



Ecosystem degradation or restoration? The evolving role of land use in China, 2000–2020

Wanxu Chen · Liyan Yang · Guangqing Chi · Jie Zeng

Received: 11 September 2023 / Accepted: 17 February 2024 / Published online: 26 February 2024
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2024

Abstract Dramatic land use change in China affects ecosystem degradation and restoration. Identifying the evolving role of land use in ecosystem degradation and restoration in China is essential for sustainable land policy making. However, it is not clear how land use affects ecosystem degradation and restoration over time. Here, we used the revised benefit transfer approach and spatial statistics based on land use data

to determine the evolving role that land use plays in ecosystem degradation and restoration in China during 2000–2020. The study results pointed out that the deterioration of the forestland ecosystem during the study period was the main reason for ecosystem degradation, while the conversion of arable land to forestland was the main cause for ecosystem restoration. Every 1% increase of land use intensity in the periods 2000–2005, 2005–2010, 2010–2015, and 2015–2020 resulted in –1.754%, 0.697%, 1.098%, and –0.058% of the changes in ecosystem services, respectively. This study provided important policy implications for future sustainable land use management in China.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10661-024-12464-x>.

W. Chen · L. Yang · J. Zeng (✉)
Hubei Key Laboratory of Regional Ecology
and Environmental Change, School of Geography
and Information Engineering, China University
of Geosciences, Wuhan 430074, China
e-mail: zengjie@cug.edu.cn

W. Chen
Institute of Geographic Sciences and Natural Resources
Research, Chinese Academy of Sciences, Beijing 100101,
China

W. Chen
Key Laboratory of Geospatial Technology for Middle
and Lower Yellow River Regions, Henan University,
Ministry of Education, Kaifeng 475004, Henan, China

G. Chi
Department of Agricultural Economics, Sociology,
and Education, Population Research Institute, and Social
Science Research Institute, The Pennsylvania State
University, 112E Armsby, University Park, State College,
PA 16802, USA

Keywords Land use change · Ecosystem
degradation · Ecosystem restoration · Ecosystem
services · Sensitivity analysis · China

Introduction

The past century witnessed a dramatic increase in urbanization and world population (Gu, 2019; Zeng et al., 2023). With this, the extent and depth of terrestrial surface transformation have reached unprecedented levels and resulted in serious ecosystem degradation, especially in developing countries (Ceretelli et al., 2018; Desta, 2021; Právělie et al., 2021; Wang et al., 2018). Rapid urbanization in China has triggered dramatic land use changes and dominated ecosystem degradation and restoration (Song

& Deng, 2017; Yang et al., 2023b). Investigating the role of land use in ecosystem degradation and restoration in China, the largest developing country in the world, provides optimal basic conditions and typical cases for global study of ecosystem degradation and restoration.

Ecosystem degradation is defined by some elements of the ecosystem or the system as a whole are not conducive to biological and human survival requirements of quantitative change and qualitative change and the structure and function of the ecosystem shift in the opposite direction from the original equilibrium state or evolution disturbed by natural factors, human factors, or both (Delgado & Marín, 2020). The concept of ecosystem restoration, as opposed to ecosystem degradation, represents the process by which the structure and function of a regional ecosystem evolves in a more stable direction. In response to ecosystem degradation caused by rapid urbanization, China introduced a series of ecosystem restoration measures and expects to achieve ecosystem restoration by changing land use cover (Han et al., 2021; He et al., 2020). Land use affects the structure and function of land-based ecological processes such as energy exchange, the water cycle, soil erosion and accumulation, and crop production, as well as soil, climate, hydrology, biogeochemical cycles, and biodiversity (Chen et al., 2021b; Lei et al., 2021; Li et al., 2021b). Peer studies have extensively researched the concepts, classification, mechanisms, evaluation, and monitoring of ecosystem degradation and restoration (Cerretelli et al., 2018; Delgado & Marín, 2020; He et al., 2019; Li et al., 2022a, 2022b; Yang et al., 2023c). Studies have identified land use patterns and intensities as important factors influencing ecosystem degradation and restoration (Fan et al., 2019; Li et al., 2018a). However, previous studies still lack an integrated perspective to analyze the role of land use on ecosystem restoration and degradation (Yang et al., 2023a, 2023c).

A growing body of literature has worked to define, model, and map ecosystem degradation and restoration (Cerretelli et al., 2018; Chen et al., 2024; Chi & Ho, 2018; Delgado & Marín, 2020; Li et al., 2022b; Yang et al., 2023c). Ecosystem degradation is difficult to interpret without a clear understanding of how human and land systems interact because it is a complex and integrated dynamic process (Chen et al., 2024). In this study, we introduce

a land-use-types-based method to measure the effects of land use on ecosystem degradation (Chen et al., 2021c, Chen et al., 2020; Costanza et al., 1997). This is largely because ecosystem and land use classifications are, to a certain extent, closely related, and the ecosystem degradation effects of land use can therefore be identified by tracking land use change (Chen et al., 2019a; Costanza et al., 1997; Li et al., 2022b; Yang et al., 2023c). Land use remote-sensing monitoring data make it possible to evaluate the extent of ecosystem degradation and restoration by identifying the ecological background value of each land use type as accurately as possible and according to expert knowledge (Costanza et al., 1997; Xie et al., 2008). The land-use-types-based method used in this study is used to reflect the natural equilibrium state of ecosystems (ecosystem degradation or ecosystem restoration) under socioeconomic influence factors within a given space–time constraint and provides us a new perspective to measure the integrated ecosystem degradation.

Previous studies have focused on the effects of single land use type changes on ecosystem degradation, but little attention has been paid to the effects of comprehensive land use change on ecosystem degradation in subregions of China (Li et al., 2019, 2022b; Song & Deng, 2017; Yang et al., 2023c). How land use change drives the changes in ecosystem degradation is of great importance to sustainable land use and its corresponding policymaking. It is thus necessary to accurately identify the extent of land use changes and its subsequent interference with ecosystem degradation, given that quantitative measurement of land use change is the basic requirement and necessary premise for formulating reasonable and targeted land and ecological protection policies. Nevertheless, how to identify the spatiotemporal distribution features of the disturbance of land use activities on ecosystem needs further investigation because of the complex relationship between land use activities and ecosystem degradation.

China has become one of the world's largest economic entities, with a concurrent rapid increase in urbanization and population. Human-induced land use change has considerably spurred nationwide ecosystem degradation (Li et al., 2022b). Additionally, a series of regional development strategies, land use policies, and ecosystem conservation projects have affected ecosystem degradation and restoration (Liu

et al., 2017; Long, 2014; Yang et al., 2023c). Furthermore, identifying the regional differences in manner and extent of ecosystem degradation among different subregions is of great significance to national land use planning and conservation decision-making. However, the existing studies lacked to reveal the regional differences in the causes of ecosystem degradation from the perspective of land use change and do not well support the development of regional sustainable development policies.

Identifying the relationship between land use and ecosystem degradation and restoration is necessary for sustainable land use. However, it remains unclear in subregions of China whether the effects of land use on the ecosystem are limited to individual land types. This lack of knowledge about the impact mechanism of land use activities on ecosystem management limits sustainable land use planning and national spatial decision-making. This study fills these gaps and identifies the evolutionary role of land use on ecosystem management in China through three aspects: (1) measuring ecosystem degradation and restoration based on ecosystem service changes, (2) identifying the impact of land use change on ecosystem degradation or restoration within each subregion of China, and (3) revealing the sensitivity of ecosystem services to land use activities.

Materials and methods

Study area

The terrain in China transitions from high to low and from west to east in roughly a three-step, ladder-like distribution. The western part of China contains the Tibetan Plateau, the highest in the world, with an average elevation of more than 4000 m. Complex terrain conditions bring a variety of climate types, with continental and monsoon climates being dominant. Because of the complex climate and topography conditions, China's population and economy are concentrated mainly in the eastern monsoon region, and a significant imbalance of land use patterns has thereby occurred.

Economic development in China made a huge leap from 2000 to 2020. The gross domestic product (GDP) output increased from 10.028 trillion CNY (~1.610 trillion USD) in 2000 to 101.6 trillion CNY

(~14.72 trillion USD) in 2020, and the population increased from 12.67 billion in 2000 to 14.12 billion in 2020. As part of that increase, China's percentage of urban population increased from 36.22% in 2000 to 63.89% in 2020. Dramatic growth of population and urbanization has led to the rapid expansion of construction land, which has significantly interfered with the natural equilibrium state of the ecosystem. In addition, the widely distributed deserts in the northwestern region and a series of ecosystem conservation projects have had important effects on China's ecosystem restoration. Thus, examining ecosystem degradation and identifying its driving forces is of great significance to provide guidance for national land use policy making. To fully understand the ecosystem degradation and restoration caused by land use, we subdivided mainland China into ten subregions according to integrated agricultural regionalization and physical–geographical contexts (Ge et al., 2018; Li et al., 2018a) (Fig. 1).

Data sources and processing

The 1-km resolution land use data used in this study were obtained from the Data Center for Resources and Environmental Sciences (RESDC), Chinese Academy of Sciences (Liu et al., 2014; Ning et al., 2018). The data production in 2000 and 2005 is based on the Landsat Thematic Mapper remote-sensing images, and the land use data in 2015 and 2020 is based on Landsat-8 remote-sensing images. Land use data is generated by manual visual interpretation. The accuracy of the land use data is more than 90% (Li et al., 2018a). On the basis of previous studies, we reclassified land use types to seven ecosystem types: arable land, forestland, grassland, water area, construction land, unused land, and wetland (Chen et al., 2021c). The normalized difference vegetation index (NDVI) data with a spatial resolution of 1 km were also derived from RESDC.

Measuring ecosystem degradation based on ecosystem services

We employed a method based on land use types—the benefit transfer approach—to examine the natural equilibrium state of ecosystem degradation or restoration in China from 2000 through 2020 (Costanza et al., 1997, 2014; Song & Deng, 2017; Xie et al.,

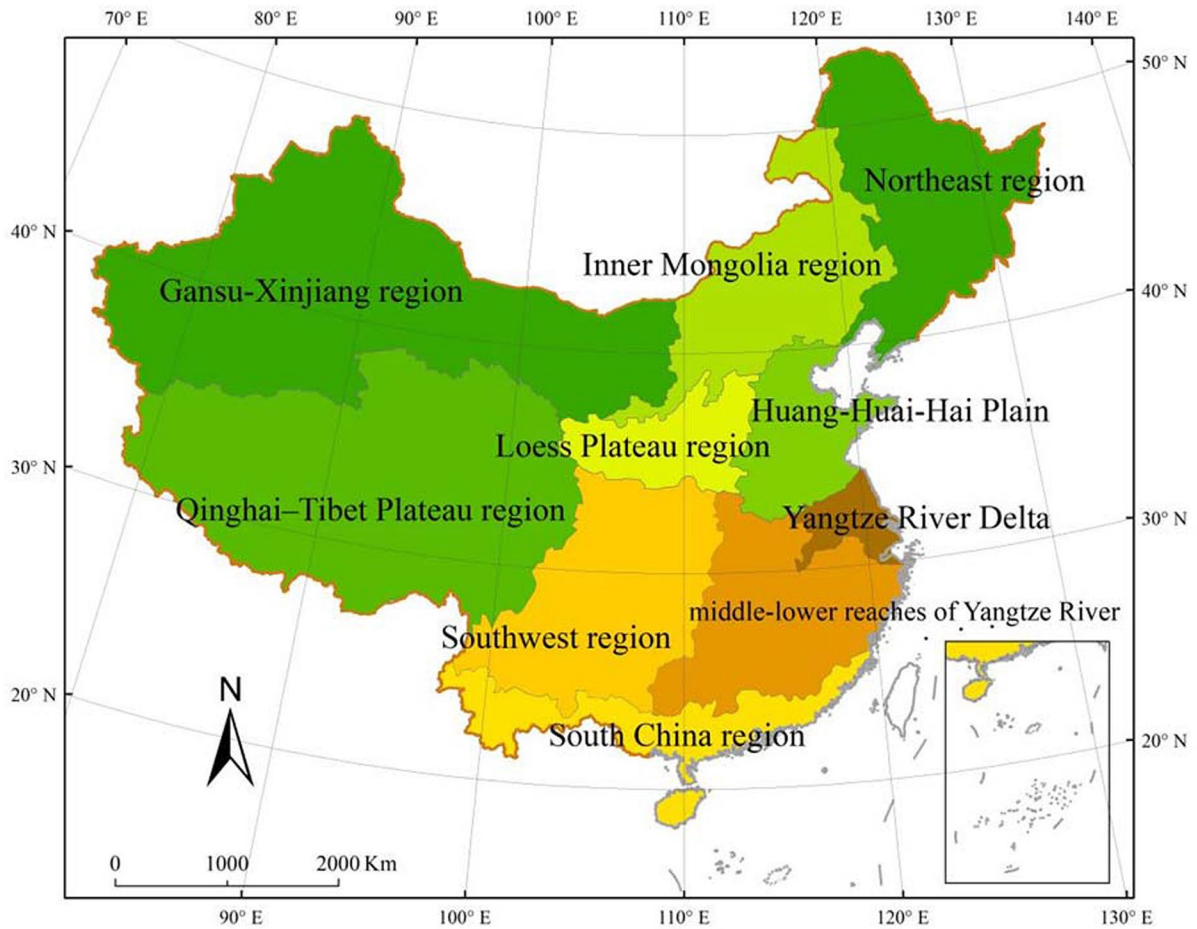


Fig. 1 Map of ten regions in China

2008). The ecosystem services value (ESV) per unit area (EV) in this study was sourced from previous studies (Table S1) (Xie et al., 2008). The diversity of the ecosystem itself and environmental conditions leads to the spatial heterogeneity of ESV. A unified national equivalent value coefficient is difficult to use in determining the spatial heterogeneity of ESV (Xie et al., 2008). Therefore, in this study, we referred to the research of Chen et al. (2020) and spatialized the ESV based on the biomass on arable land (Chen et al., 2020). The equations are as follows:

$$AESV_t = \frac{VCI_j}{\overline{VCI_f}} \times \frac{\sum_{i=1}^n (LA_{(i,t)} \times EV_{(i,t)})}{\sum_{i=1}^n LA_{(i,t)}} \quad (1)$$

$$CAESV_{(t1,t2)} = (AESV_{t2} - AESV_{t1}) / AESV_{t1} \times 100\% \quad (2)$$

where $AESV_t$ is the average ecosystem services value in certain county at time t , $LA_{(i,t1)}$ and $LA_{(i,t2)}$ are the area of the i th land use type area at $t1$ and $t2$, $EV_{(i,t1)}$ and $EV_{(i,t2)}$ are the ESVs per unit area of i th land use type at $t1$ and $t2$, and n is the number of land use types in the study area. VCI_j and $\overline{VCI_f}$ were, respectively, the vegetation condition index of the i th county and China. $CAESV_{(t1,t2)}$ denotes the change of average ecosystem services value from $t1$ to $t2$: $CAESV_{(t1,t2)} > 0$ denotes ecosystem restoration occurred in a certain study area from $t1$ to $t2$; $CAESV_{(t1,t2)} < 0$ denotes ecosystem degradation occurred in a certain study area from $t1$ to $t2$; and $CAESV_{(t1,t2)} = 0$ denotes no change occurred in a certain study area from $t1$ to $t2$.

Measuring ecosystem degradation by each single land use change

We also measured ecosystem degradation for each single land use change. To do so, we used the following equation (Chen et al., 2019c):

$$EL_{i-j} = \frac{(EV_{(j,t1)} - EV_{(i,t2)}) \times \Delta LA_{i-j}}{\sum_{i=1}^n \sum_{j=1}^n [(EV_{(j,t1)} - EV_{(i,t2)}) \times \Delta LA_{i-j}]} \times 100\% \tag{3}$$

where EL_{i-j} measures a single land use change from i th to j th land use type—that is, when the i th land use type converts to the j th land use type. $EV_{(i,t1)}$ and $EV_{(j,t2)}$ are the i th and j th ecosystem services value of the i th land use type and j th land use type at $t1$ and $t2$, respectively (Table S1); and ΔLA_{i-j} is the area of land use type i converted to land use type j ($j = 1, 2, \dots, n$) during the study period. $EL_{i-j} > 0$, indicating that land use type i converted to land use type j , reflects ecosystem restoration $EL_{i-j} < 0$, indicating that land use type i converted to land use type j , reflects ecosystem degradation. $EL_{i-j} = 0$ indicates that no change happened in a certain study area when land use type i was converted to land use type j .

Sensitivity of ecosystem services to land use intensity

We also measured ecosystem degradation to gain perspective on overall land use activities. In doing so, we employed the elasticity measure as used in economic theories (Mansfield, 1985). The elastic analysis method was developed based on previous studies and can be defined as the ratio of the change in $AESV$ (%) to land use intensity (LUI) (%) (Chen et al., 2019c). The equations are as follows:

$$SI_{LUI} = \frac{(AESV_{t2} - AESV_{t1})/AESV_{t1}}{(LUI_{t2} - LUI_{t1})/LUI_{t1}} \times \frac{1}{T} \times 100\% \tag{4}$$

$$LUI = \sum_{i=1}^n \frac{LA_{(i,t)}}{\sum_{i=1}^n LA_{(i,t)}} \times D_i \tag{5}$$

where SI_{LUI} is the elasticity of changes in $AESV$ in response to LUI; $AESV_{t1}$ and $AESV_{t2}$ are the $AESV$ in year $t1$ and $t2$, respectively; T is the study period; and LUI is the land use intensity as described by Eq. (5). D_i is the grade index of land use intensity of land use

type i , and the specific source can be referred to in Li et al. (2019). Previous studies have proved that LUI can effectively measure the maintenance state of the natural balance of land natural complex under the influence of socioeconomic factors (Chen et al., 2019c; Xu et al., 2020). Analysis of the response of ecosystem services to LUI can effectively reveal the impact of land use activities on ecosystem services.

Results

Ecosystem services responses to land use change in China

The ESV supplying capacity in China decreased between 2000 and 2005 and between 2015 and 2020, while it increased between 2005 and 2015. The contribution of forestland to ESV in China was the largest (over 48% of the total ESV in China), followed by grassland (over 24% of the total ESV in China). The contribution of unused land was the lowest (less than 2.3%). The low-value AESV counties were distributed mainly throughout the Gansu–Xinjiang, Qinghai–Tibet Plateau, and Inner Mongolia regions (Fig. S1). In addition, the Huang–Huai–Hai Plain, the Sichuan Basin, the Yangtze River Delta region, the middle Yangtze River region, and the southwest of Heilongjiang, the east of Inner Mongolia, and the west of Jilin and Liaoning provinces in the Northeast China Plain were also low-value AESV regions. High-value AESV counties were distributed mainly throughout the mountainous counties (e.g., Greater Khingan Mountains, Lesser Khingan Range, Changbai Mountains, Wu Mountains, and Xuefeng Mountains) in monsoon climates.

Figure 2 presents the spatial pattern of changes in AESV in different counties. During the periods 2000–2005, 2000–2005, 2005–2015, and 2015–2020, 53.695%, 49.667%, 48.371%, and 79.685%, respectively, of the counties had a reduced AESV (ecosystem degraded). Specifically, the counties with obvious ecosystem restoration between 2000 and 2005 were distributed primarily in Loess Plateau, Chengdu Plain, Huaihe River Basin, and the Greater Khingan Mountains. Ecosystem degradation occurred mainly in the southern part of China, including the southern part of Yunnan, Guangxi, Guizhou, Jiangxi, Zhejiang, Fujian, and Shanghai. Between 2005 and 2010,

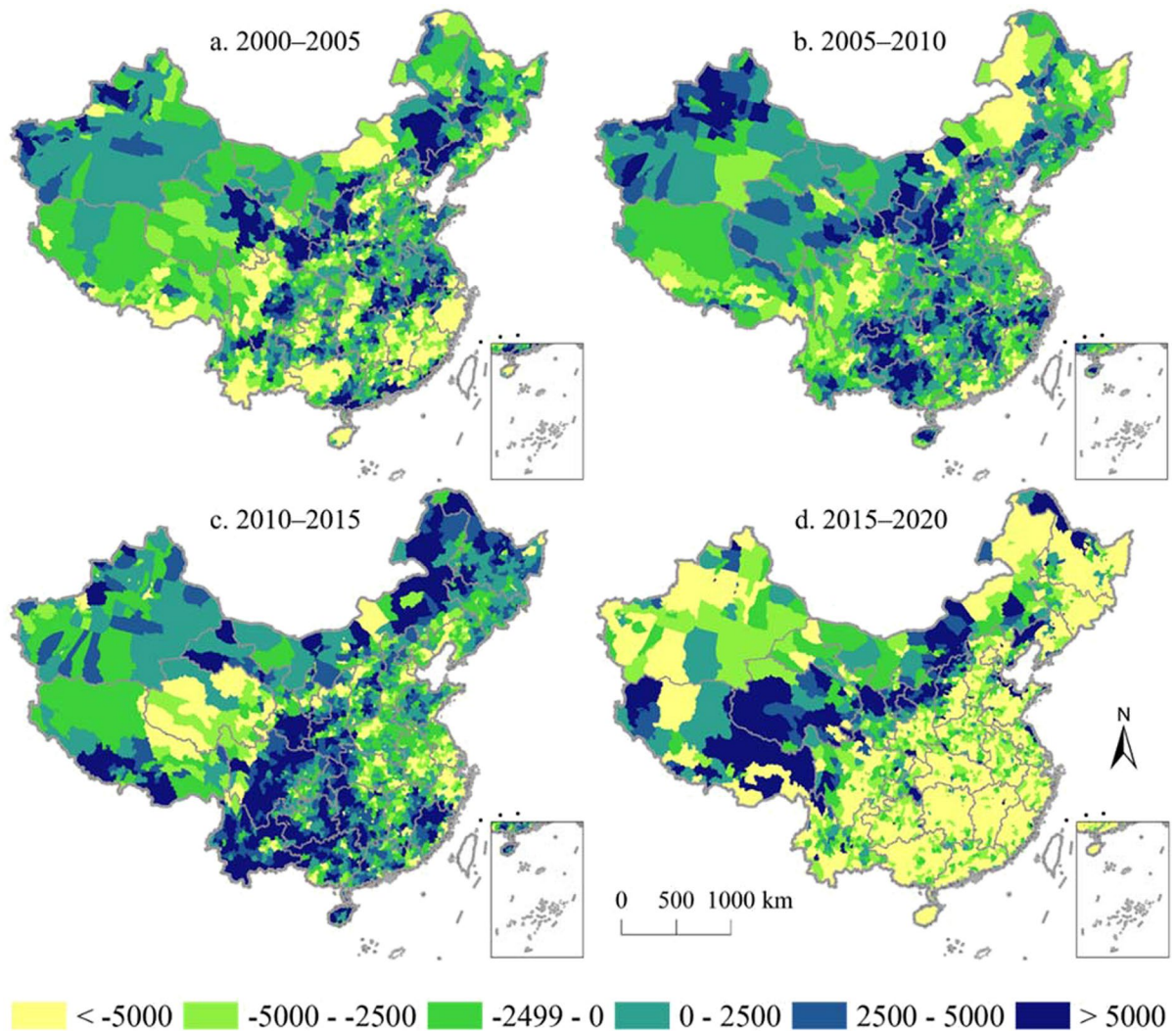


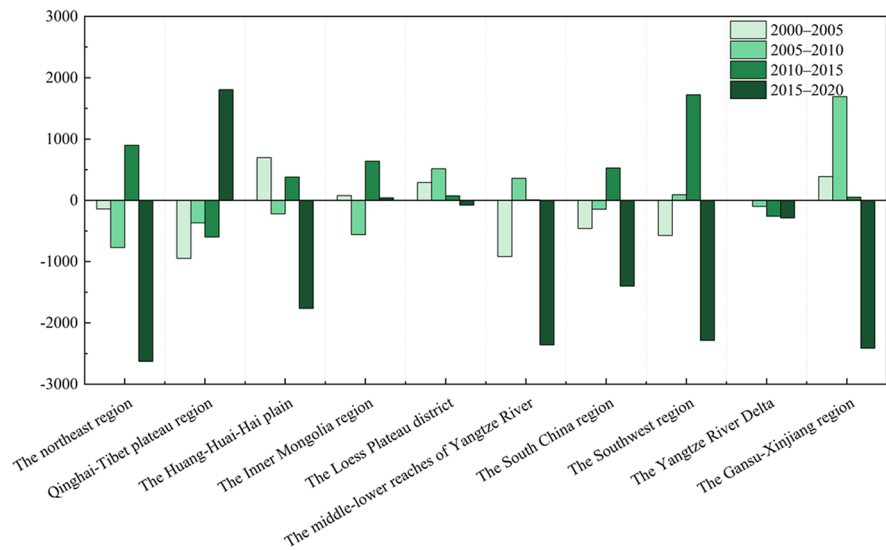
Fig. 2 Spatial pattern of changes in AESV in China

counties with obvious ecosystem restoration were distributed mainly in the northwest of Xinjiang, the Loess Plateau, the middle reaches of the Yangtze River, and Guizhou and Guangxi in southwest China. Ecosystem-degraded counties were distributed in the Sichuan Plain, the eastern part of Inner Mongolia, Heilongjiang, and the southeastern coastal areas of Shandong, Jiangsu, Fujian, and Xizang. Between 2010 and 2015, the counties with ecosystem deterioration were distributed in Qinghai, Heilongjiang, and most parts of southeast China. The counties with a restored ecosystem were distributed primarily in southwest China, the North China Plain, the

northwestern part of Xizang, and the southeastern areas of Xinjiang. Between 2015 and 2020, ecosystem restoration took place in the Inner Mongolia central region, the Lesser Khingan Mountains, Qinghai province and its surrounding areas, and the Loess Plateau. Ecosystem-degraded counties were distributed in east of the Hu Huanyong Line and the western areas of Xinjiang.

From the 10 subregions (Fig. 3), Central China was the main area where ecosystem restoration occurred between 2000 and 2005, while all other subregions experienced differing degrees of ecosystem degradation. Among them, the Qinghai–Tibet Plateau region

Fig. 3 Changes in AESV in the various subregions



and the middle and lower reaches of Yangtze River had the greatest degree of degradation. Between 2005 and 2010, the Gansu–Xinjiang region was the main area where ecosystem restoration occurred, while the northeast region was the main area where ecosystem degradation occurred. Between 2010 and 2015, all subregions except the Qinghai–Tibet Plateau experienced varying degrees of ecosystem restoration. During 2015–2020, eastern China was the primary area with ecosystem degradation, while the Qinghai–Tibet Plateau region was the main area of ecosystem restoration.

Effects of land use change on ecosystem degradation in China

Figure 4 illustrates ecosystem degradation or restoration under different subregions related to land use change between 2000 and 2020. Nationally, conversion of grassland to forest land (21.877%) and conversion of arable land to forest land (25.201%) were the main causes of ecosystem restoration, while conversion of forest land to grassland (−17.225%) and conversion of forest land to arable land (−22.660%) were the main causes of ecosystem degradation. Marked differences in physical and socioeconomic contexts in different subregions of China affect the way land is used, and land use changes in these subregions therefore have different effects on ecosystem degradation. Specifically, conversion of arable land to forestland was the main cause of ecosystem restoration in the

southwest (53.251%), the middle and lower reaches of the Yangtze River (55.785%), south China (51.249%), and northeast China (25.198%). Conversion of grassland to forest land is the main reason for ecosystem restoration in the Loess Plateau (24.742%), Inner Mongolia (27.222%), and the Qinghai–Tibet Plateau (29.482%). In the Huang–Huai–Hai Plain, the conversion of construction land to arable land is leading to maximum ecosystem restoration (25.936%). The conversion of arable land to water area is an important factor leading to ecosystem restoration in the Yangtze River Delta (38.7772). In Gansu–Xinjiang, revegetation of unused land is the main reason for the restoration of its ecosystem (42.839%).

Additionally, the deterioration of the forestland ecosystem is in turn a major driver of ecosystem degradation in most subregions. Specifically, the conversion of forestland to arable land contributed to 51.091%, 37.713%, and 38.573% ecosystem degradation in the southwest, the middle and lower reaches of the Yangtze River, and south China, respectively. In the Huang–Huai–Hai Plain and the Yangtze River Delta, the occupation of arable land by construction land contributed to 33.454% and 24.052% ecosystem degradation, respectively. The deterioration of the forestland ecosystem is the main cause of ecosystem degradation in northeast China (22.414%). The conversion of forestland to grassland contributed to 31.730% and 22.235% ecosystem degradation in the Loess Plateau and Inner Mongolia, respectively. In western China, the conversion of grassland to unused

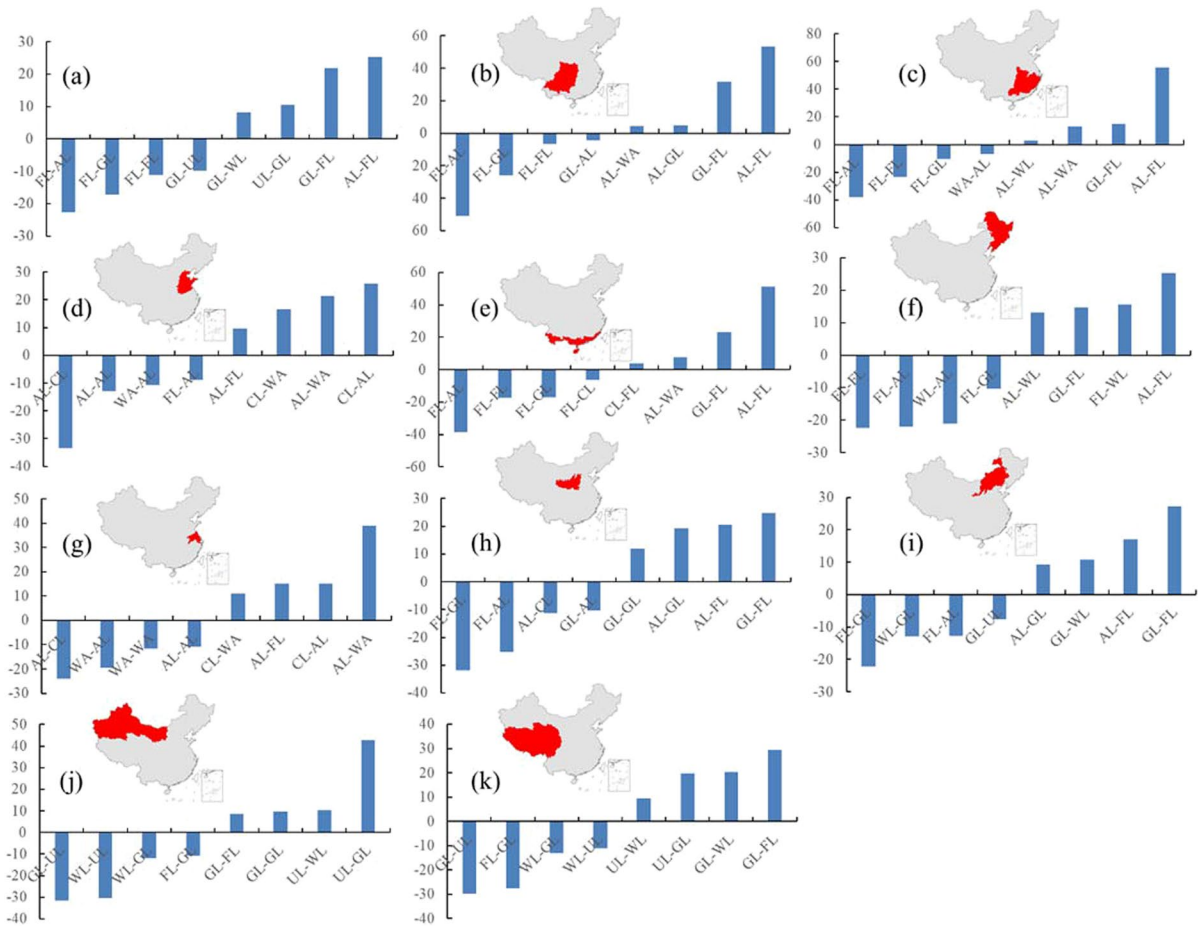


Fig. 4 Effects of land use change on ecosystem degradation in different regions of China between 2000 and 2020: **a** China, **b** southwest China, **c** middle and lower reaches of the Yangtze River, **d** Huang-Huai-Hai Plain, **e** south China, **f** northeast China, **g** Yangtze River Delta, **h** Loess Plateau, **i** Inner Mongo-

lia, **j** Gansu-Xinjiang, **k** Qinghai-Tibet Plateau. X-bar: Arable land (AL), forestland (FL), grassland (GL), construction land (CL), water area (WA), unused land (UL), wetland (WL). FL-AL represents forestland land converted to arable land; other codes follow the same rule

land was the main cause of ecosystem degradation, contributing to 31.379% and 29.767% ecosystem degradation in Gansu-Xinjiang and the Qinghai-Tibet Plateau, respectively.

Figs. S2–5 show ecosystem degradation and ecosystem restoration brought about by the transitions between various land use types in different regions of China during the periods 2000–2005, 2005–2010, 2010–2015, and 2015–2020. The conversion of low-quality arable land to high-quality arable land between 2000 and 2005 contributed the highest proportion of ecosystem restoration (18.179%), and the conversion of arable land to water area contributed to 13.579% of ecosystem restoration. The low-coverage

to high-coverage grassland conversion contributed 29.204% of the ecosystem restoration between 2005 and 2010, and low-coverage to high-coverage wetland conversion contributed 15.841% of the ecosystem restoration between 2005 and 2010. The low-quality to high-quality forestland conversion contributed 70.436% of ecosystem restoration between 2010 and 2015. The conversion of arable land to forestland contributed 25.064% of ecosystem restoration between 2015 and 2020. Meanwhile, the land use change not only brought about ecosystem restoration but also contributed to ecosystem degradation. The conversion of high-quality forestland to low-quality forestland contributed 59.938% and 34.150% of ecosystem

degradation between 2000 and 2005 and between 2005 and 2010, respectively. The conversion of forestland to arable land resulted in 17.138% of ecosystem degradation between 2010 and 2015, and the conversion of arable land to construction land contributed 12.7032% and 16.694% of ecosystem degradation between 2005 and 2010 and between 2010 and 2015, respectively. Between 2015 and 2020, the conversion of forestland to arable land became the main cause of ecosystem degradation, contributing 22.640%. What can be seen is that the low-coverage to high-coverage arable land, grassland, and forestland were the main contributors to ecosystem restoration, while decline in forestland quality and deforestation were the main causes of ecosystem degradation.

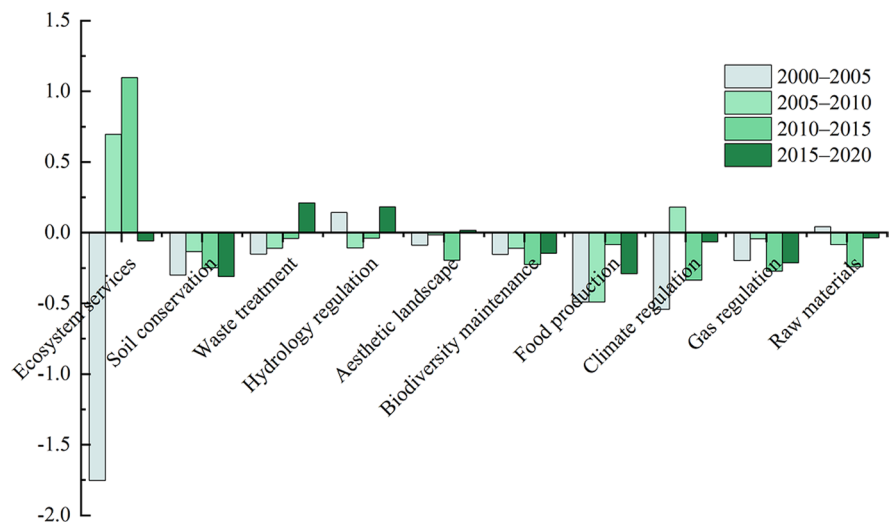
Sensitivity of ecosystem services to LUI in China

The sensitivities of ecosystem services to LUI for the years 2000–2005, 2005–2010, 2010–2015, and 2015–2020 were -1.754 , 0.697 , 1.098 , and -0.058 , respectively, which indicates that every 1% increase of LUI during those four periods resulted in -1.754% , 0.697% , 1.098% , and -0.058% , respectively of the changes in ecosystem services. The LUI during the first and fourth periods corresponded to overall ecosystem degradation, while the LUI during the other two periods corresponded to overall ecosystem restoration (Fig. 5). Conversely, LUI led to the restoration of hydrology regulation and raw materials function in the first period. The increase of LUI led to the decrease of climate regulation between 2000 and

2005 and between 2010 and 2020, while the increase of LUI between 2005 and 2010 led to the increase of climate regulation. The increase of LUI led to the increase of waste treatment and aesthetic landscape between 2015 and 2020, while the increase of LUI in between 2000 and 2015 led to the deterioration of waste treatment and aesthetic landscape. Increased LUI also led to the degradation of other ecosystem functions such as soil conservation, biodiversity maintenance, food production, and gas regulation.

The increase in LUI between 2015 and 2020 resulted in a significantly higher number of counties with an ESV increase than between 2000 and 2015 (Fig. 6). In particular, the counties with high sensitivity to LUI between 2000 and 2005 were distributed mainly in the Hengduan Mountains in the southwest of China. There were also a considerable number of counties, scattered throughout central and eastern China, where the increase of LUI evidently improved the ESV. In addition, some counties in Yunnan and Guangxi, as well as the Gansu–Xinjiang region and southeast coastal areas of China were counties with low sensitivity to LUI. The counties with high sensitivity to LUI between 2005 and 2010 were distributed mainly in the central and eastern regions of China, while the counties with low sensitivity to LUI were distributed mainly in Inner Mongolia, the Sanjiangyuan region in Qinghai Province, the Loess Plateau, the North China Plain, the Yunnan–Guizhou Plateau, and the southeast coastal provinces of Guangdong and Fujian. Counties with high sensitivity to LUI

Fig. 5 Sensitivity coefficient of ecosystem services in China, 2000 through 2020



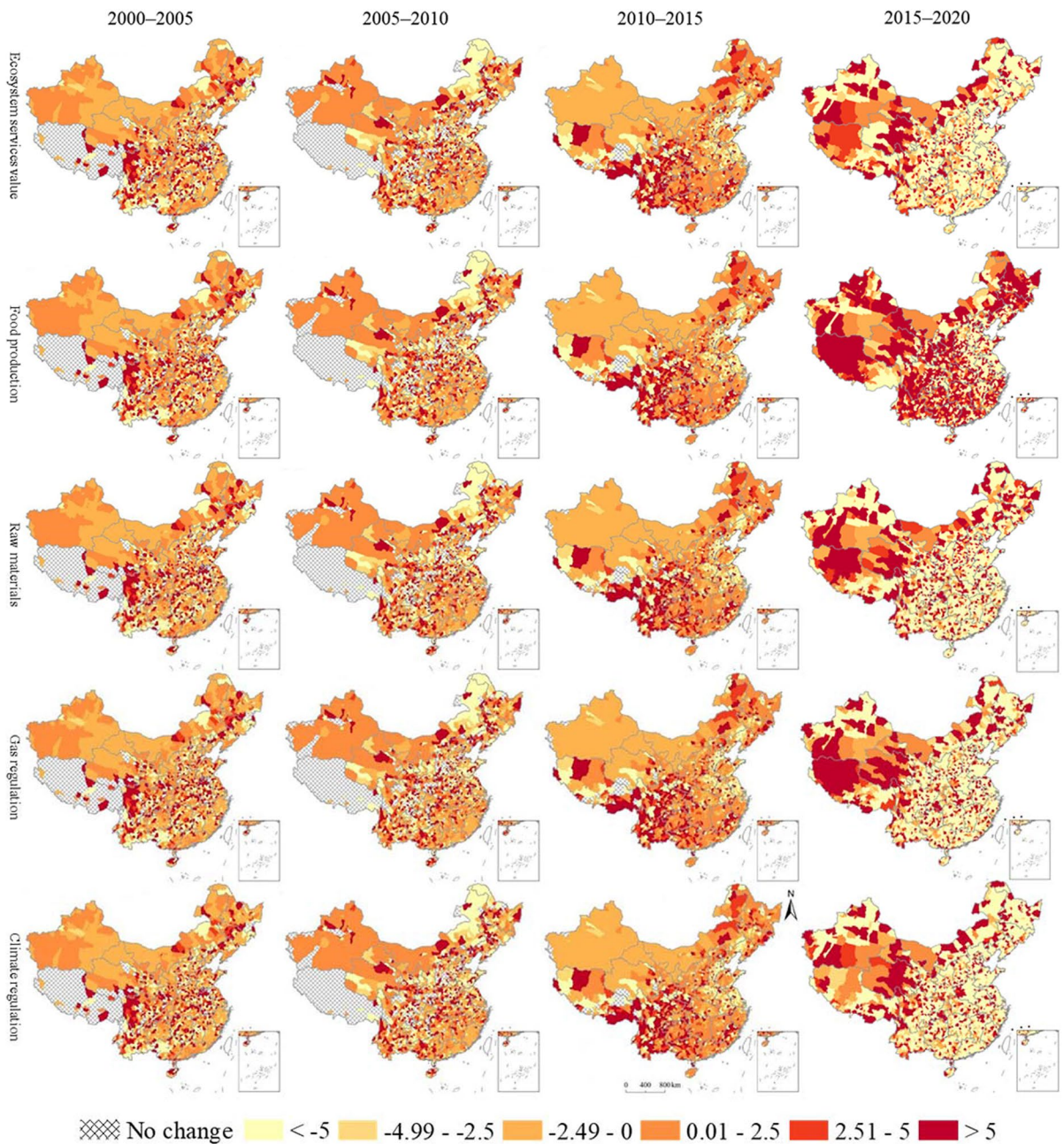


Fig. 6 Spatial distribution of ESV sensitivity coefficient to LUI in China

in 2010–2015 were distributed mainly in southwest China, northeast China, and Fujian Province. The sensitivity was low in the North China Plain and the Gansu–Xinjiang region. In 2020, counties with high sensitivity were located mainly west of China, including Inner Mongolia, Qinghai, Tibet, and

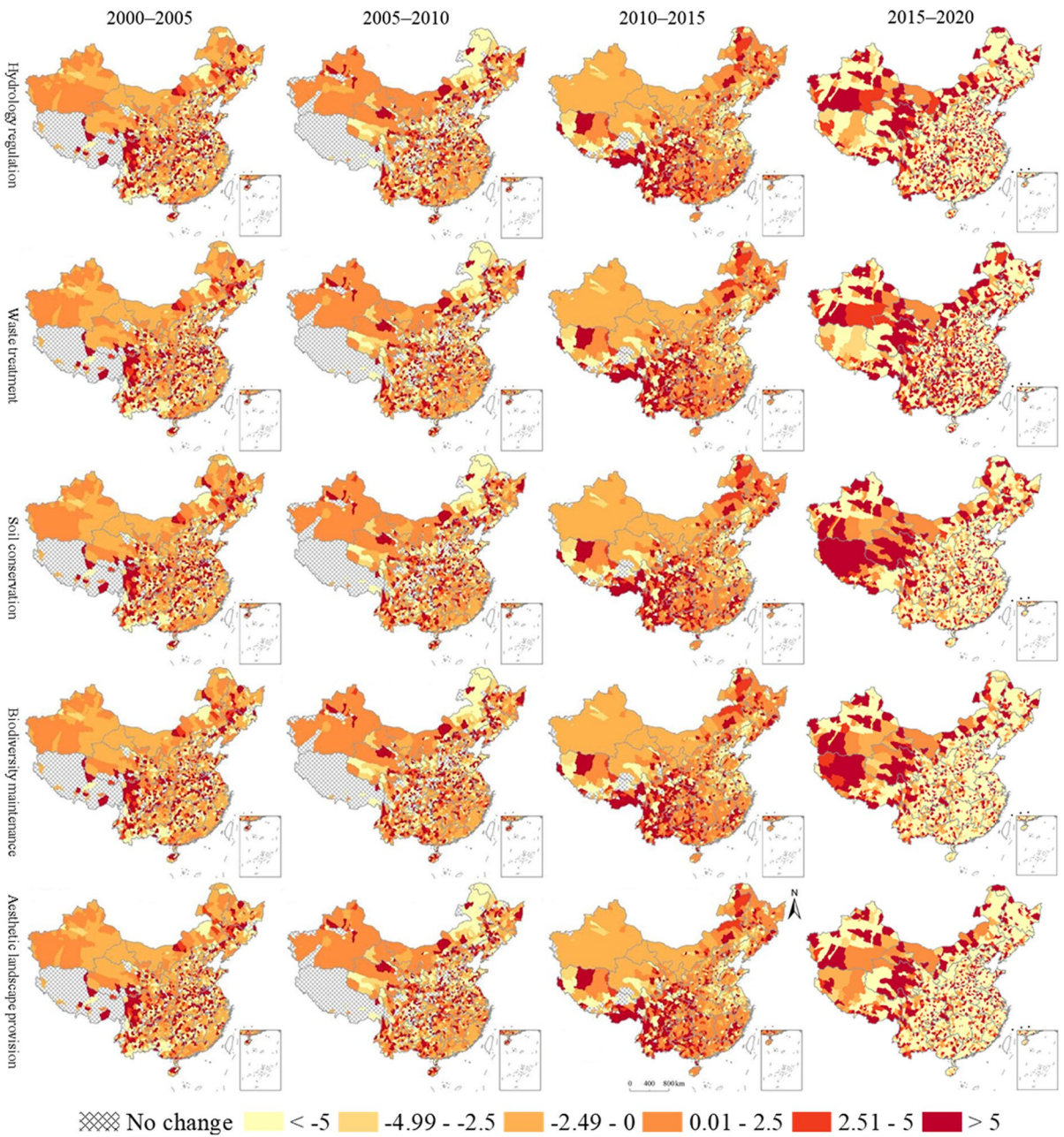


Fig. 6 (continued)

Xinjiang provinces, while counties in the eastern plains tended to exhibit lower sensitivity.

Discussion

Land use change and land use policies in China

Since the inception of the Chinese Reform and Opening-Up Policy, urbanization and industrialization have increased rapidly and led to a tremendous expansion of urban construction land, a rapid increase in industrial and transportation land—thus, a shortage of arable land (Liu et al., 2017). The conflict between the lack of arable land and the continuous increase in population has led to a series of undesirable land use activities such as deforestation and turning water areas or wetlands into arable land. Additionally, ecological protection policies such as Grain for Green, Grain for Blue, key shelterbelt construction programs, and the Natural Forest Conservation Program have greatly threatened the amount of arable land (Liu et al., 2008; Li et al., 2018a; Song and Pijanowski, 2014). At the same time, arable land protection policies such as land reclamation, the Arable Land Requisition–Compensation Balance Policy, basic arable land protection regulations, and an increase versus decrease balance alleviate the reduction of arable land to a certain extent (Chen et al., 2021a; Gao et al., 2019; Li et al., 2021a). The deterioration of arable land is related to the occupation of arable land by construction land and low arable land coverage and is found mostly in the eastern region. In addition, under the top-down policy constraint, deforestation and filling of lakes to make fields continue to occur, also threatening the management of ecosystems in the eastern region. However, compensatory arable land is more likely distributed in counties with undeveloped economies that have arable land available at low cost (Chen et al., 2019d). This has led to the gradual movement of arable land to the northwest of China and the continuous reduction of arable land quality (Gao et al., 2019; Song & Pijanowski, 2014). Compensatory arable land in western China has proven to have equally dramatic impacts on ecosystem management, leading to changes in regional land use structure.

In addition, in the western region, the degradation of wetland ecosystems and grassland ecosystems

is another phenomenon that requires the attention of policymakers. The main manifestation is the contradiction between the western development policy and the western ecological environment restoration, deforestation, filling of lakes and fields, steep slopes, and other phenomena, which seriously threaten effective ecosystem management in the western region. On the Loess Plateau, policy-led afforestation and reforestation have greatly contributed to ecosystem restoration and led to the continuous improvement of the ecosystem in the Yellow River Basin, setting a benchmark for effective ecosystem management. Under China's ecosystem management, policymakers should give full play to the initiative of people and policies to implement effective ecosystem management strategies tailored to local conditions and to better support the continuous improvement of human well-being.

Evolution of ecosystem degradation in China

Change in ecosystem degradation is affected by the combination of socioeconomic (e.g., gross domestic product, population) and physical (e.g., precipitation, temperature) contexts, while land use change is the direct driver (Grimm et al., 2008; Paz-Kagan et al., 2014). Physical factors provide external conditions for ecosystem degradation, while human factors, especially undesirable human activities, are the main cause of ecosystem degradation. Frequent conversions between land use types with similar ESV provision capacity, such as conversion between grassland and water area, do not necessarily lead to significant changes in ecosystem degradation. However, the conversion between land use types with marked differences in ESV provision capacity, such as conversions between unused land and arable land or between forestland and construction land, may result in significant changes in ecosystem degradation or ecosystem restoration. The conversion of low-coverage to high-coverage arable land, grassland, and forestland posed the greatest effect on ecosystem restoration between 2000 and 2020, while decline in forestland quality and deforestation were the primary causes for ecosystem degradation during that period, according to the findings of this study. However, the expansion of construction land in those same years posed a significant threat to ecosystem restoration. Except for northeast China, the Gansu–Xinjiang region, and the Loess Plateau, the expansion of construction land played an

important role in the process of ecosystem degradation. Especially on the Loess Plateau, the middle and lower reaches of Yangtze River, and the Yangtze River Delta, construction land occupied arable land and forestland, which led to evident ecosystem degradation. Worldwide observations have shown that urbanization-led land use change brought about significant change in terrestrial ecosystem degradation, the same phenomenon has proven to be very common in China (Li et al., 2018b, 2022b).

Urbanization has directly or indirectly changed the regional land use structure and has had a dramatic impact on the degradation and restoration of regional ecosystems. The evolution of the natural equilibrium state of ecosystems was not only the direct result of land use conversions but also the indirect result of the flow of matter or energy (e.g., information, capital, and population)—and natural and human systems are tightly connected through these flows. (Wang et al., 2018). Additionally, natural–environmental systems are not only influenced by local elements but also, because of the increasingly telecoupled world, by socioeconomic and land use activities that occur in distant locations (Ma et al., 2020). Thus, new land use institutional developments and governance arrangements can be formed through telecoupled natural–environmental systems (Chen et al., 2019d). Distant connections exist in human and natural coupling systems; for example, ecosystem degradation can be affected by international trade (such as timber and agricultural trade), investment, and migration (Ma et al., 2020; Sun et al., 2020). Some international and domestic policies also have significant effects on land use change, which in turn affects ecosystem degradation (Chen et al., 2019b). Therefore, the integration of a telecoupling analysis framework into future land use change study is necessary to understand the evolution mechanism of ecosystem degradation.

Factors including revision methods, equivalence coefficients, scales, and data sources contribute to the wide variation in results of China's ESV assessment from different studies. Comparing the existing studies, Li et al. (2022a) found that ESV in China showed a trend of increasing and then decreasing in 2000–2020, while Song and Deng (2017) found that a continuous decrease occurred in 1988–2008, Shi et al. (2012) found that the same decrease occurred between 1999 and 2008, and Chen and Chi (2022) found that ESV in China decreased between 2000 and

2005 and increased between 2005 and 2015. In this study, we found that ESV in China declined between 2000 and 2005 and between 2015 and 2020, and it increased between 2005 and 2015, showing some agreement with the above studies.

However, there are also some studies with results that differ significantly from those in our study. For example, Pan et al. (2023) found that ESV in China declined in the periods 2000 through 2010 and increased from 2010 to 2015. Yang et al. (2022) analyzed the changes in ESV in China over a long time series and found a continuous decline between 1992 and 2008, with only brief increases in 2002, 2004, and 2014. Xing et al. (2021) found that China experienced a small increase in ESV between 2000 and 2005 and a large decrease between 2005 and 2015. Previous studies have made substantial efforts to assess ESV in China but still have not produced a uniform result. Nevertheless, the relatively uniform results regarding the spatial variation of ESV can still provide policymakers with recommendations for differentiated control of ESV.

Sensitive area identification and protection policies

The counties with high sensitivity to LUI were distributed mainly in southwest China. Land use in these regions may promote ecosystem restoration—the improvement of forestland and the conversion of arable land to forestland were the primary reasons for ecosystem restoration in this region. At the same time, the degradation of forestland and grassland ecosystem and the occupation of forestland by construction land were the main reasons leading to ecosystem degradation. The Grain for Green (grassland and forestland) policy in southwest China contributed to most of the ecosystem restoration. Therefore, it can be argued that strengthening the Grain for Green policy and natural vegetation rehabilitation were good measures to maintain the fragile ecological environment of the Loess Plateau (Yu et al., 2020).

The counties in Inner Mongolia, the Gansu–Xinjiang region, the southeastern coastal regions, the Loess Plateau, the North China Plain, and the Yunnan–Guizhou Plateau were also areas that were sensitive to land degradation. Desertification in Inner Mongolia and construction land expansion in the middle and lower reaches of the Yangtze River and southeastern coastal regions were the main causes for

ecosystem degradation. Thus, different management and protection strategies should be formulated for differing ecological sensitivity occurrences in counties based on the occurrence mechanisms and sensitivity levels in these counties. For example, afforestation and grassland restoration in Inner Mongolia should be considered an important measure to improve the natural equilibrium state of land systems and ecosystem resilience, while ecosystem restoration in the middle and lower reaches of the Yangtze River and southeastern coastal regions should require limiting the rapid expansion of construction land and promoting the protection of arable land. The focus in those regions should be on land consolidation and land rehabilitation to alleviate conflicts between humans and the ecosystem and to mitigate ecosystem degradation and resource misallocation.

Moreover, it should be kept in mind that economic development and ecosystem restoration are contradictory: simply put, economic development inevitably leads to ecosystem degradation. Ecological compensation mechanisms should therefore be established, especially in fragile and ecologically sensitive counties, to support and help those regions better protect the ecosystem. The beneficiaries of ecological protection achievements should pay corresponding fees and guarantee the reasonable return of ecological investors. In this context, identifying the ecosystem degradation effects of land use change is increasingly important and practical. It can be used as a criterion in land use planning and as a scientific reference for ecological compensation (Qin & Wang, 2022; Sun et al., 2022; Yu & Zhao, 2022).

Specifically, the transition of unused land in the northwest and the conversion of arable land to other land use types (forestland, water area, grassland) in the eastern monsoon region of China may lead to ecosystem restoration. Undesirable land use activity (e.g., overgrazing, grassland reclamation, excessive digging) in these two areas should be limited to avoid unfavorable outcomes such as soil erosion, salinization, and desertification (Song & Deng, 2017). The land use transition in these regions happened mainly between unused land and other land use types because of the widely distributed unused land. The Western Development Strategy and the Three-North Shelterbelt program, also known as the Great Green Wall, had a significant effect on the sensitivity of ecosystem restoration in those regions.

Validity and uncertainty of this study

This study focused only on the sensitivity of ecosystem degradation to land use, and the linear and non-linear relationships and the spatial and nonspatial associations between land use and ecosystem degradation were not considered. Future studies should pay more attention to spatial dependence and heterogeneity of the ecosystem degradation effects of land use change. The evolution of ecosystem degradation was formed under the combined effects of physical factors (e.g., topography, climate), socioeconomic factors (e.g., economy, population, urbanization), and governmental policies (He et al., 2019; Xiao et al., 2022). This study considered only the effects of land use activities on ecosystem degradation and ignored the effects of other factors; it is necessary in future studies to comprehensively consider the other factors that influence ecosystem degradation. Furthermore, the world is increasingly closely integrated, and interconnection and dependence are unprecedentedly enhanced because of contemporary globalization and economic flows. The indirect and direct drivers of land use change and associated ecosystem degradation in future studies can be analyzed by telecoupling analysis between coupled human and natural systems over distances (Sun et al., 2020).

Conclusion

We employed an integrated method including spatial analysis, revised benefit transfer approach, and elasticity analysis in this study to understand the role of land use in ecosystem degradation and restoration in China. Specifically, we found that land use activities during 2005–2015 promoted ecosystem restoration, while ecosystem degradation was caused by land use activities during 2000–2005 and during 2015–2020. Restoration of cropland and grassland ecosystem was the main contributor to ecosystem restoration during 2000–2005 and during 2005–2010, while the restoration of forestland ecosystem contributed the most toward ecosystem restoration during 2010–2020. Degradation of forestland ecosystem was the core driving factor for ecosystem degradation during those two decades. Additionally, the causes of ecosystem degradation and restoration vary in different subregions of

China. Specifically, the restoration and degradation of arable land ecosystem in the eastern region and the restoration and degradation of grassland ecosystem in the western region are the main causes of the restoration and degradation of their respective ecosystems. Further, the results of ecosystem service response to LUI in different regions indicate that land use activities in mountainous areas are more likely to lead to severe ecosystem degradation.

The identified driving factors and ecologically fragile area indices are vital for land managers, stakeholders, and policymakers to better understand the relationship between land use change and ecosystem degradation under complex physical circumstances, regional development strategies, and land use policies, and to better explain the uneven land use and ecosystem degradation patterns in China. We recommend controlling land use patterns and intensities according to local conditions and controlling land use changes that lead to ecosystem degradation in different regions, in order to achieve sustainable land use management.

Author contribution Wanxu Chen: writing—original draft, formal analysis, conceptualization, data curation, methodology, software, writing—review and editing; Liyan Yang: writing—original draft, writing—review and editing, conceptualization, methodology, software, formal analysis; Guangqing Chi: writing—review and editing; Jie Zeng: writing—review and editing.

Funding This study was supported in part by the National Natural Science Foundation of China (Grant numbers 42371258 and 42001187) and this study was also supported by the Key Laboratory of Geospatial Technology for Middle and Lower Yellow River Regions (Henan University), Ministry of Education (No. GTYR202205).

Data availability Not applicable.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval This is an observational study. The Research Ethics Committee has confirmed that no ethical approval is required.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of the case report to the journal.

Conflict of interest The authors declare no competing interests.

References

- Cerretelli, S., Poggio, L., Gimona, A., Yakob, G., Boke, S., Habte, M., Coull, M., Peressotti, A., & Black, H. (2018). Spatial assessment of land degradation through key ecosystem services: The role of globally available data. *Science of The Total Environment*, 628–629, 539–555. <https://doi.org/10.1016/j.scitotenv.2018.02.085>
- Chen, L., Zhao, H., Song, G., & Liu, Y. (2021a). Optimization of cultivated land pattern for achieving cultivated land system security: A case study in Heilongjiang Province China. *Land Use Policy*, 108, 105589. <https://doi.org/10.1016/j.landusepol.2021.105589>
- Chen, M., Tan, Y., Xu, X., & Lin, Y. (2024). Identifying ecological degradation and restoration zone based on ecosystem quality: A case study of Yangtze River Delta. *Applied Geography*, 162, 103149. <https://doi.org/10.1016/j.apgeog.2023.103149>
- Chen, W., & Chi, G. (2022). Ecosystem services trade-offs and synergies in China, 2000–2015. *International Journal of Environmental Science and Technology*. <https://doi.org/10.1007/s13762-022-04141-8>
- Chen, W., Chi, G., & Li, J. (2019a). The spatial association of ecosystem services with land use and land cover change at the county level in China, 1995–2015. *Science of the Total Environment*, 669, 459–470. <https://doi.org/10.1016/j.scitotenv.2019.03.139>
- Spatial heterogeneity and formation mechanism of eco-environmental effect of land use change in China (in Chinese). (2019b). *Geographical Research*, 38(9), 2173–2187. <https://doi.org/10.11821/dlyj020180659>
- Chen, W., Li, J., & Zhu, L. (2019c). Spatial heterogeneity and sensitivity analysis of ecosystem services value in the Middle Yangtze River region (in Chinese). *Journal of Natural Resources*, 34(2), 325–337. <https://doi.org/10.31497/zrzyxb.20190209>
- Chen, W., Ye, X., Li, J., Fan, X., Liu, Q., & Dong, W. (2019d). Analyzing requisition–compensation balance of farmland policy in China through telecoupling: A case study in the middle reaches of Yangtze River urban agglomerations. *Land Use Policy*, 83, 134–146. <https://doi.org/10.1016/j.landusepol.2019.01.031>
- Chen, W., Zeng, J., Chu, Y., & Liang, J. (2021b). Impacts of landscape patterns on ecosystem services value: A multi-scale buffer gradient analysis approach. *Remote Sensing*, 13(13), 2551. <https://doi.org/10.3390/rs13132551>
- Chen, W., Zeng, J., Zhong, M., & Pan, S. (2021c). Coupling analysis of ecosystem services value and economic development in the Yangtze River economic belt: A case study in Hunan Province China. *Remote Sensing*, 13(8), 1552. <https://doi.org/10.3390/rs13081552>
- Chen, W., Zhao, H., Li, J., Zhu, L., Wang, Z., & Zeng, J. (2020). Land use transitions and the associated impacts

- on ecosystem services in the middle reaches of the Yangtze River economic belt in China based on the geoinformatic Tupu method. *Science of the Total Environment*, 701, 134690. <https://doi.org/10.1016/j.scitotenv.2019.134690>
- Chi, G., & Ho, H. (2018). Population stress: A spatiotemporal analysis of population change and land development at the county level in the contiguous United States, 2001–2011. *Land Use Policy*, 70, 128–137. <https://doi.org/10.1016/j.landusepol.2017.10.008>
- The value of the world's ecosystem services and natural capital. (1997). *Nature*, 387, 253–260. <https://doi.org/10.1038/387253a0>
- Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, L., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, 26, 152–158. <https://doi.org/10.1016/j.gloenvcha.2014.04.002>
- Delgado, L. E., & Marín, V. H. (2020). Ecosystem services and ecosystem degradation: Environmentalist's expectation? *Ecosystem Services*, 45, 101177. <https://doi.org/10.1016/j.ecoser.2020.101177>
- Desta, H. (2021). Local perceptions of ecosystem services and human-induced degradation of lake Ziway in the Rift Valley region of Ethiopia. *Ecological Indicators*, 127, 107786. <https://doi.org/10.1016/j.ecolind.2021.107786>
- Fan, F., Liang, C., Tang, Y., Harker-Schuch, I., & Porter, J. R. (2019). Effects and relationships of grazing intensity on multiple ecosystem services in the Inner Mongolian steppe. *Science of the Total Environment*, 675, 642–650. <https://doi.org/10.1016/j.scitotenv.2019.04.279>
- Gao, X., Cheng, W., Wang, N., Liu, Q., Ma, T., Chen, Y., & Zhou, C. (2019). Spatio-temporal distribution and transformation of cropland in geomorphologic regions of China during 1990–2015. *Journal of Geographical Sciences*, 29, 180–196. <https://doi.org/10.1007/s11442-019-1591-4>
- Ge, D., Long, H., Zhang, Y., Ma, L., & Li, T. (2018). Farmland transition and its influences on grain production in China. *Land Use Policy*, 70, 94–105. <https://doi.org/10.1016/j.landusepol.2017.10.010>
- Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., & Bai, X. (2008). Global change and the ecology of cities. *Science*, 319, 756. <https://doi.org/10.1126/science.1150195>
- Gu, C. (2019). Urbanization: Processes and driving forces. *Science China Earth Sciences*, 62(9), 1351–1360. <https://doi.org/10.1007/s11430-018-9359-y>
- Han, X., Yu, J., Shi, L., Zhao, X., & Wang, J. (2021). Spatiotemporal evolution of ecosystem service values in an area dominated by vegetation restoration: Quantification and mechanisms. *Ecological Indicators*, 131, 108191. <https://doi.org/10.1016/j.ecolind.2021.108191>
- He, J., Pan, Z., Liu, D., & Guo, X. (2019). Exploring the regional differences of ecosystem health and its driving factors in China. *Science of the Total Environment*, 673, 553–564. <https://doi.org/10.1016/j.scitotenv.2019.03.465>
- He, J., Shi, X., Fu, Y., & Yuan, Y. (2020). Evaluation and simulation of the impact of land use change on ecosystem services trade-offs in ecological restoration areas China. *Land Use Policy*, 99, 105020. <https://doi.org/10.1016/j.landusepol.2020.105020>
- Lei, J., Wang, S., Wu, J., Wang, J., & Xiong, X. (2021). Land-use configuration has significant impacts on water-related ecosystem services. *Ecological Engineering*, 160, 106133. <https://doi.org/10.1016/j.ecoleng.2020.106133>
- Li, C., Chen, L., Liu, D., Wei, J., He, J., & Duan, X. (2021a). The hidden risk in China's cropland conversion from the perspective of slope. *CATENA*, 206, 105536. <https://doi.org/10.1016/j.catena.2021.105536>
- Li, F., Yin, X., & Shao, M. (2022a). Natural and anthropogenic factors on China's ecosystem services: Comparison and spillover effect perspective. *Journal of Environmental Management*, 324, 116064. <https://doi.org/10.1016/j.jenvman.2022.116064>
- Li, J., Wang, Z., Lai, C., Wu, X., Zeng, Z., Chen, X., & Lian, Y. (2018a). Response of net primary production to land use and land cover change in mainland China since the late 1980s. *Science of the Total Environment*, 639, 237–247. <https://doi.org/10.1016/j.scitotenv.2015.12.067>
- Li, J., Zhang, C., & Zhu, S. (2021b). Relative contributions of climate and land-use change to ecosystem services in arid inland basins. *Journal of Cleaner Production*, 298, 126844. <https://doi.org/10.1016/j.jclepro.2021.126844>
- Li, S., Bing, Z., & Jin, G. (2019). Spatially explicit mapping of soil conservation service in monetary units due to land use/cover change for the Three Gorges Reservoir Area China. *Remote Sensing*, 11(4), 468. <https://doi.org/10.3390/rs11040468>
- Li, S., Zhang, Y., Wang, Z., & Li, L. (2018b). Mapping human influence intensity in the Tibetan Plateau for conservation of ecological service functions. *Ecosystem Services*, 30, 276–286. <https://doi.org/10.1016/j.ecoser.2017.10.003>
- Li, W., Wang, Y., Xie, S., & Cheng, X. (2022b). Spatiotemporal evolution scenarios and the coupling analysis of ecosystem health with land use change in Southwest China. *Ecological Engineering*, 179, 106607. <https://doi.org/10.1016/j.ecoleng.2022.106607>
- Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., & Chi, W. (2014). Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. *Journal of Geographical Sciences*, 24(2), 195–210. <https://doi.org/10.1007/s11442-014-1082-6>
- Liu, J., Li, S., Ouyang, Z., Tam, C., & Chen, X. (2008). Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences*, 105(28), 9477–9482. <https://doi.org/10.1073/pnas.0706436105>
- Liu, X., Zhao, C., & Song, W. (2017). Review of the evolution of cultivated land protection policies in the period following China's reform and liberalization. *Land Use Policy*, 67, 660–669. <https://doi.org/10.1016/j.landusepol.2017.07.012>
- Long, H. (2014). Land use policy in China: Introduction. *Land Use Policy*, 40, 1–5. <https://doi.org/10.1016/j.landusepol.2014.03.006>
- Ma, E., Cai, J., Han, Y., Liao, L., & Lin, J. (2020). Research progress and prospect of telecoupling of human-earth system. *Progress in Geography*, 39(2), 310–326.
- Mansfield, E. (1985). *Microeconomics: Theory and applications* (5th ed.). W.W. Norton.

- Ning, J., Liu, J., Kuang, W., Xu, X., Zhang, S., Yan, C., Li, R., Wu, S., Hu, Y., Du, G., Chi, W., Pan, T., & Ning, J. (2018). Spatiotemporal patterns and characteristics of land-use change in China during 2010–2015. *Journal of Geographical Sciences*, 28, 547–562. <https://doi.org/10.1007/s11442-018-1490-0>
- Pan, Y., Dong, F., & Du, C. (2023). Is China approaching the inflection point of the ecological Kuznets curve? Analysis based on ecosystem service value at the county level. *Journal of Environmental Management*, 326, 116629. <https://doi.org/10.1016/j.jenvman.2022.116629>
- Paz-Kagan, T., Shachak, M., Zaady, E., & Karnieli, A. (2014). Evaluation of ecosystem responses to land-use change using soil quality and primary productivity in a semi-arid area Israel. *Agricultural Ecosystem Environment*, 193, 9–24. <https://doi.org/10.1016/j.agee.2014.04.024>
- Právělie, R., Patriche, C., Borrelli, P., Panagos, P., Roşca, B., Dumitraşcu, M., Nita, I., Săvulescu, I., Birsan, M., & Bandoc, G. (2021). Arable lands under the pressure of multiple land degradation processes A Global Perspective. *Environmental Research*, 194, 110697. <https://doi.org/10.1016/j.envres.2020.110697>
- Qin, Y., & Wang, W. (2022). Research on ecological compensation mechanism for energy economy sustainable based on evolutionary game model. *Energies*, 15(8), 2895. <https://doi.org/10.3390/en15082895>
- Shi, Y., Wang, R., Huang, J., & Yang, W. (2012). An analysis of the spatial and temporal changes in Chinese terrestrial ecosystem service functions. *Chinese Science Bulletin*, 57(17), 2120–2131. <https://doi.org/10.1007/s11434-012-4978-5>
- Song, W., & Deng, X. (2017). Land-use/land-cover change and ecosystem service provision in China. *Science of the Total Environment*, 576, 705–719. <https://doi.org/10.1016/j.scitotenv.2016.07.078>
- Song, W., & Pijanowski, B. C. (2014). The effects of China's cultivated land balance program on potential land productivity at a national scale. *Applied Geography*, 46, 158–170. <https://doi.org/10.1016/j.apgeog.2013.11.009>
- Sun, J., Liu, J., Yang, X., Zhao, F., Qin, Y., Yao, Y., Wang, F., Lun, F., Wang, J., Qin, B., Liu, T., Zhang, C., Huang, B., Cheng, Y., Shi, J., Zhang, J., Tang, H., Yang, P., & Wu, W. (2020). Sustainability in the Anthropocene: Telecoupling Framework and Its Applications. *Acta Geographica Sinica*, 75(11), 2408–2416. <https://doi.org/10.11821/dlxb202011010>
- Sun, R., Jin, X., Han, B., Liang, X., Zhang, X., & Zhou, Y. (2022). Does scale matter? Analysis and measurement of ecosystem service supply and demand status based on ecological unit. *Environmental Impact Assessment*, 95, 106785. <https://doi.org/10.1016/j.eiar.2022.106785>
- Wang, J., Lin, Y., Zhai, T., He, T., Qi, Y., Jin, Z., & Cai, Y. (2018). The role of human activity in decreasing ecologically sound land use in China. *Land Degradation and Development*, 29(3), 446–460. <https://doi.org/10.1002/ldr.2874>
- Xiao, Z., Liu, R., Gao, Y., Yang, Q., & Chen, J. (2022). Spatiotemporal variation characteristics of ecosystem health and its driving mechanism in the mountains of southwest China. *Journal of Cleaner Production*, 345, 131138. <https://doi.org/10.1016/j.jclepro.2022.131138>
- Xie, G., Zhen, L., Lu, C., Xiao, Y., & Chen, C. (2008). Expert knowledge based valuation method of ecosystem services in China. *Journal of Natural Resources*, 23(5), 911–919.
- Xing, L., Zhu, Y., & Wang, J. (2021). Spatial spillover effects of urbanization on ecosystem services value in Chinese cities. *Ecological Indicators*, 121, 107028. <https://doi.org/10.1016/j.ecolind.2020.107028>
- Xu, F., Wang, Z., Chi, G., & Zhang, Z. (2020). The impacts of population and agglomeration development on land use intensity: New evidence behind urbanization in China. *Land Use Policy*, 95, 104639. <https://doi.org/10.1016/j.landusepol.2020.104639>
- Yang, L., Chen, W., Pan, S., Zeng, J., Yuan, Y., & Gu, T. (2023a). Spatial relationship between land urbanization and ecosystem health in the Yangtze River Basin China. *Environmental Monitoring and Assessment*, 195, 957. <https://doi.org/10.1007/S10661-023-11563-5>
- Yang, L., Chen, W., Zeng, J., Pan, S., Zhong, Y., & Gu, T. (2023b). Regional differences and driving forces of ecosystem health in Yangtze River Basin China. *Environmental Science and Pollution Research*, 30, 70985–71000. <https://doi.org/10.1007/S11356-023-27230-8>
- Yang, L., Pan, S., Chen, W., Zeng, J., Xu, H., & Gu, T. (2023c). Spatially non-stationary response of habitat quality to land use activities in World's protected areas over 20 years. *Journal of Cleaner Production*, 419, 138245. <https://doi.org/10.1016/j.jclepro.2023.138245>
- Yang, R., Ren, F., Xu, W., Ma, X., Zhang, H., & He, W. (2022). China's ecosystem service value in 1992–2018: Pattern and anthropogenic driving factors detection using Bayesian spatiotemporal hierarchy model. *Journal of Environmental Management*, 302, 114089. <https://doi.org/10.1016/j.jenvman.2021.114089>
- Yu, Y., Zhao, W., Martinez-Murillo, J., & Pereira, P. (2020). Loess Plateau: From degradation to restoration. *Science of the Total Environment*, 738, 140206. <https://doi.org/10.1016/j.scitotenv.2020.140206>
- Yu, Z., & Zhao, Q. (2022). Research on the coordinated governance mechanism of cross-regional and cross-basin ecological compensation in the Yangtze River Delta. *International Journal of Environmental Research and Public Health*, 19(16), 9881. <https://doi.org/10.3390/ijerph19169881>
- Zeng, J., Cui, X., Chen, W., & Yao, X. (2023). Impact of urban expansion on the supply-demand balance of ecosystem services: An analysis of prefecture-level cities in China. *Environmental Impact Assessment Review*, 99, 107003. <https://doi.org/10.1016/j.eiar.2022.107003>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.