



Evolution of landscape pattern and the association with ecosystem services in the Ili-Balkhash Basin

Feng Huang · Carlos G. Ochoa ·
W. Todd Jarvis · Ruisen Zhong · Lidan Guo

Received: 22 August 2021 / Accepted: 29 January 2022 / Published online: 11 February 2022
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

Abstract The Ili-Balkhash Basin in Central Asia is an arid endorheic basin shared by China and Kazakhstan. Population growth, socio-economic development, ecological conservation measures, and climate change have spurred land use and land cover changes and ecosystem services variations. This study used the long-term dataset from 1992 to 2018 to detect the landscape pattern evolution and its association with ecosystem services. The landscape pattern was quantified using landscape metrics, and the GeoDetector model quantified the driving factors of landscape pattern evolution. The ecosystem service value was assessed using the benefit transfer method. The time

series trend was identified by the linear regression analysis combined with the Mann–Kendall algorithm, and Pearson’s correlation coefficient was used to confirm the correlation. The temporal dynamics of the landscape pattern indicated the significant conversion of bare land to grassland. Cropland and urban land expanded significantly at the expense of forestland, grassland, and bare land. Various landscape elements tended to be more uniformly distributed across the basin with more regular shape and higher aggregation. The ecosystem service value increased significantly, and its correlation with the landscape pattern varied according to land use and land cover (LULC) types. The weakened shape complexity, the strengthened aggregation degree, and the more uniform distribution of different LULC types helped elevate total ecosystem service value. The results advanced the understanding of landscape pattern evolution and provided the scientific reference for land management regarding ecosystem services. Given the watershed ecosystem’s

Highlights

- Landscape patterns and ecosystem services changed in the Ili-Balkhash Basin.
- Climate change and anthropogenic activities spurred landscape pattern evolution.
- Landscape pattern evolution affected ecosystem services. Transboundary cooperation is necessary to reinforce watershed sustainability.

F. Huang (✉)
College of Hydrology and Water Resources, Hohai
University, Nanjing 210098, China
e-mail: huangfeng1987@hhu.edu.cn

F. Huang · C. G. Ochoa
College of Agricultural Sciences-Ecohydrology Lab,
Oregon State University, Corvallis, OR 97331, USA

W. T. Jarvis
Institute for Water and Watersheds, Oregon State

University, Corvallis, OR 97331, USA

R. Zhong
Xinjiang Institute of Ecology and Geography, Chinese
Academy of Sciences, Urumqi 830011, China

L. Guo
International River Research Centre, Hohai University,
Nanjing 211100, China

L. Guo
Business School, Hohai University, Nanjing 211100, China

integrity, transboundary cooperation between China and Kazakhstan was suggested to reinforce watershed sustainability through integrated watershed land resource planning and the joint adaptive strategies to climate change.

Keywords Land use and cover · Ecological value · Spatiotemporal dynamics · Driving forces · Transboundary cooperation · Central Asia

Introduction

Land use and land cover changes (LULCC) are global multi-scale processes affecting ecosystems, with potential implications for ecological processes and the biological communities supporting them (Guerra et al., 2019). The LULCC processes reflect and shape the global interplay between socio-economic development and biodiversity conservation (Tesfaw et al., 2018). Landscape pattern emerges from the composition and spatial configuration of its essential elements (Turner, 2005), including human-managed and natural land use and land cover (LULC). Under the combined impact of climate change and the intensification of anthropogenic activities, the worldwide landscape pattern has undergone significant changes (Zhao et al., 2019). The evolution of landscape pattern exerts multiple impacts on hydrological processes, nutrient transport, and ecological function and health, resulting in an effect on the provision of ecosystem services, and excessive utilization of land resources may lead to severe degradation or loss of regional ecosystem services (Yushanjiang et al., 2018; Zhao et al., 2019). A key challenge of ecosystem management and conservation is determining how to manage multiple ecosystem services across landscapes (Raudsepp-Hearne et al., 2010).

Ecosystem services refer to the direct and indirect benefits that human beings obtain from ecosystems, such as provisioning services, regulating services, supporting services, and cultural services (Costanza et al., 1997). The assessment of ecosystem service values has been increasingly employed as a framework worldwide for ecological restoration and conservation, watershed management, and sustainable development policy-making (Sun et al., 2017). Illuminating the correlation between ecosystem service values and the landscape pattern is necessary to design, implement, and revise management strategies

to achieve sustainable development (Costanza et al., 1997; Yushanjiang et al., 2018). Many studies have addressed this issue in worldwide case studies and synthesized meta-data analyses (Duarte et al., 2018; Mitchell et al., 2014; Yushanjiang et al., 2018; Zhao et al., 2020). However, the knowledge gap still exists regarding a comprehensive understanding of how climate change and socio-economic development drive landscape pattern evolution and how ecological service values respond to landscape pattern changes. Few studies have shed light on the landscape pattern evolution and its association with ecosystem services in the arid endorheic basins in Central Asia.

Located in the Eurasian continent's hinterland, Central Asia is one of the most complex regions in the world, in part due to that it is crisscrossed with transboundary river basins, among which the Ili-Balkhash Basin covers China and Kazakhstan (Chen et al., 2018; Liu et al., 2020). In the past few decades, Central Asia has experienced significant and frequent changes in the landscape pattern, and irrational land resource utilization and improper management have caused severe soil erosion, desertification, and extensive land degradation (Li et al., 2019; Zou et al., 2020). For instance, due to excessive agricultural development and water resource overexploitation for irrigation in the Amu Darya River and Syr Darya River basins, the Aral Sea has shrunk and become a large salt pan (Badescu & Schuiling, 2010). Following the desiccation of the Aral Sea, Balkhash Lake has become the largest lake in Central Asia and attracted worldwide attention to prevent a repeat of the Aral Sea crisis as well as to achieve the sustainable development of the Ili-Balkhash Basin (Duan et al., 2020; Imentai et al., 2015). Previous studies have contributed to unraveling the water consumption of agricultural and natural ecosystems, the interrelationships at the interface of water-energy-food nexus, and sustainable water management, but have not yet paid attention to the relationships of watershed landscape pattern and ecosystem services (Duan et al., 2020; Pueppke et al., 2018; Thevs et al., 2017).

The Ili-Balkhash Basin represents an illustrative case for studying landscape pattern evolution and its association with ecosystem services in the arid endorheic basins in Central Asia. Based on the long-term LULC dataset, this study aims to (a) characterize the temporal changes in landscape pattern and expose the potential driving forces behind the evolution, and (b)

assess the ecosystem service values and their changes corresponding to the landscape pattern evolution. It is a first attempt to investigate the landscape pattern evolution and its association with ecosystem services in the Ili-Balkhash Basin. The novelty is embodied in (a) shedding light on the impacts of human activities and climate change on landscape evolution in the arid endorheic basin in Central Asia, and (b) adding understanding into the effect of composition and configuration of landscape elements on ecosystem services. For regional interest, the research results will provide essential information for the transboundary cooperation of China and Kazakhstan to achieve sustainable development through integrated watershed land resource planning and adaptive strategies for future climate change. The research results will also provide references for the sustainable management of other transboundary basins in Central Asia. For worldwide interest, the research results will help explain the impacts of climate change and human activities on landscape pattern evolution and the responses of ecosystem service values to landscape pattern evolution in arid inland basins.

Study area and materials

The Ili-Balkhash Basin

The Ili-Balkhash Basin is a transboundary basin shared by China and Kazakhstan (Fig. 1). It has a catchment

area of approximately 0.4 million km². The Ili River arises from three main tributaries, the Kash, Künes, and Tekes Rivers. These snow and glacier-fed tributaries originate from the Tianshan Mountains in Xinjiang, China. The Ili River descends west through the fertile Ili River Valley, which gradually opens into a broad plain before crossing the border between China and Kazakhstan. About 15% of the drainage area is in China and 85% in Kazakhstan (Kezer & Matsuyama, 2006). The Ili River forms a delta when entering Balkhash Lake. The Ili Delta is the largest natural delta and wetland complex of Central Asia and is crucial for biodiversity conservation (Imentai et al., 2015). The landscape of the Ili-Balkhash Basin becomes progressively drier from east to west. The mean annual precipitation is only 249 mm in the upper valley. It declines to 223 mm at the Saryesik Atyrau desert near Kapchagai in Kazakhstan and is 116 mm at Balkhash city on the north shore of Balkhash Lake (Kezer & Matsuyama, 2006).

Balkhash Lake is a vast terminal lake in Kazakhstan. The Uzynaral strait divides Balkhash Lake into two parts: the Ili River that mainly recharges the western lake, and several small rivers that mainly recharge the lake’s eastern portion. Besides the Ili River, the Karatal, Aksu, Lepcy, and Ayaguz Rivers flow into the Balkhash Lake. The water source difference and significant evaporation losses result in the phenomenon of “One Lake with Two Waters”: the west lake is freshwater, while the east lake is saline (Tang et al., 2019). Balkhash Lake and its delta are characterized by unique biodiversity

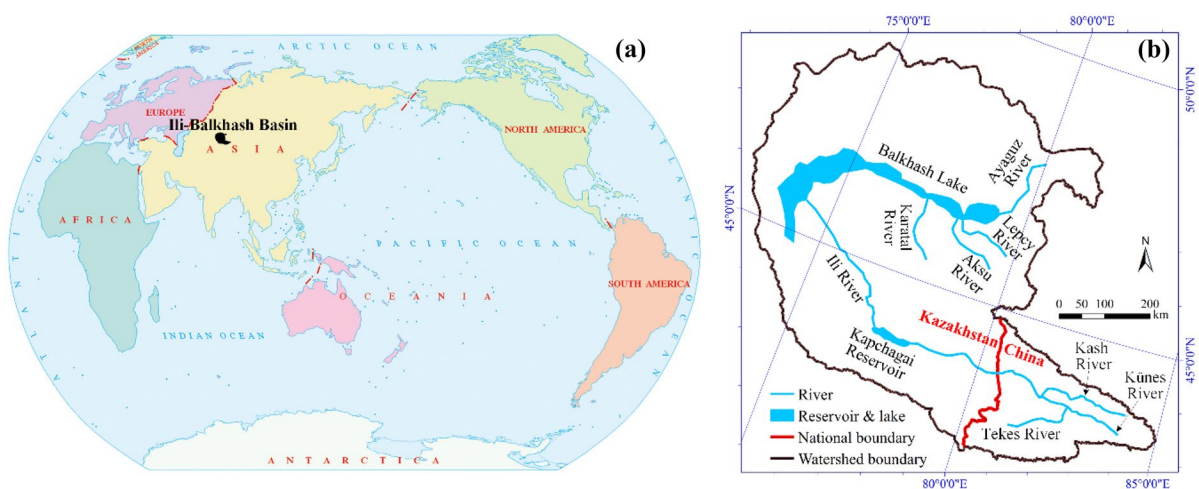


Fig. 1 Sketch of the study area: **a** geographical location of the Ili-Balkhash Basin, and **b** sketch of the river–lake system in the Ili-Balkhash Basin

that includes vertebrate fauna of significant environmental, aesthetic, and practical importance. Anthropogenic impacts on the lake ecology mostly arise from reservoir construction, water withdrawal from the tributaries for irrigation farming, the introduction of non-indigenous species, and the lake's pollution due to mining-related activities (Mischke et al., 2020). Commercial fishing in Balkhash Lake began in 1929 and is currently in a state of crisis due to building the Kapchagai Reservoir. The reservoir reduced the Ili River runoff into the lake. It regulated the natural cycle of spring floods, which resulted in a significant reduction of the spawning and feeding areas for carp (Pueppke et al., 2018).

Data sources

This study used a recently published LULC dataset that includes a yearly spatial representation of LULC from 1992 to 2018 at a spatial resolution of 300 m (Fig. 2). The European Space Agency Climate Change Initiative Land Cover project provides the dataset through <http://maps.elie.ucl.ac.be/CCI/viewer>. This study opted for this dataset because it allows continuous analysis of LULCC at a high spatial resolution with a standardized classification

and validation method (Liu et al., 2018). Because of its temporal consistency, the LULC time series dataset allows for temporally explicit interpretations and analysis of LULCC across space and time (Guerra et al., 2019). The classification types in the LULC dataset are cropland, forestland, grassland, wetland, urban land, bare land, and water bodies (Li et al., 2019).

Precipitation and temperature are two essential factors affecting vegetation growth in the Ili-Balkhash Basin. This study used annual accumulated precipitation and annual mean temperature data from 1992 to 2018 from the Climatic Research Unit of the University of East Anglia (<https://crudata.uea.ac.uk/cru/data/hrg/>). The dataset is produced by interpolating observed data at numerous monitoring stations, and it is suitable for Central Asia (Deng & Chen, 2017; Duan et al., 2020; Harris et al., 2014). Humans directly affect the surrounding ecosystems and can have a tremendous impact on developing the landscape pattern and ecosystem services (Zou et al., 2020). This study collected socio-economic data from the published literature, including population growth, agriculture development, and land management policies (Abdrahimov et al., 2020; Duan et al., 2020; Spitsyna & Spitsyna, 2007; Xu et al., 2006; Yang et al., 2014).

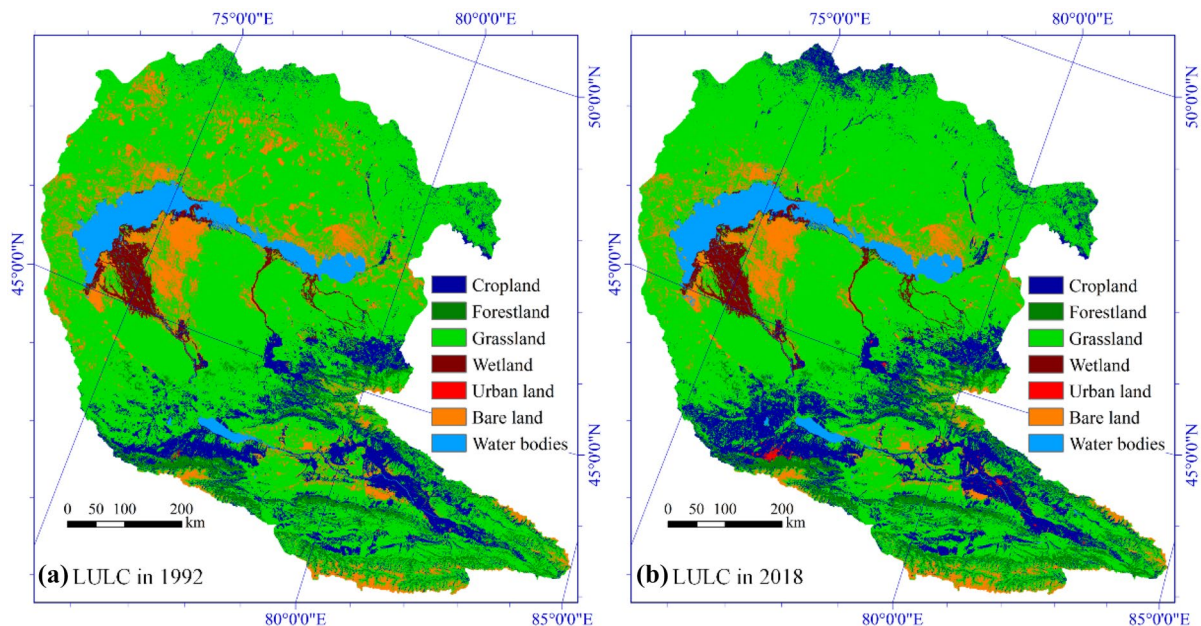


Fig. 2 LULC of the Ili-Balkhash Basin in 1992 and 2018

Methods

Methodological framework

Figure 3 illustrates the methodological framework used for analyzing the landscape pattern evolution and its association with ecosystem services in the Ili-Balkhash Basin. The LULC, climate, and social datasets provided the basis for analysis. Landscape indices that describe the area, shape, aggregation, and diversity were employed to characterize the landscape pattern. Ecosystem service values were evaluated in terms of provisioning, regulating, supporting, and culture. The landscape indices and ecosystem service values were quantified each year, producing the time series for trend detection and correlation analysis. The trend detection revealed the temporal dynamics of landscape pattern and ecosystem services, and the correlation analysis showed the impact of landscape pattern changes on ecosystem service changes. The LULC transition was analyzed for the noticeable LULCC, which was explained by anthropogenic activities and climate variability. Finally, the implications were discussed for China and Kazakhstan’s transboundary cooperation to achieve the Ili-Balkhash Basin’s sustainable development.

Landscape pattern indices

Landscape metrics have been widely applied in measuring landscape patterns and their relationship to LULCC, biodiversity distribution, ecological processes, and ecosystem functions (Uuemaa et al., 2013).

This study analyzed the landscape pattern from two levels: one was the class metrics level, which reflects the spatial characteristics of each class in the landscape, and the other was the landscape metrics level, which reflects the overall spatial features of the basin. Six landscape pattern indices were selected considering landscape area, landscape shape complexity, landscape aggregation, and landscape composition diversity (Table 1). These indices were calculated using FRAGSTATS 4.2 to measure landscape evolution’s spatiotemporal characteristics quantitatively. A detailed description of the landscape pattern indices and their ecological significance can be found in the literature (Ma et al., 2019; McGarigal et al., 2012). Using the TA_C index, the transition probability matrix $A = [A_{ij}]$ was further analyzed. A_{ij} is the percentage of areas from the i th LULC category to the j th category, $i = 1, 2 \dots, 7$ and $j = 1, 2 \dots, 7$ (Li et al., 2019).

Ecosystem service valuation

Quantifying ecosystems’ benefits can be achieved by evaluating ecosystem service values in monetary units (Costanza et al., 2014). The revealed preference methods, the stated preference methods, the cost-based methods, and the benefit transfer methods can be used to evaluate ecosystem services (Liu et al., 2010). The benefit transfer methods have been widely used because of their feasibility and simplicity (Costanza et al., 1997, 2014). Since conducting original valuation research is time-consuming and financial-costly, the benefit transfer methods have been employed as a “second-best” strategy, where researchers and

Fig. 3 Schematic analysis methodology

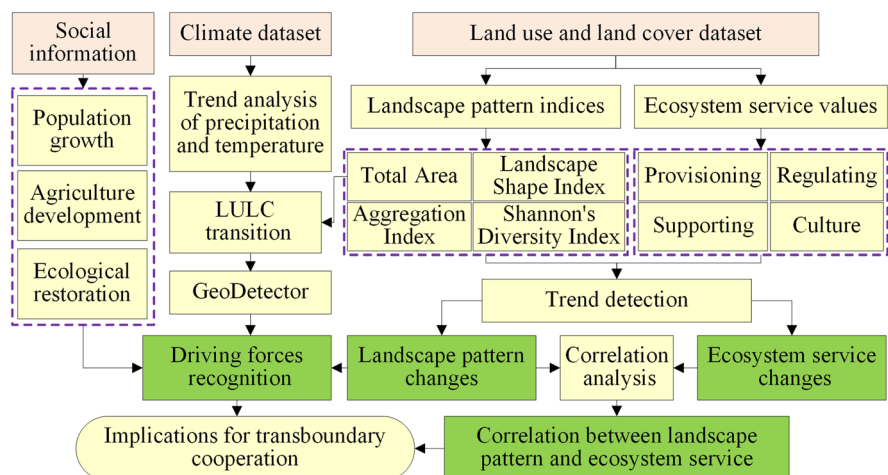


Table 1 Landscape pattern indices and the associated ecological significance

Index	Level	Acronym	Unit	Range	Ecological significance
Total area	Class	TA_C	ha	$(0, +\infty)$	The spatial range of a landscape class
Landscape shape index	Class	LSI_C	None	$[1, +\infty)$	LSI measures the complexity of landscape shape. The higher value of LSI indicates the more irregular landscape shape and the more substantial mutual interference between landscape classes
	Landscape	LSI_L			
Aggregation index	Class	AI_C	%	$[0, 100]$	AI measures the aggregation degree of the landscape composition. The higher the value of AI, the more aggregated the patches, and vice versa
	Landscape	AI_L			
Shannon's diversity index	Landscape	SDI_L	None	$[0, +\infty)$	SDI measures the richness and complexity of the landscape. SDI equals 0 when the landscape contains only one patch without any diversity. The higher value of SDI indicates the more uniform distribution of various patch types in the landscape

decision-makers seek a timely and cost-effective way to value ecosystem services (Liu et al., 2010). Benefit transfer is a procedure for taking the estimates of economic benefits gathered from one site and applying them to another (Plummer, 2009). This study estimated the static ecosystem service values based on a benefit transfer method and its updated value coefficient for each ecosystem service (Costanza et al., 1997, 2014). Table 2 lists the equivalent value coefficients used to estimate ecosystem service values in Central Asia (Li et al., 2019). The value coefficient of ecosystem service was assumed to be static from 1992 to 2018. The ecosystem service values are the products of the value coefficient and the corresponded area.

Trend and correlation analysis

Linear regression analysis was used to illustrate the trend, and the Mann–Kendall (M–K) algorithm was used to ascertain a statistically significant trend in the time series. The M–K algorithm is a non-parametric rank-based procedure, which checks the null hypothesis

of no trend versus the alternative one indicating the existence of an upward or downward trend. The statistic Z of the M–K algorithm follows a standard normal distribution with a mean of zero and a variance of one. A positive or negative Z value represents an increasing or decreasing trend, respectively. In a two-tailed test, the null hypothesis can be rejected at a significance level α if $|Z| > Z_{\alpha/2}$. This study set the significance level α to be 0.05. The published articles provided detailed information on the M–K algorithm (Huang et al., 2012; Yue et al., 2002).

Based on the time series of landscape indices and ecosystem service values, ecosystem services' responses to landscape pattern evolution were unraveled by correlation analysis that incorporated linear regression analysis and Pearson's correlation coefficient. This study set the significance level of correlation to be 0.05. A significantly positive correlation indicates that the landscape pattern evolution enhances the ecosystem services, while a significantly negative correlation shows that the landscape pattern change weakens the ecosystem services.

Table 2 Value coefficient of ecosystem service (unit: US\$ha⁻¹ year⁻¹)

Ecosystem service	Cropland	Forestland	Grassland	Wetland	Urban land	Bare land	Water bodies
Provisioning: food and raw material	2542	480	1246	1153	0	0	106
Regulating: gas, climate, and water	811	343	112	9488	921	0	9322
Supporting: soil-formation and retention, waste-treatment, and biodiversity	2132	1324	2615	10,837	0	0	918
Culture: recreation, cultural, and tourism	82	990	193	4203	5740	0	2166
Total value	5567	3137	4166	25,681	6661	0	12,512

Driving forces analysis

The factors affecting the landscape pattern evolution and the corresponded ecosystem service changes mainly include anthropogenic activities and climate variability. In terms of the impact of human activities, this study qualitatively discussed the effects of population growth, agriculture development, and land management policies on landscape pattern changes. In terms of the impact of climate change, this study investigated the effects of precipitation and temperature changes. Based on the gridded climatic dataset from 1992 to 2018, the multi-year mean value was calculated, and the linear regression analysis was conducted on every pixel, resulting in the spatial distribution of precipitation and temperature and their changing tendencies. The impact of climate change on the LULCC was analyzed using the GeoDetector.

The GeoDetector is a model based on spatial superposition technology and set theory that is used to identify the interactions between multiple factors (Wang et al., 2010). The model’s core hypothesis is that if a significant spatial consistency exists between independent variables (*X*) and dependent variables (*Y*), an association is present. The independent variables were multi-year mean precipitation, the change rate of precipitation, multi-year mean temperature, and the change rate of temperature. The dependent variables were the transitions between different LULC, i.e., the transition of bare land to grassland. The correlation between *X* and *Y* can be quantified by the statistic *q*, which ranges from 0 to 1. The minimum value 0 indicates no correlation between the two variables, and the

maximum value 1 indicates that *Y* is entirely dependent on *X*. The model was executed with the “geodetector” package in R (<https://CRAN.R-project.org/package=geodetector>). The GeoDetector’s detailed principle can refer to the published articles (Wang et al., 2010).

Results

Evolution of landscape pattern

The landscape evolution led to the changes in composition and configuration of LULC types in terms of the area, shape complexity, aggregation degree, and spatial diversity. Figure 4 shows the temporal dynamics of LULC areas in the Ili-Balkhash Basin, where the dominant LULC type was grassland, followed by cropland and bare land. The M–K algorithm identified significant increasing trends in the cropland, forestland, wetland, and urban land areas, and significant decreasing trends in the grassland and bare land areas.

The cropland area increased substantially from 1998 to 2002 and kept slightly rising after 2002. The forestland area experienced an abrupt increase in 2004. The grassland area remained relatively stable from 1992 to 1998, decreased considerably from 1999 to 2002, and recovered somewhat recently. The wetland area also increased considerably in the current decade. The urban land area remained relatively stable from 1992 to 2000 and increased progressively and considerably since 2001. The bare land area decreased continuously and considerably from 1992

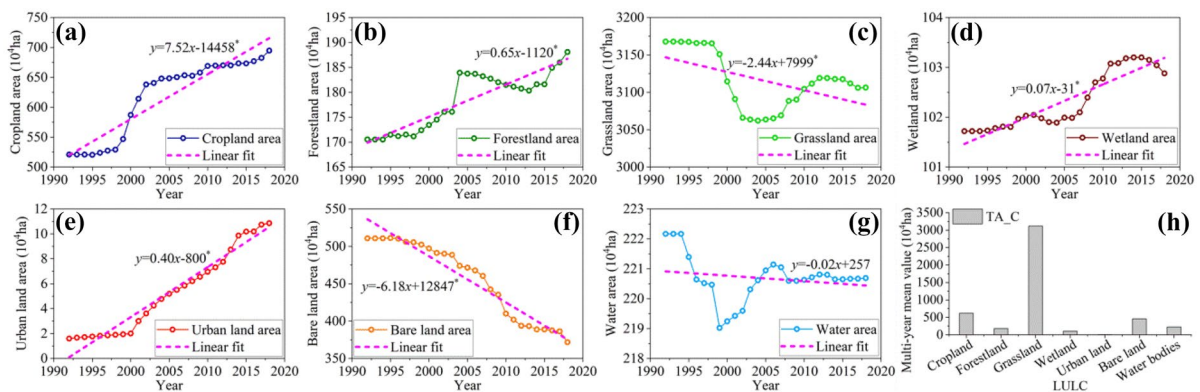


Fig. 4 Temporal dynamics of the LULC area (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

Table 3 LULC transition probability matrix from 1992 to 2018 (unit: %)

		To final state 2018						
		Cropland	Forestland	Grassland	Wetland	Urban land	Bare land	Water bodies
From initial state 1992	Cropland	94.10	1.35	3.10	0	1.26	0.15	0.04
	Forestland	3.33	94.12	1.26	0.84	0.15	0.22	0.08
	Grassland	6.00	0.61	93.15	0	0.07	0.15	0.02
	Wetland	0	0.57	0	99.41	0	0	0.02
	Urban land	0	0	0	0	100	0	0
	Bare land	1.66	0.06	26.61	0.01	0.02	71.22	0.42
	Water bodies	0.23	0.16	0.65	0.12	0	0.87	97.97

to 2018. The water area fluctuated from 1992 to 2018 without significantly changing tendency. It shrunk from 1992 to 1999 but recovered gradually from 2000 to 2018. Table 3 lists the LULC transition probability from 1992 to 2018. The conversion of cropland contributed to the recovery of grassland and forestland and the development of urban land. Meanwhile, the exploitation of forestland, grassland, and bare land contributed to the expansion of cropland. A noticeable change was the recovery of bare land to grassland, resulting in a significant reduction of bare land area. The expansion or shrinkage of various LULC types occurred with the dispersion or aggregation of landscape patches, which resulted in the changes in the spatial configuration of landscape patches and the corresponding spatial pattern characteristics.

Figure 5 illustrates the temporal dynamics of the landscape shape index at the class level in the Ili-Balkhash Basin. Bare land, cropland, and grassland had relatively high multi-year mean values of LSI,

followed by forestland, wetland, urban land, and water bodies. The LSI of cropland remained relatively stable across the whole study period, and the M–K algorithm detected no significant trend. The LSI of forestland, grassland, wetland, and bare land decreased significantly, while the LSI of urban land and water bodies increased significantly.

Figure 6 depicts the temporal dynamics of the aggregation index at the class level in the Ili-Balkhash Basin. Water bodies, grassland, and wetland had relatively high AI values, and cropland, forestland, bare land, and urban land had a bit smaller AI values. The AI of cropland increased significantly, and an abrupt increase occurred around 2000. The AI of forestland rose substantially across the whole study period. It increased continually from 1992 to 2004 and remained relatively stable after then. The AI of urban land experienced a dramatic increment in 2001. The AI of grassland and wetland fluctuated from 1992 to 2018 and increased slightly across the whole study period.

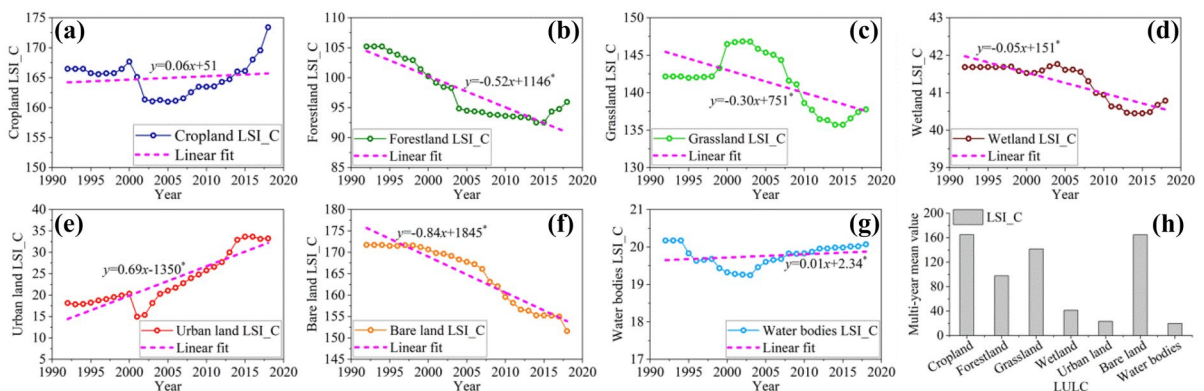


Fig. 5 Temporal dynamics of landscape shape index at the class level (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

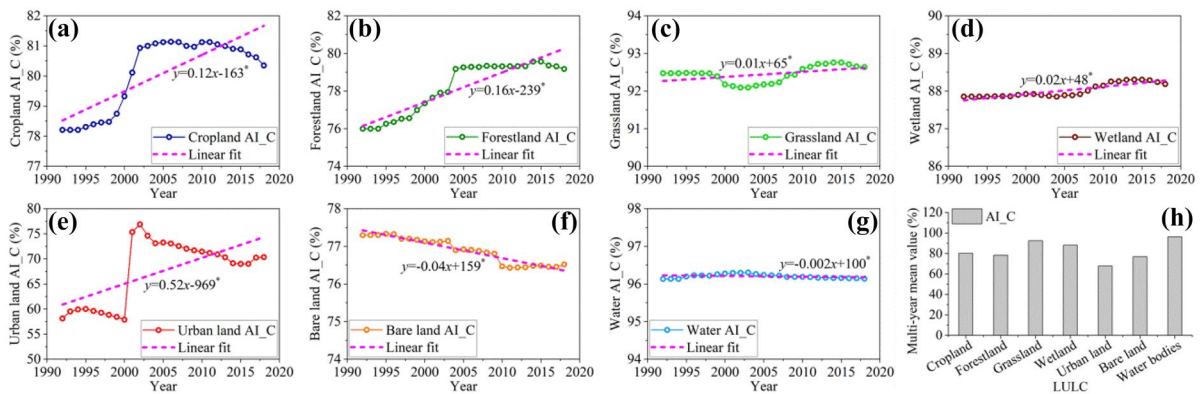


Fig. 6 Temporal dynamics of aggregation index at the class level (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

The AI of water bodies decreased somewhat, while the AI of bare land reduced significantly.

Figure 7 displays the temporal dynamics of spatial pattern indices at the landscape level in the Ili-Balkhash Basin. The LSI_L decreased significantly, which indicated that the landscape shape across the basin tended to be more regular. The AI_L increased significantly, indicating that the landscape patches across the basin grew to more aggregate. The SHDI_L experienced a significant increase from 1992 to 2018, which unraveled that various LULC types followed a more uniform distribution in the Ili-Balkhash Basin.

Driving forces of landscape pattern evolution

Political context

In the entire Ili-Balkhash Basin, from 2000 to 2015, the population density increased by approximately 32.41% (Duan et al., 2020). In Kazakhstan, the Ili-Balkhash Basin is the most densely populated and

economically developed region, where it is the center of large agro-industrial complexes, numerous settlements, and cities (Abdrahimov et al., 2020). The city of Almaty in Kazakhstan had the most massive increase in population density, the peak of which reached 850 persons per km² every 5 years. Population growth and the corresponding socio-economic development promoted the expansion of urban land and cropland (Fig. 8), driving the transition of other LULC types, eventually resulting in the evolution in the watershed landscape pattern and the associated ecosystem services. In Kazakhstan, agriculture developed very well in the Ili-Balkhash Basin in the 1970s. After the Soviet Union collapsed, the economic activity in the basin went down, and the agriculture became unpopular. A land reform process was initiated in 1994 and most of the land was transferred to farmers or companies, through private ownership or long-term leases. From 2001, the interest in agriculture has returned, leading to a fast agricultural development and an increase in cropland

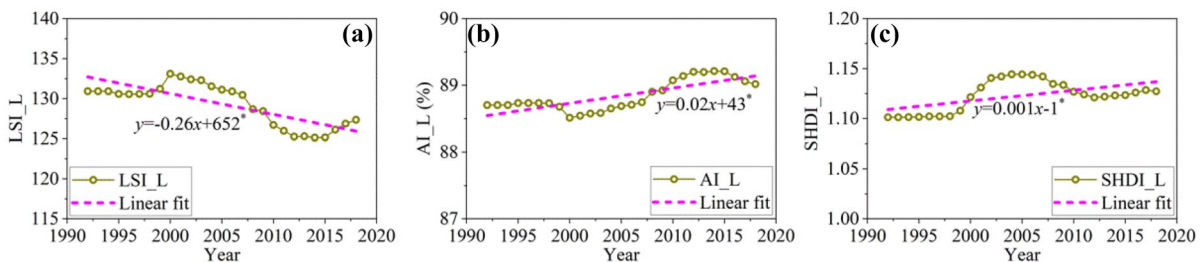


Fig. 7 Temporal dynamics of spatial pattern indices at the landscape level (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

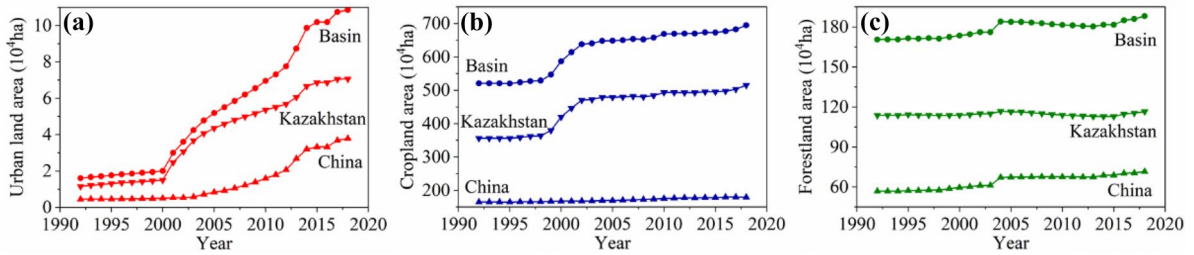


Fig. 8 Changes in urban land, cropland, and forestland area in Kazakhstan and China

area (Fig. 8). The condition of forests has drastically deteriorated during the reform and reorganization (Spitsyna & Spitsyna, 2007).

Besides the impact of development pressure on landscape evolution, the recognition of sustainability and the related policies and strategies were other critical factors affecting landscape dynamics. China has initiated several ecological restoration projects in the late 1990s and early 2000s, such as the Grain for Green Program, the Natural Forest Protection Project, and the Sloping Land Conversion Project. The Grain for Green Program, launched in 1999, is the most renowned large-scale initiative, aiming to restore degraded, decertified, and cultivated land on steep slopes by banning grazing and farming (Xu et al., 2006; Yang et al., 2014). These projects have driven forestland recovery in the Ili-Balkhash Basin in China (Fig. 8).

Climate change

In addition to anthropogenic activities, climate change was essential for driving the LULCC and the ecosystem service dynamics. Impacts from climate change have been reported in Central Asia with rising temperature trends and changes in precipitation amounts and patterns (Chen et al., 2018). The analysis using the dataset from 1992 to 2018 corroborated the increasing precipitation and temperature across the Ili-Balkhash Basin (Fig. 9). Water availability is a primary environmental factor affecting vegetation growth in arid endorheic basins. The increase in precipitation helped relieve the water scarcity for vegetation growth and restore the bare land to grassland. Figure 9 shows that the expansion of grassland occurred in these areas with relatively low multi-year mean precipitation and a relatively high precipitation change rate.

The statistic q values of the GeoDetector model are listed in Table 4, where a larger q value indicates a

more significant explanation. In viewing the explanatory power of a single factor, among the four factors, i.e., multi-year mean precipitation, change rate of precipitation, multi-year mean temperature, and change rate of temperature, the change rate of precipitation contributed mostly to the transition from bare land to grassland. In viewing the factor interactions, the change rate of precipitation combined with the multi-year mean precipitation mainly explained the transition from bare land to grassland, followed by the combination of the change rate of precipitation and the change rate of temperature. The results indicated that the increased precipitation was probably a critical factor driving bare land converted to grassland.

Changes in ecosystem service values

Figure 10 displays the contribution of LULC to ecosystem services and the temporal dynamics of service values. Grassland was a predominant contributor to the provisioning service, accounting for 68.35% of the provisioning service value. Cropland accounted for 27.65% of the provisioning service value, followed by wetland and forestland. Due to the development of cropland and the recovery of grassland, the provisioning service value increased significantly and progressively. Water bodies dominated the regulating service, accounting for 52.16% of the regulating service value, followed by wetland, cropland, and grassland. The LULCC spurred a significant increment of the regulating service value. The contribution of grassland to the supporting service was predominant, making up 73.98% of the supporting service value. Cropland and wetland accounted for 11.96% and 10.07% of the supporting service value, respectively. The supporting service value had a pronounced increase across the entire study period, especially after 2004. Grassland, water bodies, wetland,

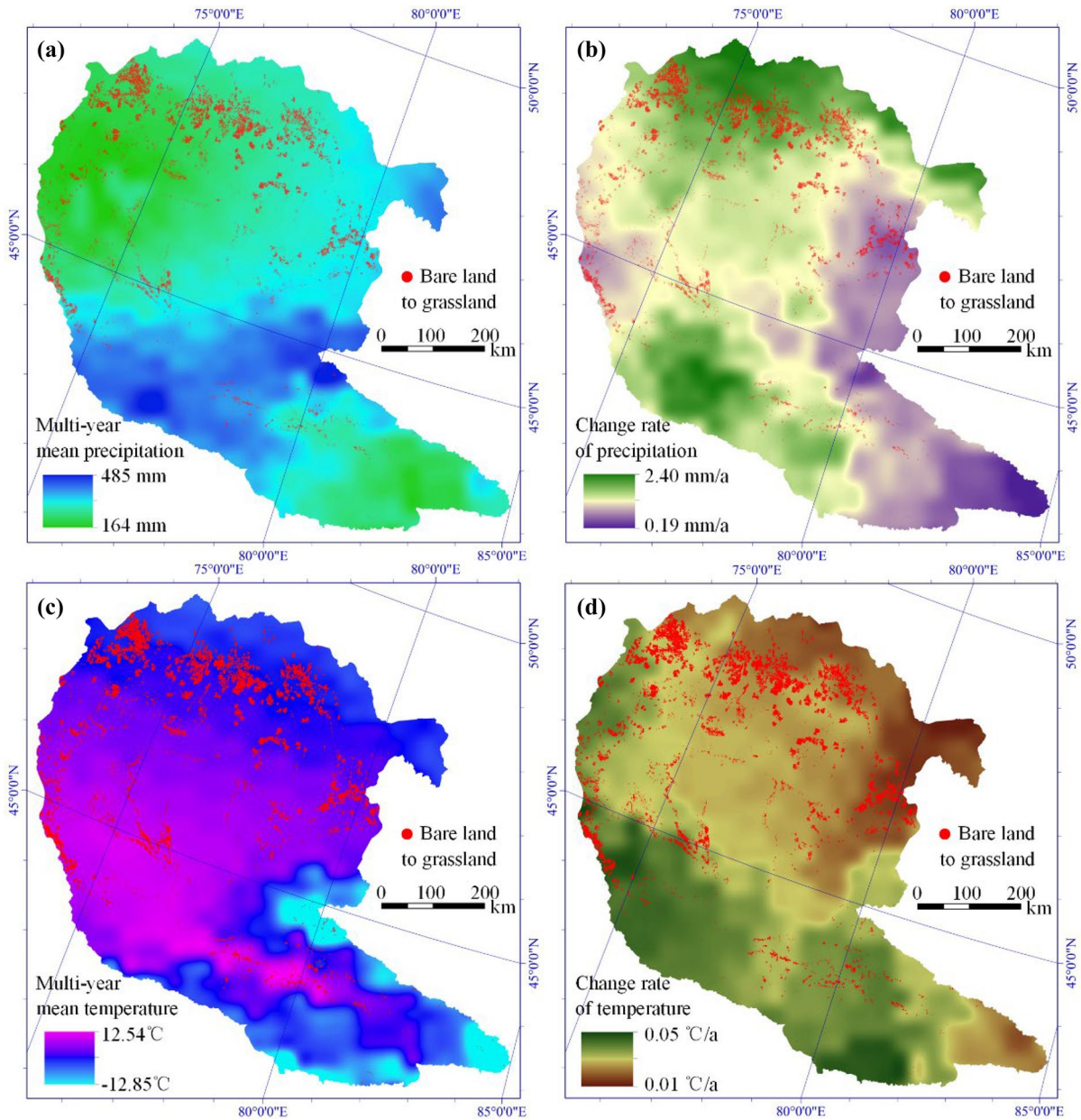


Fig. 9 Spatial features of precipitation and temperature and the distribution of the transition from bare land to grassland

and forestland contributed 34.02%, 27.05%, 24.34%, and 9.99%, respectively, to the culture service value, which remained relatively stable from 1992 to 2000 and increased continuously after then.

The changes in ecosystem services (i.e., provisioning, regulating, supporting, and culture) jointly affected their total value. Figure 11 shows the compositions of the global ecosystem service value and its

temporal dynamics. Grassland was a dominant LULC type that accounted for 57.93% of the ecosystem service value. Cropland, water bodies, and wetland made up 15.35%, 12.33%, and 11.73% of the contribution. The rest of the contribution was produced by forestland and urban land, accounting for 2.50% and 0.16%, respectively. The supporting service dominated the ecosystem service value, making up to 49.15% of the

Table 4 Contributions of precipitation and temperature to the transition of bare land to grassland (unit: %)

	Multi-year mean precipitation	Change rate of precipitation	Multi-year mean temperature	Change rate of temperature
Multi-year mean precipitation	1.61 ^a			
Change rate of precipitation	32.06 ^b	24.10 ^a		
Multi-year mean temperature	4.42 ^b	28.35 ^b	3.67 ^a	
Change rate of temperature	7.48 ^b	31.90 ^b	7.36 ^b	3.66 ^a

The superscript “a” denotes the explanatory power of a single factor, and the superscript “b” represents the interactive explanatory power of two factors

total amount. The remaining ecosystem service value arose from the provisioning, regulating, and culture service, corresponding to 25.35%, 17.61%, and 7.89%, respectively.

Correlation between landscape pattern and ecosystem service

Figure 12 illustrates the correlation of ecosystem service value and landscape shape index at the class level. Various LULC types showed different correlations between the LSI and the service value. There was a weak correlation between the LSI and the service value for cropland and grassland, indicating that the impact of shape complexity on the service value was marginal. A significantly negative correlation existed between the LSI and the service value for forestland and

wetland, which indicated that a more regular landscape shape helped promote the service value. Conversely, for urban land and water bodies, the service value was significantly and positively correlated with the LSI, indicating that a higher complexity of landscape shape corresponded to a more considerable service value.

In addition to the impact of landscape shape complexity, the dispersion and aggregation of landscape patches also affect the ecosystem services. Figure 13 depicts the correlation of ecosystem service value and landscape aggregation index at the class level. The correlations between the AI and the service value varied according to the different LULC types. A higher aggregation degree of landscape patches of cropland, forestland, grassland, wetland, and urban land was conducive for enhancing their ecosystem services, resulting in significantly positive correlations

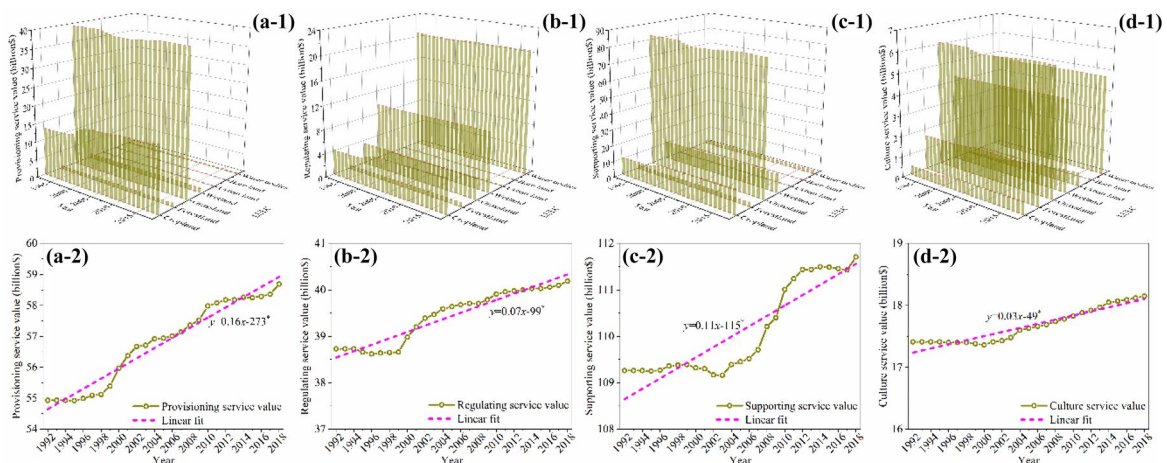


Fig. 10 Changes in ecosystem services of provisioning, regulating, supporting, and culture (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

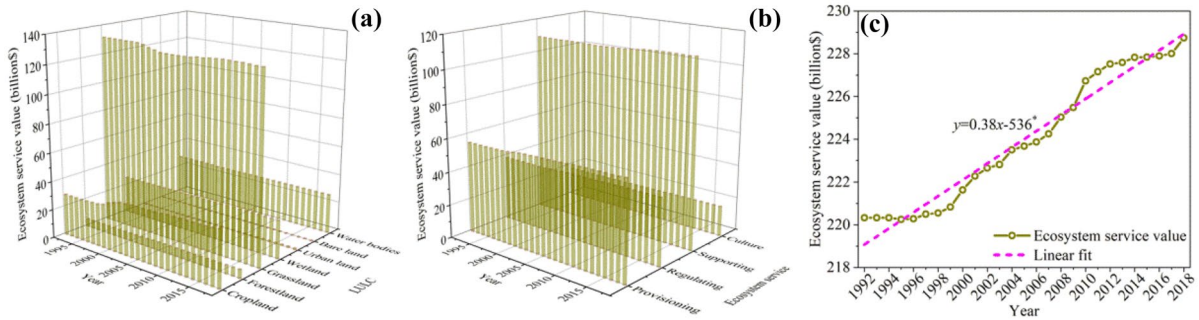


Fig. 11 Temporal dynamics of total ecosystem service value (the * indicates a significant trend at the 0.05 level confirmed by the M–K algorithm)

between the AI and the service values of these five LULC categories. On the contrary, the expansion and dispersion of water bodies reinforced its ecosystem service, leading to a significantly negative correlation between the AI and water bodies’ service value.

The correlation between the overall ecosystem service value and the watershed landscape pattern was a composite result of the class-level correlations. The correlations between ecosystem service value and landscape pattern indices at the landscape level were

significant (Fig. 14). The ecosystem service value was negatively correlated with the LSI_L and positively correlated with the AI_L. The results showed that a more regular shape and a more aggregated patch of landscape element were conducive for the growth of ecosystem service value. A significant and positive correlation existed between ecosystem service value and SHDI_L, indicating that the more uniform distribution of various LULC types across the entire basin helped enhance the ecosystem services.

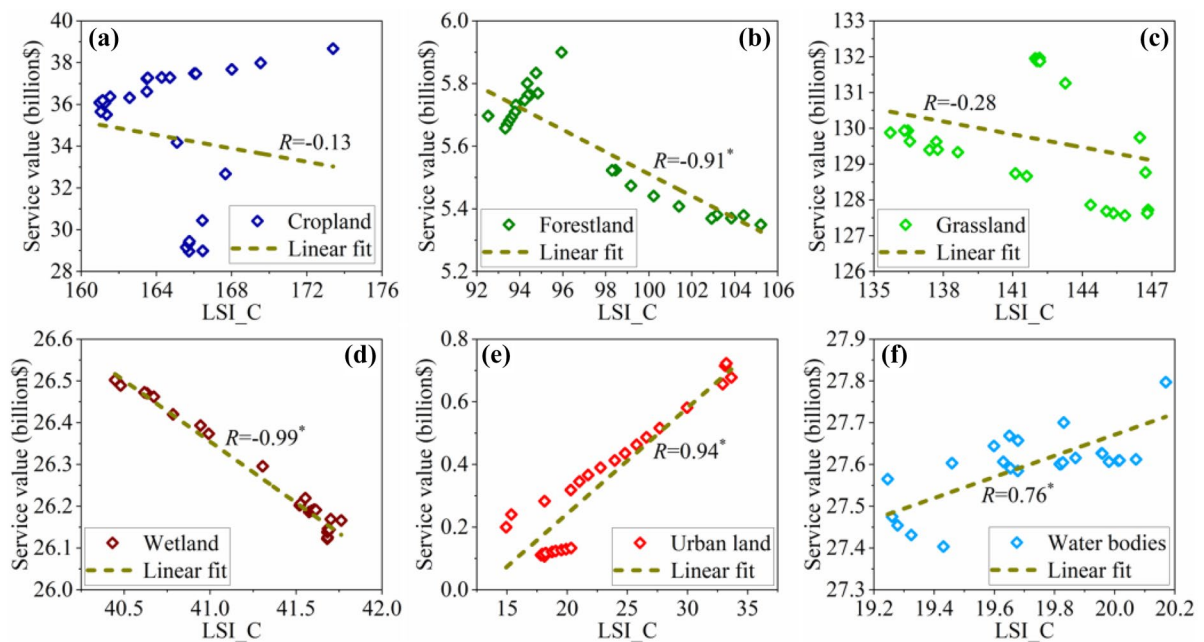


Fig. 12 The correlation between ecosystem service value and LSI_C (the * indicates the correlation is significant at the 0.05 level of the two-tailed test)

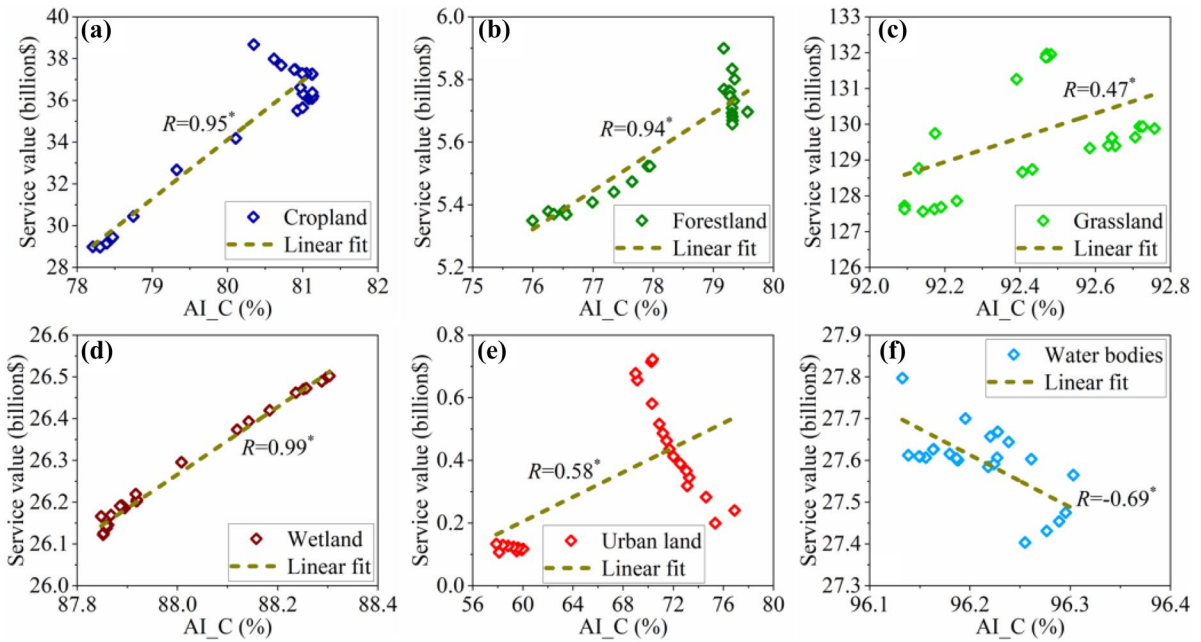


Fig. 13 The correlation between ecosystem service value and AI_C (the * indicates the correlation is significant at the 0.05 level of the two-tailed test)

Discussion

Implications for transboundary cooperation

Integrated watershed land resource planning

The landscape pattern evolution was sensitive to human interference and climate change, which eventually affected ecosystem services. Cropland, forestland, grassland, wetland, urban land, and water bodies played different roles in the ecosystem services of provisioning,

regulating, supporting, and culture. Population growth and socio-economic development stimulated the expansion of cropland for food production and urban land for settlement at the expense of forestland, grassland, and bare land. Ecological restoration measures, accompanied by the climate change that improved the water resources, promoted the recovery of forestland, grassland, wetland, and water bodies. The transitions of different LULC types resulted in the tradeoffs between the ecosystem services of provisioning, regulating, supporting, and culture. In viewing the watershed ecosystem’s

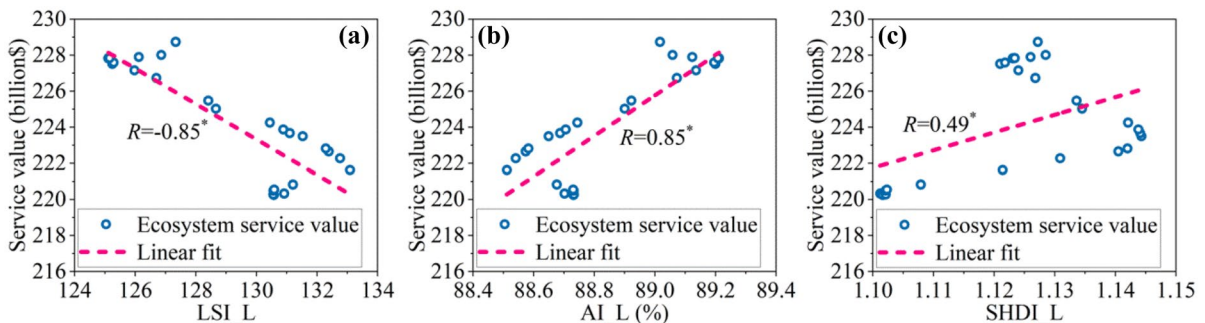


Fig. 14 The correlation between ecosystem service value and landscape pattern indices (the * indicates the correlation is significant at the 0.05 level of the two-tailed test)

integrity, the Ili-Balkhash Basin's sustainable development requires China and Kazakhstan's joint efforts. An integrated watershed land resource planning that required negotiation and cooperation between China and Kazakhstan would help meet human beings' needs, balance the provision of various ecosystem services, and enhance watershed sustainability. The correlation analysis of the landscape pattern and ecosystem services would provide scientific references for working out this land resource planning.

Adaption to climate change

Agriculture in the Ili-Balkhash Basin is dependent upon irrigation, which consumed river runoff and affected the distribution of wetland and water bodies. The Ili Delta is the largest natural delta and wetland complex in Central Asia and is a crucial fish spawning ground for Balkhash Lake (Thevs et al., 2017). Given the Ili Delta and Balkhash Lake's ecological function and significance, the transboundary cooperation should pay attention to the tradeoff between the agricultural development and the conservation of wetland and water bodies due to the water conflict between the engineered and natural systems. Climate change in the past decades, in terms of the increased precipitation and temperature, led to an increase in water supply, promoted the recovery of wetland and water bodies, drove the conversion of bare land to grassland, and eventually helped elevate the watershed ecosystem service value. If future climate change were to reduce the water resource availability, the potential water crisis would exacerbate the conflict between the engineered and natural systems, probably resulting in the degeneration of lake, wetland, and grassland and the expansion of bare land without ecosystem service value. For example, in a watershed draining into the Caspian Sea in northern Iran, the combined modeling of the impacts of climate and LULC change scenarios showed the substantial spatial variation of the adverse effects of water supply and future water security across the watershed. The water insecurity further increased the pressure on inhabitants, economic activities, and ecological values (Daneshi et al., 2021).

The landscape pattern evolution in the water crisis context would negatively impact ecosystem services and interfere with watershed sustainability (Mahmoud & Gan, 2018; Vitule et al., 2015). Therefore, China and Kazakhstan's cooperation is necessary to adapt

to climate change and reinforce ecological resilience. Primarily, rational use of water resources with high efficiency and modernization of water-saving irrigation systems is vital for supporting agricultural development and reducing water consumption to satisfy environmental water requirements and protect lake and wetland ecosystems.

Rational protection of the Ili Delta and Balkhash Lake

In terms of protecting the Ili Delta and Balkhash Lake, rational protection targets are the basis of the integrated watershed land resource planning and adaptive strategies for future climate change. The Ili Delta's protection targets mainly include the delta area, vegetation species, and community structure. Balkhash Lake's protection targets mainly include the lake area, water level, water quality, and aquatic biodiversity. Because the delta and lake's area is crucial for wetland and aquatic habitats, it is a vital protection target. In the inland basins, the water discharged into the lake affects the terminal delta and lake's area. The expansion of cropland and urban land stimulated by population growth and socio-economic development consumes water resources and reduces the water discharged into the lake. Under the water resource constraints, excessive expansion of cropland and urban land would shrink delta and lake's area and degrade wetland and aquatic ecosystems. On the other hand, overprotection of the wetland and aquatic ecosystems requires more water to be discharged into the lake and would restrain socio-economic development. Therefore, a rational protection area of the Ili Delta and Balkhash Lake is an important issue of China and Kazakhstan's cooperation in the integrated watershed land resource planning and adaptive strategies for future climate change. In viewing the intrinsic water conflict between the engineered and natural systems and the countries' responsibility to ensure human well-being, it is unrealistic to conserve the Ili Delta and Balkhash Lake to their original status. Based on the tradeoffs between the ecosystem services of different LULC types, the sensible protection area should help improve the basin's total ecosystem service value and involve the uncertainty of future climate change. It is a major scientific issue that requires in-depth study through cooperation between the two countries. Therefore, China and Kazakhstan's joint efforts are

necessary to evaluate the rational protection area of the Ili Delta and Balkhash Lake and the environmental water required to sustain the protection area.

Limitations and future research

This study had some limitations that need to be addressed in future research. The intrinsic uncertainty embedded in the LULC dataset would result in the uncertainty of the analysis of landscape pattern evolution, which would probably be relaxed using the updated dataset. When evaluating the ecosystem service values, the Ili-Balkhash Basin's specific value coefficient was still missing and the referenced value coefficient was assumed to be static, leading to uncertainty in the evaluation results. Future efforts would be conducted for a comprehensive and accurate assessment of ecosystem service values using a dynamic ecosystem service valuation model to guide land resource management's decision-making. Long-term climate change in the arid inland basins is the driving force for the ecosystem service evolution through the chain reaction. The impact of climate change on ecosystem services is worth further study. The potential water crisis resulting from future climate change would negatively affect ecosystem services and watershed sustainability. In response to climate change, more efforts are required to assess the water crisis's impact on the engineered and natural ecosystems and predict the landscape pattern evolution and the associated ecosystem service values.

Conclusions

Under the combined influence of anthropogenic activities and climate change, the landscape pattern and the associated ecosystem services have changed significantly in the past three decades. Due to population growth and socio-economic development, cropland and urban land expanded substantially at the expense of forestland, grassland, and bare land. Ecological conservation measures in response to the recognition of sustainable development helped recover forestland and grassland from cropland. Climate change in terms of increased precipitation and temperature promoted the transition of bare land to grassland. The spatial pattern features had been changing, accompanied by the expansion, dispersion, or shrinkage of LULC types. At the class level, the shape complexity of forestland,

grassland, wetland, and bare land decreased significantly, whereas the shape complexity of urban land and water bodies increased significantly. The aggregation degree of cropland, forestland, and urban land experienced a substantial increment, and that of bare land decreased significantly. At the landscape level, various LULC types were more uniformly distributed across the basin with a more regular shape and higher aggregation.

Regarding the landscape pattern evolution in the Ili-Balkhash Basin, the ecosystem services of provisioning, regulating, supporting, and culture rose progressively and significantly, resulting in a pronounced increase in the total ecosystem service value. The correlation between the ecosystem service value and the landscape pattern varied according to the LULC types. At the class level, ecosystem service value had a significantly negative correlation with forestland and wetland's shape complexity and a significantly positive correlation with urban land and water bodies' shape complexity. The correlation between the ecosystem service value and the aggregation degree of cropland, forestland, grassland, wetland, and urban land was positive. In contrast, the correlation between the ecosystem service value and the aggregation degree of water bodies was negative. At the landscape level, the total ecosystem service value increased with the weakened shape complexity and the strengthened aggregation degree of LULC types. A more uniform distribution of various LULC types helped elevate the total ecosystem service value.

The dynamics of landscape pattern and the associated ecosystem services were sensitive to human activities and climate change. Transboundary cooperation between China and Kazakhstan would reinforce watershed sustainability through integrated watershed land resource planning and joint adaptive strategies to the potential water crisis resulting from climate change. Future research would address the uncertainties in evaluating the ecosystem service values and quantify the impact of climate change.

Author contribution Feng Huang: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, software, validation, visualization, writing — original draft. Carlos G. Ochoa: methodology, resources, software, supervision, validation, writing — review and editing. W. Todd Jarvis: methodology, resources, supervision, validation, writing — review and editing. Ruisen Zhong: investigation, resources, validation, funding acquisition. Lidan Guo: funding acquisition, project administration, validation.

Funding This work was supported by the Fundamental Research Funds for the Central Universities [grant number B200202023]; the Xinjiang Water Program [grant number 2020.E-001.2.4]; the China Scholarship Council [grant number 201906715005]; and the National Natural Science Foundation of China [grant number 42071049].

Availability of data and material All data generated or analyzed during this study are included in this published article. Please see the section “Data sources.”

Declarations

Conflict of interest The authors declare no competing interests.

References

Abdrahimov, R., Amirgaliyeva, A., Tastambek, K., Zhumalipov, A., & Polyakova, S. (2020). Annual river runoff of the Ile-Balkhash Basin and prospects of its assessment due to climatic changes and water economy activities. *International Journal of Geomate*, 18(69), 230–239. <https://doi.org/10.21660/2020.69.32068>

Badescu, V., & Schuiling, R. D. (2010). Aral Sea: Irrecoverable loss or irtysk imports? *Water Resources Management*, 24(3), 597–616. <https://doi.org/10.1007/s11269-009-9461-y>

Chen, Y. N., Li, Z., Fang, G. H., & Li, W. H. (2018). Large hydrological processes changes in the transboundary rivers of Central Asia. *Journal of Geophysical Research-Atmospheres*, 123(10), 5059–5069. <https://doi.org/10.1029/2017jd028184>

Costanza, R., & dArge R, deGroot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, Oneill RV, Paruelo J, Raskin RG, Sutton P, vandenBelt M. (1997). The value of the world’s ecosystem services and natural capital. *Nature*, 387(6630), 253–260. <https://doi.org/10.1038/387253a0>

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change-Human and Policy Dimensions*, 26, 152–158. <https://doi.org/10.1016/j.gloenvcha.2014.04.002>

Daneshi, A., Brouwer, R., Najafinejad, A., Panahi, M., Zarandian, A., & Maghsood, F. F. (2021). Modelling the impacts of climate and land use change on water security in a semi-arid forested watershed using InVEST. *Journal of Hydrology*, 593, 125621. <https://doi.org/10.1016/j.jhydrol.2020.125621>

Deng, H. J., & Chen, Y. N. (2017). Influences of recent climate change and human activities on water storage variations in Central Asia. *Journal of Hydrology*, 544, 46–57. <https://doi.org/10.1016/j.jhydrol.2016.11.006>

Duan, W. L., Zou, S., Chen, Y. N., Nover, D., Fang, G. H., & Wang, Y. (2020). Sustainable water management for cross-border resources: The Balkhash Lake Basin of Central Asia, 1931–2015. *Journal of Cleaner Production*, 263, 121614. <https://doi.org/10.1016/j.jclepro.2020.121614>

Duarte, G. T., Santos, P. M., Cornelissen, T. G., Ribeiro, M. C., & Paglia, A. P. (2018). The effects of landscape patterns

on ecosystem services: Meta-analyses of landscape services. *Landscape Ecology*, 33(8), 1247–1257. <https://doi.org/10.1007/s10980-018-0673-5>

Guerra, C. A., Rosa, I. M. D., & Pereira, H. M. (2019). Change versus stability: Are protected areas particularly pressured by global land cover change? *Landscape Ecology*, 34(12), 2779–2790. <https://doi.org/10.1007/s10980-019-00918-4>

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset. *International Journal of Climatology*, 34(3), 623–642. <https://doi.org/10.1002/joc.3711>

Huang, F., Xia, Z. Q., Li, F., Guo, L. D., & Yang, F. C. (2012). Hydrological changes of the Irtysh River and the possible causes. *Water Resources Management*, 26(11), 3195–3208. <https://doi.org/10.1007/s11269-012-0067-4>

Imentai, A., Thevs, N., Schmidt, S., Nurtazin, S., & Salmurzauli, R. (2015). Vegetation, fauna, and biodiversity of the Ile Delta and southern Lake Balkhash—A review. *Journal of Great Lakes Research*, 41(3), 688–696. <https://doi.org/10.1016/j.jglr.2015.04.002>

Kezer, K., & Matsuyama, H. (2006). Decrease of river runoff in the Lake Balkhash basin in Central Asia. *Hydrological Processes*, 20(6), 1407–1423. <https://doi.org/10.1002/hyp.6097>

Li, J. Y., Chen, H. X., Zhang, C., & Pan, T. (2019). Variations in ecosystem service value in response to land use/land cover changes in Central Asia from 1995–2035. *PeerJ*, 7, e7665. <https://doi.org/10.7717/peerj.7665>

Liu, S., Costanza, R., Farber, S., & Troy, A. (2010). Valuing ecosystem services: Theory, practice, and the need for a transdisciplinary synthesis. *Annals of the New York Academy of Sciences*, 1185, 54–78. <https://doi.org/10.1111/j.1749-6632.2009.05167.x>

Liu, X. X., Yu, L., Si, Y. L., Zhang, C., Lu, H., Yu, C. Q., & Gong, P. (2018). Identifying patterns and hotspots of global land cover transitions using the ESA CCI Land Cover dataset. *Remote Sensing Letters*, 9(10), 972–981. <https://doi.org/10.1080/2150704x.2018.1500070>

Liu, Y., Wang, P., Ruan, H. W., Wang, T. Y., Yu, J. J., Cheng, Y. P., & Kulmatoy, R. (2020). Sustainable use of groundwater resources in the transboundary aquifers of the five central Asian countries: Challenges and perspectives. *Water*, 12(8), 2101. <https://doi.org/10.3390/w12082101>

Ma, L. B., Bo, J., Li, X. Y., Fang, F., & Cheng, W. J. (2019). Identifying key landscape pattern indices influencing the ecological security of inland river basin: The middle and lower reaches of Shule River Basin as an example. *Science of the Total Environment*, 674, 424–438. <https://doi.org/10.1016/j.scitotenv.2019.04.107>

Mahmoud, S. H., & Gan, T. Y. (2018). Impact of anthropogenic climate change and human activities on environment and ecosystem services in arid regions. *Science of the Total Environment*, 633, 1329–1344. <https://doi.org/10.1016/j.scitotenv.2018.03.290>

McGarigal, K., Cushman, S. A., & Ene, E. (2012). *FRAG-STATS v4: Spatial pattern analysis program for categorical and continuous maps*. University of Massachusetts.

Mischke, S., Zhang, C. J., & Plessen, B. (2020). Lake Balkhash (Kazakhstan): Recent human impact and natural variability in the last 2900 years. *Journal of Great Lakes*

- Research*, 46(2), 267–276. <https://doi.org/10.1016/j.jglr.2020.01.008>
- Mitchell, M. G. E., Bennett, E. M., & Gonzalez, A. (2014). Agricultural landscape structure affects arthropod diversity and arthropod-derived ecosystem services. *Agriculture Ecosystems & Environment*, 192, 144–151. <https://doi.org/10.1016/j.agee.2014.04.015>
- Plummer, M. L. (2009). Assessing benefit transfer for the valuation of ecosystem services. *Frontiers in Ecology and the Environment*, 7(1), 38–45. <https://doi.org/10.1890/080091>
- Pueppke, S. G., Iklasov, M. K., Beckmann, V., Nurtazin, S. T., Thevs, N., Sharakhmetov, S., & Hoshino, B. (2018). Challenges for sustainable use of the fish resources from Lake Balkhash, a fragile lake in an arid ecosystem. *Sustainability*, 10(4), 1234. <https://doi.org/10.3390/su10041234>
- Pueppke, S. G., Nurtazin, S. T., Graham, N. A., & Qi, J. G. (2018). Central Asia's Ili River ecosystem as a wicked problem: Unraveling complex interrelationships at the interface of water, energy, and food. *Water*, 10(5), 541. <https://doi.org/10.3390/w10050541>
- Raudsepp-Hearne, C., Peterson, G. D., & Bennett, E. M. (2010). Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, 107(11), 5242–5247. <https://doi.org/10.1073/pnas.0907284107>
- Spitsyna, A., & Spitsyna, T. (2007). Preliminary Sustainability Assessment of water resources management in the Ili-Balkhash Basin of Central Asia. *Royal Institute of Technology*, Stockholm.
- Sun, G., Hallema, D., & Asbjornsen, H. (2017). Ecohydrological processes and ecosystem services in the Anthropocene: A review. *Ecological Processes*, 6, 35. <https://doi.org/10.1186/s13717-017-0104-6>
- Tang, H. L., Lu, S. L., Cheng, Y. P., Ge, L. Q., Zhang, J. K., Dong, H., & Shao, H. Y. (2019). Analysis of dynamic changes and influence factors of Lake Balkhash in the last twenty years. *Journal of Groundwater Science and Engineering*, 7(3), 214–223. <https://doi.org/10.19637/j.cnki.2305-7068.2019.03.002>
- Tesfaw, A. T., Pfaff, A., Kroner, R. E. G., Qin, S. Y., Medeiros, R., & Mascia, M. B. (2018). Land-use and land-cover change shape the sustainability and impacts of protected areas. *Proceedings of the National Academy of Sciences of the United States of America*, 115(9), 2084–2089. <https://doi.org/10.1073/pnas.1716462115>
- Thevs, N., Beckmann, V., Akimalieva, A., Kobbing, J. F., Nurtazin, S., Hirschelmann, S., Piechotka, T., Salmurzauli, R., & Baibagysov, A. (2017). Assessment of ecosystem services of the wetlands in the Ili River Delta. *Kazakhstan. Environmental Earth Sciences*, 76(1), 30. <https://doi.org/10.1007/s12665-016-6346-2>
- Thevs, N., Nurtazin, S., Beckmann, V., Salmurzauli, R., & Khalil, A. (2017). Water consumption of agriculture and natural ecosystems along the Ili River in China and Kazakhstan. *Water*, 9(3), 207. <https://doi.org/10.3390/w9030207>
- Turner, M. G. (2005). Landscape ecology: What is the state of the science? *Annual Review of Ecology Evolution and Systematics*, 36, 319–344. <https://doi.org/10.1146/annurev.ecolsys.36.102003.152614>
- Uuemaa, E., Mander, U., & Marja, R. (2013). Trends in the use of landscape spatial metrics as landscape indicators: A review. *Ecological Indicators*, 28, 100–106. <https://doi.org/10.1016/j.ecolind.2012.07.018>
- Vitule, J. R. S., Azevedo-Santos, V. M., Daga, V. S., Lima, D. P., de Magalhaes, A. L. B., Orsi, M. L., Pelicice, F. M., & Agostinho, A. A. (2015). Brazil's drought: Protect biodiversity. *Science*, 347(6229), 1427–1428. <https://doi.org/10.1126/science.347.6229.1427-b>
- Wang, J. F., Li, X. H., Christakos, G., Liao, Y. L., Zhang, T., Gu, X., & Zheng, X. Y. (2010). Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun Region, China. *International Journal of Geographical Information Science*, 24(1), 107–127. <https://doi.org/10.1080/13658810802443457>
- Xu, J. T., Yin, R. S., Li, Z., & Liu, C. (2006). China's ecological rehabilitation: Unprecedented efforts, dramatic impacts, and requisite policies. *Ecological Economics*, 57(4), 595–607. <https://doi.org/10.1016/j.ecolecon.2005.05.008>
- Yang, H. F., Mu, S. J., & Li, J. L. (2014). Effects of ecological restoration projects on land use and land cover change and its influences on territorial NPP in Xinjiang, China. *CATENA*, 115, 85–95. <https://doi.org/10.1016/j.catena.2013.11.020>
- Yue, S., Pilon, P., & Cavadias, G. (2002). Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, 259(1–4), 254–271. [https://doi.org/10.1016/S0022-1694\(01\)00594-7](https://doi.org/10.1016/S0022-1694(01)00594-7)
- Yushanjiang, A., Zhang, F., Yu, H. Y., & Kung, H. T. (2018). Quantifying the spatial correlations between landscape pattern and ecosystem service value: A case study in Ebinur Lake Basin, Xinjiang, China. *Ecological Engineering*, 113, 94–104. <https://doi.org/10.1016/j.ecoleng.2018.02.005>
- Zhao, F., Li, H., Li, C. H., Cai, Y. P., Wang, X., & Liu, Q. (2019). Analyzing the influence of landscape pattern change on ecological water requirements in an arid/semi-arid region of China. *Journal of Hydrology*, 578, Unsp 124098. <https://doi.org/10.1016/j.jhydrol.2019.124098>
- Zhao, Q. J., Wen, Z. M., Chen, S. L., Ding, S., & Zhang, M. X. (2020). Quantifying land use/land cover and landscape pattern changes and impacts on ecosystem services. *International Journal of Environmental Research and Public Health*, 17(1), 126. <https://doi.org/10.3390/ijerph17010126>
- Zou, J., Ding, J. L., Welp, M., Huang, S., & Liu, B. H. (2020). Using MODIS data to analyse the ecosystem water use efficiency spatial-temporal variations across Central Asia from 2000 to 2014. *Environmental Research*, 182, 108985. <https://doi.org/10.1016/j.envres.2019.108985>

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