, S., Steffen, W., and Syvitski, J.: Methods and approaches to modelling the Anthropocene, Global Environmental Change, 39, 328–340, https://doi.org/10.1016/j.gloenvcha.2015.08.007, 2016.

van Vliet, J.: Direct and indirect loss of natural area from urban expansion, Nat Sustain, 2, 755–763, https://doi.org/10.1038/s41893-019-0340-0, 2019.

Waidelich, P., Batibeniz, F., Rising, J., Kikstra, J. S., and Seneviratne, S. I.: Climate damage projections beyond annual temperature, Nat. Clim. Chang., 14, 592–599, https://doi.org/10.1038/s41558-024-01990-8, 2024.

Wang, M., Sun, R., Zhu, A., and Xiao, Z.: Evaluation and Comparison of Light Use Efficiency and Gross Primary Productivity Using Three Different Approaches, Remote Sensing, 12, 1003, https://doi.org/10.3390/rs12061003, 2020a.

Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., and Wang, Y.: Reduced sediment transport in the Yellow River due to anthropogenic changes, Nature Geosci, 9, 38–41, https://doi.org/10.1038/ngeo2602, 2016.

Wang, S., Song, S., Zhang, H., Yu, L., Jiao, C., Li, C., Wu, X., Zhao, W., Best, J., Roberts, P., and Fu, B.: Anthropogenic impacts on the Yellow River Basin, Nat Rev Earth Environ, 6, 656–671, https://doi.org/10.1038/s43017-025-00718-2, 2025.

Wang, T., Teng, F., and Zhang, X.: Assessing global and national economic losses from climate change: a study based on CGEM-IAM in China, Clim. Change Econ., 11, 2041003, https://doi.org/10.1142/S2010007820410031, 2020b.

Wang, Y., Zhao, W., Wang, S., Feng, X., and Liu, Y.: Yellow River water rebalanced by human regulation, Sci Rep, 9, 9707, https://doi.org/10.1038/s41598-019-46063-5, 2019.

Wei, Z., Jian, Z., Sun, Y., Pan, F., Han, H., Liu, Q., and Mei, Y.: Ecological sustainability and high-quality development of the Yellow River Delta in China based on the improved ecological footprint model, Sci Rep, 13, 3821, https://doi.org/10.1038/s41598-023-30896-2, 2023.

Wu, J. and Gao, X.: Agridded daily observation dataset over China region and comparison with the other datasets, Chinese Journal of Geophysics, 56, 1102–1111, https://doi.org/10.6038/cjg20130406, 2013.

Wu, X., Yan, Z., Yang, H., Wang, S., Zhang, H., Shen, Y., Song, S., Liu, Y., Guo, Y., Yang, D., and Fu, B.: Ecological restoration in the Yellow River Basin enhances hydropower potential, Nat Commun, 16, 2566, https://doi.org/10.1038/s41467-025-57891-7, 2025.

Wu, Z., Li, Y., Wang, R., Xu, X., Ren, D., Huang, Q., Xiong, Y., and Huang, G.: Evaluation of irrigation water saving and salinity control practices of maize and sunflower in the upper Yellow River basin with an agro-hydrological model based method, Agricultural Water Management, 278, 108157, https://doi.org/10.1016/j.agwat.2023.108157, 2023.

Xu, S., Wang, R., Gasser, T., Ciais, P., Peñuelas, J., Balkanski, Y., Boucher, O., Janssens, I. A., Sardans, J., Clark, J. H., Cao, J., Xing, X., Chen, J., Wang, L., Tang, X., and Zhang, R.: Delayed use of bioenergy crops might threaten climate and food security, Nature, 609, 299–306, https://doi.org/10.1038/s41586-022-05055-8, 2022.

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull, V., Wang, Z., Zheng, H., Liu, J., Polasky, S., Jiang, L., Xiao, Y., Shi, X., Rao, E., Lu, F., Wang, X., Daily, G. C., and Ouyang, Z.: Strengthening protected areas for biodiversity and ecosystem services in China, Proc. Natl. Acad. Sci. U.S.A., 114, 1601–1606, https://doi.org/10.1073/pnas.1620503114, 2017.

Xu, X., Liu, J., Zhang, S., Li, R., Yan, C., and Wu, S.: China land use remote sensing monitoring dataset, https://doi.org/10.12078/2018070201, 2018.

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Yan, Z., Wang, T., Ma, T., and Yang, D.: Water-carbon-sediment synergies and trade-offs: Multi-faceted impacts of large-scale ecological restoration in the Middle Yellow River Basin, Journal of Hydrology, 634, 131099, https://doi.org/10.1016/j.jhydrol.2024.131099, 2024.

Yang, D., Shao, W., Yeh, P. J.-F., Yang, H., Kanae, S., and Oki, T.: Impact of vegetation coverage on regional water balance in the nonhumid regions of China, Water Resources Research, 45, https://doi.org/10.1029/2008WR006948, 2009.

Yang, Z., Li, Q., Xue, W., and Xu, Z.: Impacts of nature reserves on local residents' income in China, Ecological Economics, 199, 107494, https://doi.org/10.1016/j.ecolecon.2022.107494, 2022.

Ye, Q., Liu, Q., Swamy, D., Gao, L., Moallemi, E. A., Rydzak, F., and Eker, S.: FeliX 2.0: An integrated model of climate, economy, environment, and society interactions, Environmental Modelling & Software, 179, 106121, https://doi.org/10.1016/j.envsoft.2024.106121, 2024.

Yin, P., Gao, Y., Chen, R., Liu, W., He, C., Hao, J., Zhou, M., and Kan, H.: Temperature-related death burden of various neurodegenerative diseases under climate warming: a nationwide modelling study, Nat Commun, 14, 8236, https://doi.org/10.1038/s41467-023-44066-5, 2023a.

Yin, S., Gao, G., Ran, L., Lu, X., and Fu, B.: Spatiotemporal Variations of Sediment Discharge and In-Reach Sediment Budget in the Yellow River From the Headwater to the Delta, Water Resources Research, 57, e2021WR030130, https://doi.org/10.1029/2021WR030130, 2021.

Yin, S., Gao, G., Ran, L., Li, D., Lu, X., and Fu, B.: Extreme streamflow and sediment load changes in the Yellow River Basin: Impacts of climate change and human activities, Journal of Hydrology, 619, 129372, https://doi.org/10.1016/j.jhydrol.2023.129372, 2023b.

Yoon, J., Klassert, C., Selby, P., Lachaut, T., Knox, S., Avisse, N., Harou, J., Tilmant, A., Klauer, B., Mustafa, D., Sigel, K., Talozi, S., Gawel, E., Medellín-Azuara, J., Bataineh, B., Zhang, H., and Gorelick, S. M.: A coupled human–natural system analysis of freshwater security under climate and population change, Proceedings of the National Academy of Sciences, 118, e2020431118, https://doi.org/10.1073/pnas.2020431118, 2021.

YRCCMWR: Yellow River Basin Comprehensive Planning (2012-2030), 2015.

YRCCMWR: Yellow River Water Resources Bulletin, 2020.

Yu, T., Sun, R., Xiao, Z., Zhang, Q., Liu, G., Cui, T., and Wang, J.: Estimation of Global

https://doi.org/10.5194/egusphere-2025-5597
Preprint. Discussion started: 19 November 2025

Vegetation Productivity from Global LAnd Surface Satellite Data, Remote Sensing, 10, 327, https://doi.org/10.3390/rs10020327, 2018.

Zhang, H., Li, R., Cai, X., Zheng, C., Liu, L., Liu, M., Zhang, Q., Lin, H., Chen, L., and Wang, X.: Do electricity flows hamper regional economic–environmental equity?, Applied Energy, 326, 120001, https://doi.org/10.1016/j.apenergy.2022.120001, 2022a.

Zhang, Q., Gu, X., Singh, V. P., Kong, D., and Chen, X.: Spatiotemporal behavior of floods and droughts and their impacts on agriculture in China, Global and Planetary Change, 131, 63–72, https://doi.org/10.1016/j.gloplacha.2015.05.007, 2015.

Zhang, T., Su, X., Zhang, G., Wu, H., and Liu, Y.: Projections of the characteristics and probability of spatially concurrent hydrological drought in a cascade reservoirs area under CMIP6, Journal of Hydrology, 613, 128472, https://doi.org/10.1016/j.jhydrol.2022.128472, 2022b.

Zhou, F., Bo, Y., Ciais, P., Dumas, P., Tang, Q., Wang, X., Liu, J., Zheng, C., Polcher, J., Yin, Z., Guimberteau, M., Peng, S., Ottle, C., Zhao, X., Zhao, J., Tan, Q., Chen, L., Shen, H., Yang, H., Piao, S., Wang, H., and Wada, Y.: Deceleration of China's human water use and its key drivers, Proceedings of the National Academy of Sciences, 117, 7702–7711, https://doi.org/10.1073/pnas.1909902117, 2020.

Zhu, Y., Jia, X., Qiao, J., and Shao, M.: What is the mass of loess in the Loess Plateau of China?, Science Bulletin, 64, 534–539, https://doi.org/10.1016/j.scib.2019.03.021, 2019.