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Spatiotemporal characteristics and influencing factors of ecosystem services in Central Asia

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Abstract: Land use/land cover (LULC) change and climate change are two major factors affecting the provision of ecosystem services which are closely related to human well-being. However, a clear understanding of the relationships between these two factors and ecosystem services in Central Asia is still lacking. This study aimed to comprehensively assess ecosystem services in Central Asia and analyze how they are impacted by changes in LULC and climate. The spatiotemporal patterns of three ecosystem services during the period of 2000–2015, namely the net primary productivity (NPP), water yield, and soil retention, were quantified and mapped by the Carnegie-Ames-Stanford Approach (CASA) model, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, and Revised Universal Soil Loss Equation (RUSLE). Scenarios were used to determine the relative importance and combined effect of LULC change and climate change on ecosystem services. Then, the relationships between climate factors (precipitation and temperature) and ecosystem services, as well as between LULC change and ecosystem services, were further discussed. The results showed that the high values of ecosystem services appeared in the southeast of Central Asia. Among the six biomes (alpine forest region (AFR), alpine meadow region (AMR), typical steppe region (TSR), desert steppe region (DSR), desert region (DR), and lake region (LR)), the values of ecosystem services followed the order of AFR>AMR>TSR>DSR>DR>LR. In addition, the values of ecosystem services fluctuated during the period of 2000–2015, with the most significant decreases observed in the southeast mountainous area and northwest of Central Asia. LULC change had a greater impact on the NPP, while climate change had a stronger influence on the water yield and soil retention. The combined LULC change and climate change exhibited a significant synergistic effect on ecosystem services in most of Central Asia. Moreover, ecosystem services were more strongly and positively correlated with precipitation than with temperature. The greening of desert areas and forest land expansion could improve ecosystem services, but unreasonable development of cropland and urbanization have had an adverse impact on ecosystem services. According to the results, ecological stability in Central Asia can be achieved through the natural vegetation protection, reasonable urbanization, and ecological agriculture development.

Keywords: ecosystem services; land use/land cover change; climate change; net primary productivity; water yield; soil retention; Central Asia

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1 Introduction

Ecosystem services create a close connection between natural ecosystems and human well-being (Costanza et al., 1998). Natural ecosystems and the services produced by ecological processes are essential to support the sustainable development of the world (Cairns and Niederlehner, 1995; Costanza et al., 2017). However, global ecosystem services are under threat due to human activities and environmental change (Vitousek et al., 1997; Millennium Ecosystem Assessment, 2005). The Millennium Ecosystem Assessment (2005) revealed that 15 ecosystem services are currently in decline, including erosion regulation and water supply. Thus, it is necessary to analyze the spatiotemporal characteristics of ecosystem services and assess their influencing factors, which could provide key information useful for monitoring ecosystem change, managing resources, and halting environmental deterioration (Wei et al., 2017; Rimal et al., 2019; Ashrafi et al., 2022).

The influences of land use/land cover (LULC) change and climate change on ecosystem functions are two major determinants of ecosystem services (Bateman et al., 2013; Hoyer and Chang, 2014; Fu et al., 2017; Rai et al., 2018; Qiu et al., 2022). Current studies have been implemented in different ecosystems, including mountain–oasis–desert systems (Fu et al., 2017), river basins (Rimal et al., 2019; Ashrafi et al., 2022), agricultural ecosystems (Lorencová et al., 2013), urban areas (Carvalho and Szlafsztein, 2019), and natural reserves (Sannigrahi et al., 2020). LULC change alters ecological processes and ecosystem services by changing ecosystem patterns (Su et al., 2012; Muleta et al., 2016; Fu et al., 2017; Zhang et al., 2021). For example, urban expansion challenges environmental sustainability via decreasing biological diversity (Poppenborg and Koellner, 2013), while an increase in agricultural areas could decrease soil conservation services (Li et al., 2020). Moreover, LULC change has significant impacts on the future provision pattern of ecosystem services (Lautenbach et al., 2011; Qiu et al., 2022). Climate change seriously threatens the security of ecosystems worldwide (Weiskopf et al., 2020) and affects ecosystem services by modifying the biophysical processes of ecosystems, such as through changes in the hydrological processes, temperature, and CO_2 concentration (Nelson et al., 2013; Bai et al., 2019). In particular, climate extremes have negative impacts on ecosystem services. For example, drought negatively influences crop yields (Vermeulen et al., 2012; Vogel et al., 2019), while precipitation extremes result in storms and floods, devastating public properties (Olorunfemi and Raheem, 2013). Investigating the impacts of changes in both LULC and climate on ecosystem services may provide vital insights and guidance to support policy-making that will improve the sustainability of ecosystem functions (Bai et al., 2019).

Central Asia is the core arid region of the Eurasian continent, and its ecosystem is fragile and sensitive to global change (Jilili and Ma, 2015). Recently, with the increasing imbalance between the supply and demand of natural resources, the proper utilization of natural resources and the maintenance of healthy ecosystems have become key issues in Central Asia (Petrov and Normatov, 2010; Chen et al., 2013). Investigating the spatiotemporal characteristics of ecosystem services under the background of LULC change and climate change in Central Asia could provide useful information for the sustainable management of natural resources and ecosystem protection (Chen et al., 2013; Li et al., 2020; Li et al., 2021; Yu et al., 2021).

Although previous studies have discussed the influences of LULC change and climate change on ecosystem services (Chen et al., 2013; Li et al., 2020; Li and Zhang, 2021), they ignored the relative contributions of these two factors to ecosystem services and the influence of their combined effect. Therefore, the objectives of the study were: (1) to investigate the spatiotemporal characteristics of ecosystem services; (2) to identify the relative importance and combined effect of LULC change and climate change (alterations in precipitation and temperature) on ecosystem services from a geospatial perspective; and (3) to formulate corresponding natural resource management strategies in Central Asia. The logic of the study was as follows: identifying the spatiotemporal patterns of LULC and climate in Central Asia firstly; quantifying the spatiotemporal characteristics of ecosystem services, including the net primary productivity

(NPP), water yield, and soil retention; clarifying the relative importance and combined effect of LULC change and climate change on ecosystem services by designing scenarios and constructing a relative importance index and a combined effect index; discussing the relationships between climate factors and ecosystem services using correlation analysis; and determining the effects of separate LULC change on ecosystem services. The findings of this study will be of guiding significance for the ecosystem protection and sustainable development in Central Asia.

2 Materials and methods

2.1 Study area

Central Asia, located in the hinterland of the Eurasian continent, is composed of Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan (35°07′–55°26′N, 46°29′–85°25′E; Fig. 1a). It has a total area of 4.0×10^6 km^2 (Chen et al., 2013). There is a typical temperate continental climate with an annual average temperature of 8.4°C and an annual precipitation of less than 300 mm. The topography in Central Asia decreases from the mountainous area to the low-lying desert, which leads to the interception of water vapor by the mountains and the uneven spatiotemporal distribution of water resources. The upstream countries, i.e., Tajikistan and Kyrgyzstan, hold more than 90% of the total water resources in Central Asia, while water resources in the downstream countries, i.e., Uzbekistan and Turkmenistan, are scarce (Yang et al., 2017). In addition, the inappropriate management of water and land resources has exacerbated the imbalance between the supply and demand of natural resources, which has resulted in ecological degradation, such as land desertification and the shrinkage of the Aral Sea.

A biome is an area within which there is spatial coherence among the geographical characteristics associated with the quality, health, and integrity of ecosystems (Liu et al., 2015). To demonstrate the spatial pattern of ecosystem services and the influencing factors clearly, we classified Central Asia into six biomes using the terrestrial eco-region data downloaded from the World Wildlife Fund (https://www.worldwildlife.org/): alpine forest region (AFR), alpine meadow region (AMR), typical steppe region (TSR), desert steppe region (DSR), desert region (DR), and lake region (LR), as shown in Figure 1b.

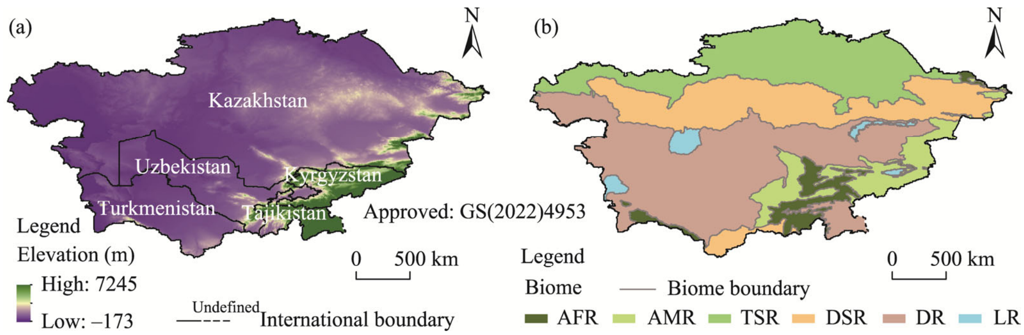

Fig. 1 Spatial patterns of elevation (a) and six biomes (b) in Central Asia. AFR, alpine forest region; AMR, alpine meadow region; TSR, typical steppe region; DSR, desert steppe region; DR, desert region; LR, lake region.

2.2 Data

The dataset used in this study included precipitation, temperature, solar radiation, normalized difference vegetation index (NDVI), soil properties (e.g., the silt, clay, and sand fractions, soil organic carbon content, soil depth, and available soil water capacity), land cover data, digital elevation model (DEM) data, and terrestrial eco-region data covering the period of 2000–2015 across Central Asia. The precipitation data were obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP, V2.8) with a temporal resolution of one month, a spatial resolution of 0.1°, and the complementary strengths of gauge-, satellite-, and reanalysis-based data (http://www.gloh2o.org./). The ERA5-land hourly temperature and solar radiation were derived from the European Centre for Medium-Range Weather Forecasts with a spatial resolution of 0.1° (https://www.ecmwf.int/). Furthermore, the 16-d NDVI was derived from the Moderate Resolution Imaging Spectroradiometer (MOD13A2 V6.1; https://lpdaac.usgs.gov/products/mod13a2v061/), which had good image quality with a spatial resolution of 1 km. The available soil water capacity was derived from the ISRIC—World Soil Information (SoilGrids250m) with a 250-m spatial resolution (https://www.isric.org/). Other soil data used in this study were obtained from the Global Soil Dataset for Earth System Modeling (GSDE), and the spatial resolution was 30 arc-seconds (http://globalchange.bnu.edu.cn/research/soilw). This dataset can provide accurate soil information (Shangguan et al., 2014). The yearly land cover with a 300-m spatial resolution published by the European Space Agency Climate Change Initiative (ESA-CCI) was also selected (http://maps.elie.ucl.ac.be/CCI/viewer). In addition, DEM data were obtained from the Shuttle Radar Topography Mission (SRTM3 V4.1; https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/) with a 90-m spatial resolution, and the eco-region data were obtained from the World Wildlife Fund (https://www.worldwildlife.org/). These data, which had a global coverage with continuity over space, were transformed to a spatial resolution of 1 km using the resampling method.

2.3 Methodology

2.3.1 Calculation of ecosystem services

The NPP, water yield, and soil retention are key ecosystem services in Central Asia (Li and Zhang, 2021; Li et al., 2021) that represent supporting, provisioning, and regulating services, respectively (Peng et al., 2020). Thus, this study focused on changes in these three ecosystem services and their influencing factors.

(1) NPP

The NPP is the balance of gross biomass production during plant photosynthesis and respiration processes (Vitousek et al., 1986). It is also the base of the food chain in the biosphere (Field et al., 1998). The Carnegie-Ames-Stanford Approach (CASA) model, which can monitor the dynamic changes of the NPP in terrestrial ecosystems on a large scale, has been widely used (Yue et al., 2022). Based on the theory of the CASA model, Zhu et al. (2007) designed an effective module to calculate the NPP (g C/m^2) that can be finished in ENVI 5.3. The theory formula is as follows:

$$\mathrm{NPP}(x,t) = APAR(x,t) \times \varepsilon(x,t)\,, \tag{1}$$

where x is the pixel position; t is the time (months); $APAR$ is the photosynthetically active radiation absorbed by the plant (g C/(m^2·month)); and ε is the actual light use efficiency (g C/MJ). The input data for this module included precipitation, temperature, solar radiation, LULC, NDVI, and the maximum light use efficiency, which can be determined using the method described in the study of Zhu et al. (2007).

(2) Water yield

Water yield refers to the difference between actual evapotranspiration and precipitation. We can estimate it based on the Budyko's hypothesis in the water-yield module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Sharp et al., 2014). The model result can show the distribution of water yield under different biophysical processes involved in LULC change (Li et al., 2021). The annual water yield ($Y(x)$; mm) for each pixel on the landscape (x) is calculated as follows:

$$Y(x) = (1 - AET(x) / P(x)) \times P(x)\,, \tag{2}$$

where $AET(x)$ is the annual actual evapotranspiration for pixel x (mm/a) and $P(x)$ is the annual precipitation on pixel x (mm/a). The evapotranspiration portion of the water balance ($AET(x)/P(x)$) is based on an expression of the Budyko curve:

$$AET(x) / P(x) = 1 + PET(x) / P(x) - [1 + (PET(x) / P(x))^{\omega}]^{1/\omega}\,, \tag{3}$$

where $PET(x)$ is the potential evapotranspiration (mm/a) defined by Equation 4, and ω is an empirical parameter that characterizes the natural climatic-soil property, which can be determined using the method of Xu et al. (2013).

$$PET(x) = K_c(l_x) \times ET_0(x), \tag{4}$$

where $K_c(l_x)$ is the vegetation evapotranspiration coefficient associated with the LULC type l on pixel x, which can be determined using the Food and Agriculture Organization of the United Nations (FAO) 56 guidelines (Allen et al., 1998). ET_0 is the reference evapotranspiration of pixel x (mm):

$$ET_0(x) = 0.0013 \times 0.408 \times RA \times (T_{av} + 17) \times (TD - 0.0123P_m)^{0.76}, \tag{5}$$

where RA is the solar radiation (MJ/(m^2•d)); T_{av} is the average of the mean daily maximum and mean daily minimum temperatures for each month (°C); TD is the difference between the mean daily maximum and mean daily minimum temperatures for each month (°C); and P_m is the monthly precipitation (mm).

(3) Soil retention

Soil retention refers to the prevention of soil loss caused by water erosion (Li et al., 2021). In this study, the Revised Universal Soil Loss Equation (RUSLE) with strong operability and applicability was adopted to calculate soil retention (Renard et al., 1997). The formula is as follows:

$$SR = R \times K \times LS \times (1 - C \times P), \tag{6}$$

where SR is the annual soil conservation amount (t/(km^2•a)); and R, K, LS, C, and P represent the rainfall erosivity factor (MJ•mm/(km^2•h•a)), soil erodibility factor (t•km^2•h/(km^2•MJ•mm)), topographic factor, vegetation cover factor, and erosion control practice factor, respectively. R can be calculated as follows:

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left[1.5\times\lg\left(\frac{PP_i^2}{PP_j}\right) - 0.08188\right]}, \tag{7}$$

where PP_i is the monthly precipitation in the i^{th} month (mm), and PP_j is the annual total precipitation in the j^{th} year (mm).

K was calculated as follows (Sharpley and Williams, 1990):

$$K = 0.1317 \times \left\{0.2 + 0.3 \times \exp\left[-0.0256 \times \mathrm{SAN}(1 - \frac{\mathrm{SIL}}{100})\right]\right\} \times \left(\frac{\mathrm{SIL}}{\mathrm{CLA+SIL}}\right)^{0.3} \times \left[1 - \frac{0.25\mathrm{SOC}}{\mathrm{SOC} + \exp(3.72 - 2.95\mathrm{SOC})}\right] \times \left[1 - \frac{0.7 \times (1 - \mathrm{SAN}/100)}{(1 - \mathrm{SAN}/100) + \exp[-5.51 + 22.9 \times (1 - \mathrm{SAN}/100)]}\right], \tag{8}$$

where SAN, SIL, and CLA are the sand, silt, and clay fractions of soil (%), respectively; and SOC is the soil organic carbon content (%).

LS was generated from the DEM using LS-TOOL developed by Zhang et al. (2013), which was based on the expressions developed by McCool et al. (1989).

C was calculated as follows:

$$C = \exp\left[-A \times \frac{\mathrm{NDVI}}{B - \mathrm{NDVI}}\right], \tag{9}$$

where A and B are the parameters controlling the shape of the NDVI curve, and they are generally set as 2 and 1, respectively (van der Knijff et al., 2000).

We determined P for different LULC types according to the study of Li et al. (2021) in Central Asia.

2.3.2 Trend analysis

Simple linear regression analysis can be used to simulate the changing trend of each pixel. It can comprehensively characterize the evolution of the regional pattern during a certain time (Liu et al., 2015). The trend can be calculated using Equation 10:

$$S = \frac{n \times \sum_{i=1}^{n} i \times X_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} X_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \tag{10}$$

where S is the trend of the slope of X; n is the length of the research period; and X_i is the value of variable X of the i^{th} year. S>0 means that there is an increasing trend of X, and vice versa. The Mann-Kendall test is a non-parametric test, and the data used for the test need not conform to a normal distribution (Mann, 1945; Kendall, 1949). In this study, the Mann-Kendall test was used to check the validity of the trend.

2.3.3 Spearman's rank correlation analysis

In this study, Spearman's rank correlation analysis (Gauthier, 2001) was applied to assess the relationship between climate factors (precipitation and temperature) and ecosystem services at the biome scale. A positive coefficient means that one factor increases (decreases) with a corresponding factor's increase (or decrease). A negative coefficient of Spearman's rank correlation indicates a trade-off between the pair of factors. If the coefficient is zero or the result is not significant, the correlation between factors is weak at the biome scale.

2.3.4 Correlation analysis

A simple correlation coefficient was selected to describe the relationship between climate factors (precipitation and temperature) and ecosystem services (Liu et al., 2015):

$$r_{xy} = \frac{\sum_{i=1}^{n}\left[(x_i - \bar{x})(y_i - \bar{y})\right]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}, \tag{11}$$

$$r_c^{ab} = \frac{r_{ab} - r_{ac} \times r_{bc}}{\sqrt{(1 - r_{ac}^2)(1 - r_{bc}^2)}}, \tag{12}$$

where r_{xy} is the simple correlation coefficient of variables x and y; x_i and y_i are the values of x and y in the i^{th} year, respectively; $\bar{x}$ and $\bar{y}$ are the average values of variables x and y for all years, respectively; r_c^{ab} is the partial correlation coefficient between variables a and b, keeping the effects of variable c constant; and r_{ab}, r_{ac}, and r_{bc} represent the simple correlation coefficients between variables a and b, a and c, and b and c, respectively.

2.3.5 Quantifying the relative and combined effect of LULC change and climate change on ecosystem services

Based on the designed LULC and climate change scenarios, we determined the relative importance and combined effect of LULC change and climate change on ecosystem services (Bai et al., 2019; Peng et al., 2020). In this study, we reclassified LULC types into rainfed cropland, irrigated cropland, grassland, forest land, urban land, bare land, and water body according to ESA-CCI land classes and the study of Li et al. (2021) in Central Asia.

(1) LULC change and climate change scenarios

Four scenarios were designed in this study. Specifically, scenario 1 was based on the real environmental conditions in 2000. In Scenario 2, constant climate factors were maintained from 2000 to 2015, leaving LULC change as the sole driver affecting ecosystem services. In Scenario 3, a constant LULC was maintained from 2000 to 2015, leaving climate change as the sole driver affecting ecosystem services. Scenario 4 was based on the real environmental conditions in 2015.

(2) Relative importance analysis

The relative importance of the effects of LULC change and climate change on ecosystem services was evaluated using the following equation:

$$\mathrm{RI} = \frac{|\mathrm{ESS2} - \mathrm{ESS1}| - |\mathrm{ESS3} - \mathrm{ESS1}|}{\max(\mathrm{ESS1})} \begin{cases} > 0, & \text{LULC} \\ = 0, & \text{equal} \\ < 0, & \text{climate} \end{cases}, \tag{13}$$

where RI reflects the relative importance of LULC and climate change on ecosystem services in each pixel. RI>0 means that LULC change has a greater effect on ecosystem services than climate change, and vice versa. RI=0 indicates that the effect of LULC change on ecosystem services has an equal importance to the effect of climate change. ESS1, ESS2, and ESS3 represent the ecosystem services under Scenario 1, Scenario 2, and Scenario 3, respectively.

(3) Combined effect analysis

The combined effect of LULC change and climate change on ecosystem services was evaluated using the following equation:

$$\mathrm{CE} = \frac{((\mathrm{ESS2} - \mathrm{ESS1}) + (\mathrm{ESS3} - \mathrm{ESS1})) - (\mathrm{ESS4} - \mathrm{ESS1})}{\max(\mathrm{ESS1})} \begin{cases} > 0, & \text{inhibitory} \\ = 0, & \text{independent} \\ < 0, & \text{synergistic} \end{cases}, \tag{14}$$

where CE reflects the combined effect of LULC change and climate change on ecosystem services in each pixel. ESS4 represents the ecosystem services under Scenario 4. CE>0 means that the combined LULC change and climate change has an inhibitory effect on ecosystem services. CE<0 indicates that the combined LULC change and climate change has a synergistic effect on ecosystem services. CE=0 means that the combined effect of LULC change and climate change on ecosystem services is independent.

3 Results

3.1 Changes in climate and LULC

3.1.1 Spatiotemporal characteristics of climate change

The climate in Central Asia exhibited clear spatial differences (Fig. 2). The average annual temperature decreased from southwest to northeast, while the average annual precipitation decreased from southeast to west. Among different biomes, the average annual temperature followed the order of DR (12.1°C)>LR (11.6°C)>AFR (7.9°C)>DSR (7.8°C)>AMR (5.8°C)>TSR (4.7°C). The average annual precipitation was high in the mountainous area of Southeast Central Asia. There was abundant precipitation in the AFR, with an average value of 529 mm, followed by the AMR (415 mm), TSR (328 mm), and DSR (247 mm). The DR and LR were arid regions with the average annual precipitation values of 181 and 162 mm, respectively.

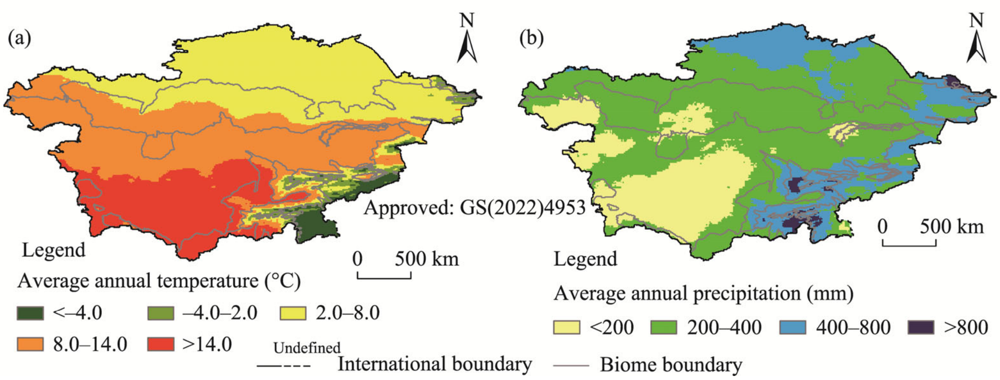

Fig. 2 Spatial distributions of the average annual temperature (a) and average annual precipitation (b) during the period of 2000–2015 in Central Asia

The climate change in Central Asia was slight from 2000 to 2015. Both the annual average temperature and annual precipitation fluctuated during the period of 2000–2015. Although there was no significant increase or decrease trend for these two factors in each biome (Fig. 3), the spatial significance test showed that in Northwest Central Asia, especially in the western Kazakh semi-desert, western Kazakh steppe, and Caspian lowland desert, there were significant decrease trends in the annual precipitation. The same pattern was also observed in the meadow and steppe regions of the Tianshan Mountains located near the Issyk-Kul Lake.

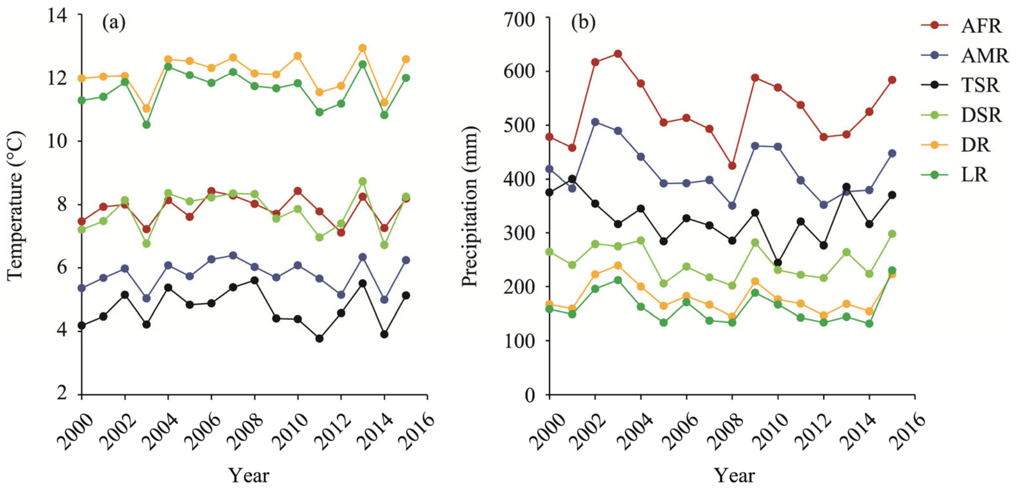

Fig. 3 Trends of the annual average temperature (a) and annual precipitation (b) during the period of 2000–2015 in each biome of Central Asia

3.1.2 Spatiotemporal characteristics of LULC change

The LULC conversion matrix from 2000 to 2015 is shown in Table 1 and Figure 4. In Central Asia, grassland was the dominant LULC type, which accounted for 55.96% of the total area in 2015 and increased by 36,309.48 km^2 from 2000 to 2015. Cropland in this region can be divided into rainfed cropland and irrigated cropland. These two types of cropland increased by 9065.79 and 2988.09 km^2, respectively, from 2000 to 2015. In addition, forest land and urban land from 2000 to 2015 increased by 2865.98 and 6366.27 km^2, respectively. In contrast, bare land and water body decreased by 35,495.81 and 22,099.80 km^2, respectively, from 2000 to 2015.

In 2015, grassland was mainly converted from bare land; cropland and forest land were primarily converted from grassland. During this period, 5.49% of bare land was converted to grassland, and 15.43% of water body was converted into bare land. From 2000 to 2015, urban land increased by 201.36%. The new urban land mainly originated from irrigated cropland (36.55%), grassland (18.47%), and rainfed cropland (9.66%).

Table 1 Land use/land cover (LULC) conversion matrix from 2000 to 2015 in Central Asia (unit: km^2)

		2015						
		Rainfed cropland	Irrigated cropland	Grassland	Forest land	Urban land	Bare land	Water body
	Rainfed cropland	373,662.88	3.38	4245.69	753.74	920.47	146.07	57.86
	Irrigated cropland	0.00	232,996.33	1618.22	101.45	3482.09	124.18	19.91
	Grassland	14,634.09	5773.17	2,224,851.37	3394.54	1759.50	3395.67	264.15
2000	Forest land	176.22	121.93	1453.65	67,103.45	23.01	12.96	85.01
	Urban land	0.00	0.00	0.00	0.00	3161.58	0.00	0.00
	Bare land	195.57	2298.41	56,069.34	48.19	177.44	962,453.34	621.10
	Water body	187.12	137.05	2143.70	440.84	3.76	19,614.26	104,579.04

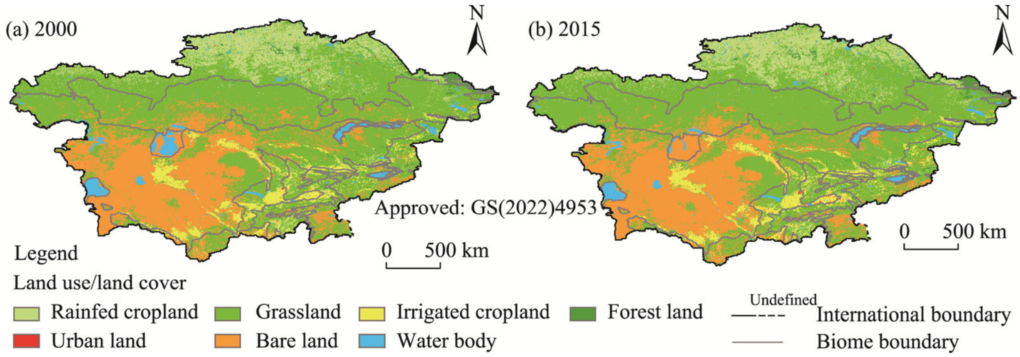

Fig. 4 Spatial patterns of land use/land cover (LULC) in 2000 (a) and 2015 (b) in Central Asia

There were different LULC changes among biomes during the period of 2000–2015. In the AFR, rainfed cropland, bare land, and water body decreased by 190.78, 1838.13, and 3.60 km^2, respectively. However, other LULC types showed an increasing trend, especially the urban land, with an increase of 567.78%. LULC change showed the same pattern during the period of 2000–2015 in the AMR, except for the water body, which increased by 211.35 km^2. In the TSR, from 2000 to 2015, grassland, bare land, and water body decreased by 6090.58, 1777.54, and 986.51 km^2, respectively, while cropland, urban land, and forest land increased by different degrees. From 2000 to 2015, both bare land and water body decreased in the DSR and DR, but other LULC types increased in these regions. In the LR, water body decreased by 18,644.00 km^2 and irrigated cropland disappeared, while other LULC types showed an increasing trend. In particular, bare land increased by 18,491.54 km^2 and was mainly converted from water body.

3.2 Changes in ecosystem services

The spatial patterns of ecosystem services showed a declining trend from east to west in Central Asia (Fig. 5). Among the six biomes, the average values of the NPP, water yield, and soil retention in the AFR were the highest, at 361.03 g C/m^2, 322.34 mm/km^2, and 189.95 t/km^2, respectively, followed by the AMR (336.32 g C/m^2, 236.06 mm/km^2, and 135.56 t/km^2, respectively), TSR (309.13 g C/m^2, 177.49 mm/km^2, and 89.31 t/km^2, respectively), DSR (208.36 g C/m^2, 104.46 mm/km^2, and 60.09 t/km^2, respectively), DR (121.52 g C/m^2, 49.48 mm/km^2, and 34.75 t/km^2, respectively), and LR (55.50 g C/m^2, 15.44 mm/km^2, and 20.11 t/km^2, respectively).

Changes in ecosystem services in each biome varied by different degrees between 2000 and 2015 (Fig. 5c, f, and i). In the AFR and AMR, the NPP and water yield increased by 39.48 g C/m^2 and 78.68 mm/km^2 and by 23.71 g C/m^2 and 14.23 mm/km^2, respectively, but soil retention decreased by 3.01 and 7.46 t/km^2, respectively. In the TSR, all three of these ecosystem services (the NPP, water yield, and soil retention) declined, with the change values of 8.36 g C/m^2, 1.35 mm/km^2, and 5.96 t/km^2, respectively. The decreases of ecosystem services were mainly observed in the western and eastern regions of the TSR. However, an opposite trend was observed in the DSR and DR, with the values of the NPP, water yield, and soil retention rising by 15.59 g C/m^2, 20.13 mm/km^2, and 32.73 t/km^2, and by 6.27 g C/m^2, 15.72 mm/km^2, and 19.00 t/km^2, respectively. The increases of ecosystem services mainly occurred in the central DSR and southeastern DR. In the LR, the NPP and water yield dropped by 1.54 g C/m^2 and 5.26 mm/km^2, respectively, but soil retention increased by 26.65 t/km^2.

During the period of 2000–2015, the areas with significant declines (P<0.05) in the NPP, water yield, and soil retention occupied 18.21%, 10.20%, and 5.35% of Central Asia, respectively. These "decrease regions" for each ecosystem service were spatially consistent and distributed mainly in the southeast mountainous area and northwest of Central Asia. However, the average ecosystem services of most biomes presented fluctuant and non-significant patterns, except for the LR where the NPP and water yield decreased remarkably (P<0.05). In addition, a noticeable decline trend in the NPP (P<0.05) during the period of 2000–2015 was also observed in the DR, showing an opposite trend in contrast to the difference between 2000 and 2015.

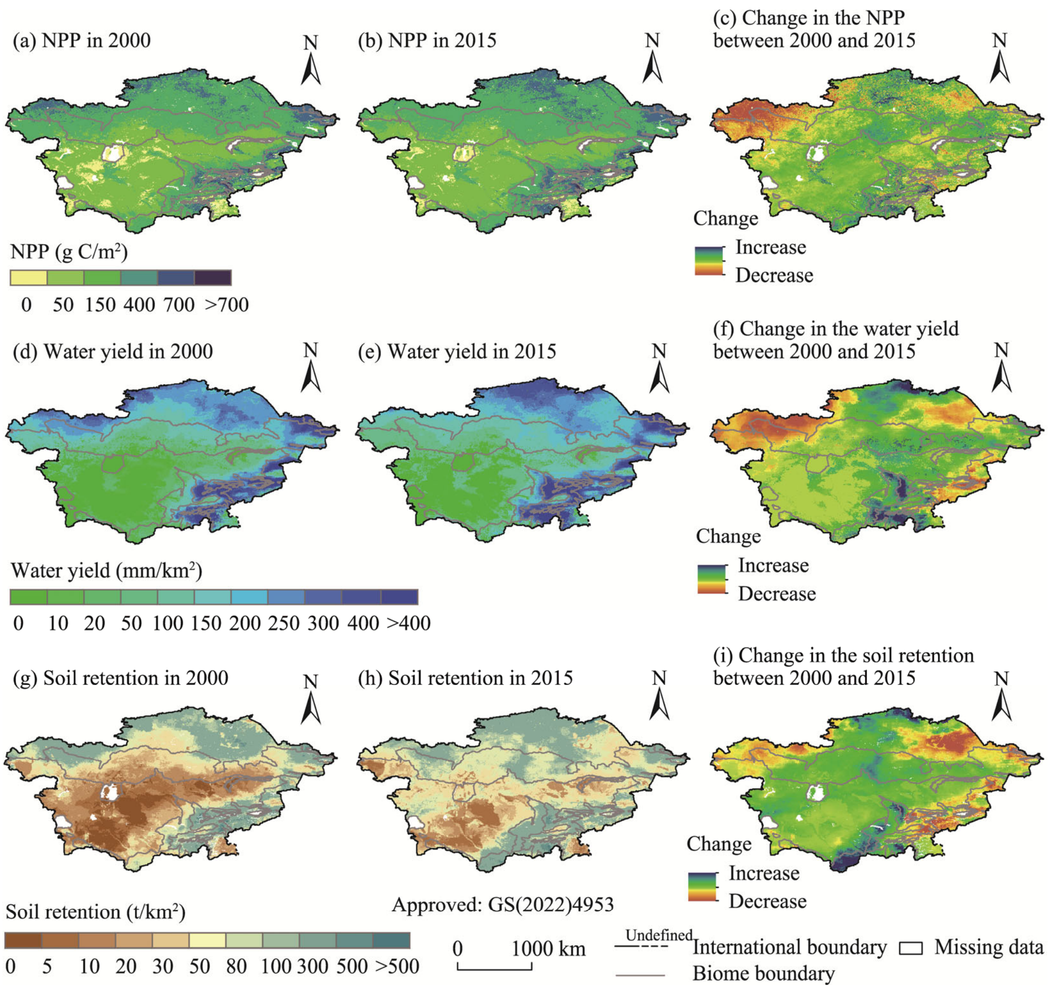

Fig. 5 Spatial patterns of the NPP (a, b), water yield (d, e), and soil retention (g, h) in 2000 and 2015, as well as their changes between 2000 and 2015 (c, NPP; f, water yield; i, soil retention) in Central Asia. NPP, net primary productivity.

3.3 Factor analysis

3.3.1 Relative importance of LULC change and climate change on ecosystem services

From the perspective of the whole Central Asia, the NPP was more strongly influenced by LULC change than climate change, with RI values in 78.34% of the total pixels in Central Asia being greater than zero (Fig. 6a). However, climate change had greater impacts on water yield and soil retention, with RI values in 74.37% and 93.76% of the total pixels in Central Asia being less than zero, respectively (Fig. 6b and c). These pixels were concentrated in the Kazakh steppe and Southeast Central Asia.

There was a similar pattern when only the LULC-changed pixels were considered. The percentages of climate change effect pixels in Central Asia for the NPP, water yield, and soil retention were 18.23%, 44.26%, and 91.34%, respectively, while the proportions of LULC change effect pixels in Central Asia for the three ecosystem services were 81.77%, 41.61%, and 8.66%, respectively. For each biome, soil retention also showed a lower sensitivity to LULC change than the NPP. In detail, the influence of climate change on soil retention decreased following the order of LR (98.18%)>DSR (97.04%)>AMR (92.90%)>AFR (89.19%)>TSR (88.30%)>DR (81.86%). The impact of LULC change on the NPP decreased following the order of LR (94.17%)>DR (89.19%)>DSR (81.16%)>AMR (79.71%)>TSR (76.55%)>AFR (75.38%). Water yield showed a more complex pattern than the other two ecosystem services. There were 69.87%, 61.65%, 68.82%, and 49.79% of pixels more strongly influenced by climate change in the AFR, AMR, TSR, and DR, respectively. LULC change had a higher impact on water yield in the DSR, with RI values in 61.48% of the total pixels being greater than zero. In the LR, the percentages of LULC change effect pixels and climate change effect pixels for water yield were 1.49% and 0.35%, respectively, and the remaining pixels were equally impacted by LULC change and climate change.

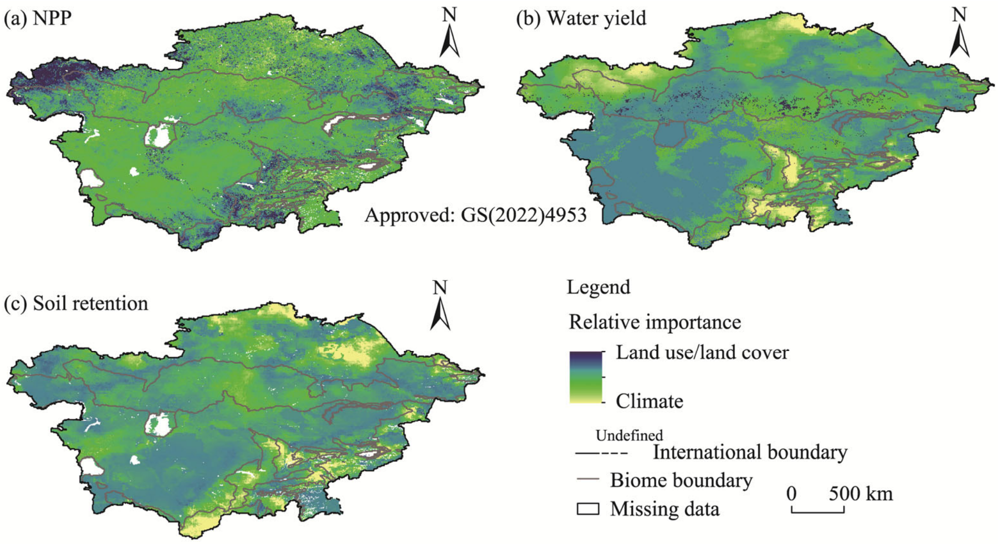

Fig. 6 Spatial distributions of relative importance of LULC change and climate change on the NPP (a), water yield (b), and soil retention (c) during the period of 2000–2015 in Central Asia

3.3.2 Combined effect of LULC change and climate change on ecosystem services

The combined LULC change and climate change presented an inhibitory effect on the NPP in 37.35% of the total pixels in Central Asia, and exhibited a synergistic effect on the NPP in 62.57% of the total pixels (Fig. 7a). The inhibitory effect and synergistic effect of combined LULC change and climate change on water yield were observed in only 1.45% and 2.06% of the total pixels, respectively, which were concentrated in the DSR (Fig. 7b). Furthermore, the combined LULC change and climate change presented an inhibitory effect on soil retention in 29.55% of the total pixels and exhibited a synergistic effect on soil retention in 69.94% of the total pixels (Fig. 7c).

When only the LULC-changed pixels were considered, the percentages of inhibitory effect pixels in Central Asia for the NPP, water yield, and soil retention were 37.71%, 35.36%, and 37.30%, respectively. The proportions of synergistic effect pixels in Central Asia for the three ecosystem services were 62.28%, 50.20%, and 62.22%, respectively. There were different combined effect patterns in the six biomes of Central Asia. For the NPP, the percentages of inhibitory effect pixels followed the order of LR (48.55%)>DSR (40.41%)>AMR (39.09%)>DR (34.52%)>TSR (34.51%)>AFR (32.87%). The percentages of synergistic effect pixels presented an opposite pattern, with most pixels in the AFR (67.13%), followed by the TSR (65.49%), DR (65.48%), AMR (60.90%), DSR (59.58%), and LR (51.45%). For water yield, the AFR possessed 50.98% of inhibitory effect pixels, followed by the AMR (48.58%), DR (43.58%), TSR (43.20%), and DSR (31.46%). The proportions of synergistic effect pixels were 65.50% in the DSR, 55.35% in the TSR, 50.13% in the DR, 48.84% in the AMR, and 46.99% in the AFR. The combined effect of LULC change and climate change for water yield in the LR was slight, with 98.16% of the total pixels influenced by LULC change and climate change independently. For soil retention, the inhibitory effect of combined LULC change and climate change was observed in 49.59% of pixels in the TSR, 47.36% of pixels in the AFR, 43.40% of pixels in the AMR, 36.11% of pixels in the DR, 30.91% of pixels in the DSR, and only 10.35% of pixels in the LR. Conversely, the synergistic effect of combined LULC change and climate change on soil retention was highest in the LR (89.65%), followed by the DSR (68.81%), DR (63.88%), AMR (55.34%), and AFR (50.87%), while the effect was lowest in the TSR (50.07%).

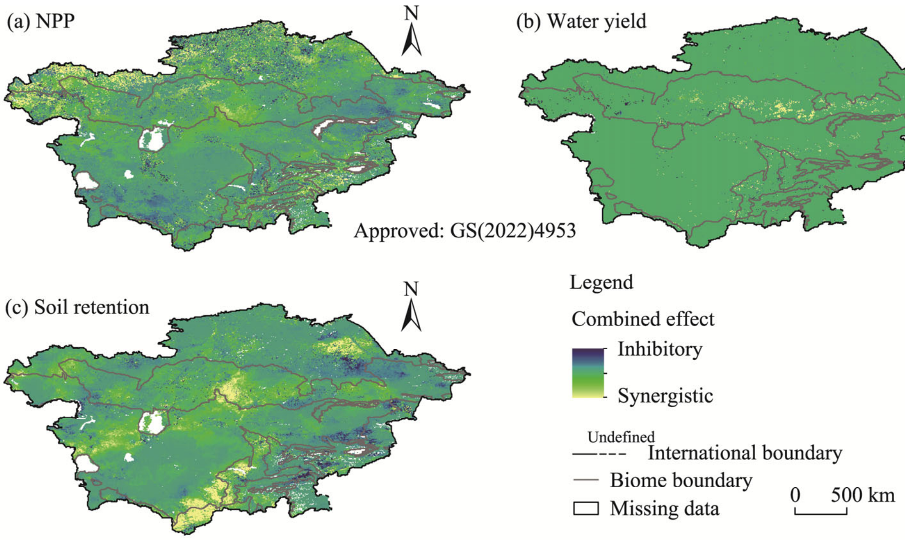

Fig. 7 Spatial distributions of the combined effect of LULC change and climate change on the NPP (a), water yield (b), and soil retention (c) during the period of 2000–2015 in Central Asia

4 Discussion

4.1 Effects of LULC change and climate change on ecosystem services

Based on the analysis of the relative importance and combined effect of LULC change and climate change on ecosystem services, it was found that a further discussion of how these two factors affect ecosystem services is also important. This can provide supplementary information for the development and utilization of natural resources in Central Asia. Results of Spearman's test showed that precipitation presented an overall positive relationship with these three ecosystem services at the biome scale, while the overall correlation between temperature and ecosystem services was not significant (Table 2). This demonstrated that the NPP, water yield, and soil retention in Central Asia were generally high in areas with high precipitation. Moreover, on a temporal scale, the positive relationship between precipitation and ecosystem services were notably greater than that between temperature and ecosystem services (Fig. 8).

Precipitation conditions in arid and semi-arid regions impose restrictions on surface water and groundwater resources (Sun et al., 2020). The increase in precipitation can directly improve the provision of fresh water (Rafiei-Sardooi et al., 2022). Moreover, precipitation pulsation can promote the photosynthetic activity of plants (Huxman et al., 2004; Mo et al., 2019) and thereby improve vegetation productivity at the community level (Reynolds et al., 2004). Thus, the increase of precipitation is beneficial for improving ecosystem services in Central Asia (Li et al., 2021). For example, the high values of ecosystem services were concentrated in the AFR and AMR, which were covered by large areas of forest land and grassland. The rich precipitation and mountain snowmelt water provide these areas with a long-term ample water supply. Moreover, the good precipitation and soil resource conditions in these areas boost plant growth and soil conservation. In contrast, the NPP, water yield, and soil retention were remarkably lower in the LR and DR than in the other biomes. These two biomes were mainly occupied by desert and semi-desert with relatively low precipitation and high temperature. Although increasing temperature can extend the vegetation growth season (Wang et al., 2003), it also increases evapotranspiration and reduces water use efficiency (Sun and Du, 2017) in desert and semi-desert, which limits the growth of plants and leads to the appearance of bare land or sparse grassland. The sand content of soil was found to be high in regions with low precipitation, which was not beneficial for plant growth (FAO, 2007; Jiao et al., 2020). Precipitation change is the most direct factor affecting soil erosion under climate change (Nearing et al., 2004). Without the interception provided by vegetation coverage, rainfall events will lead to soil erosion (Chen et al., 2018). Therefore, the low precipitation regions with large areas of bare land and sparse grassland in Central Asia are vulnerable to erosion.

Table 2 Correlation coefficients among the NPP, water yield, soil retention, precipitation, and temperature at the biome scale in Central Asia

	NPP	Water yield	Soil retention	Precipitation
Water yield	1.00**			
Soil retention	1.00**	1.00**		
Precipitation	1.00**	1.00**	1.00**	
Temperature	–0.54	–0.54	–0.54	–0.54

Note: **, *P*<0.01 level.

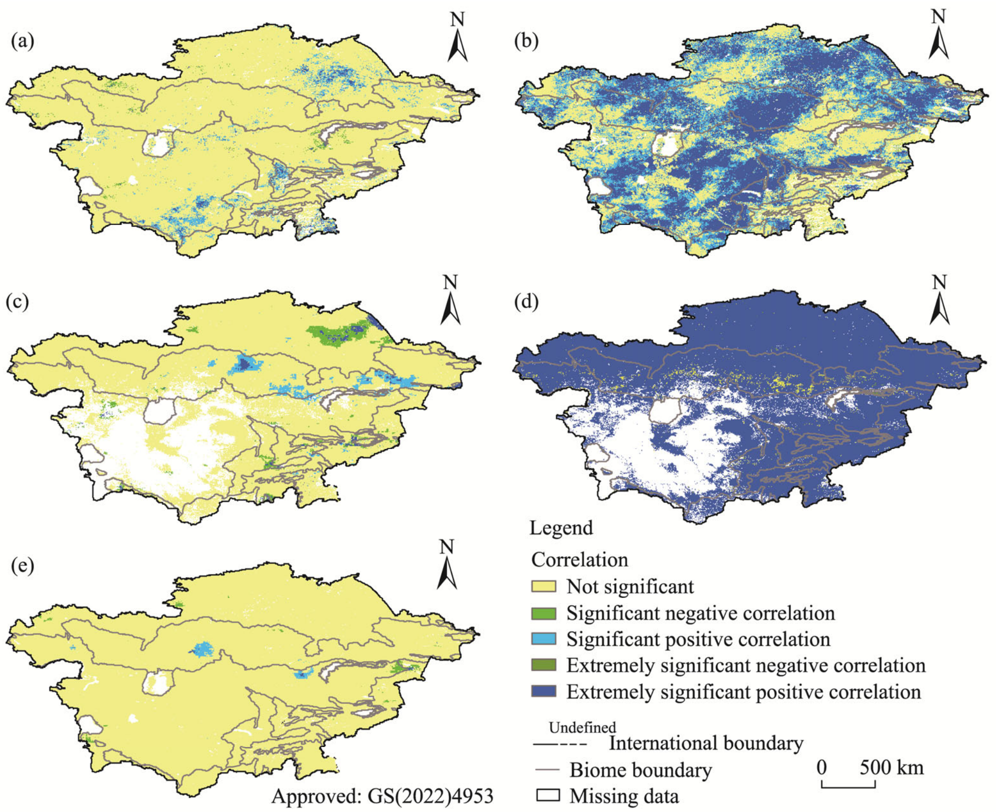

Fig. 8 Partial correlations of the NPP with temperature (a) and precipitation (b), partial correlations of water yield with temperature (c) and precipitation (d), and simple correlation between soil retention and temperature (e)

In Central Asia, grassland, cropland, urban land, and forest land were found to be the main LULC types with increase trends from 2000 to 2015. The expanded grassland areas were mainly concentrated in the DSR, which were converted from a large area of bare land. When only considering the effect of LULC change, grassland expansion occurred along with increases of the NPP, water yield, and soil retention (6.03%, 60.29%, and 1.03%, respectively). The same patterns were observed in the forest land expansion region and irrigated cropland expansion region converted from bare land. However, rainfed cropland expansion was accompanied by the decreases of the NPP (3.05%), water yield (8.45%), and soil retention (8.20%), which mainly occurred in the TSR. Urban development in Central Asia had the same effects on ecosystem services. This suggests that while the greening of desert areas benefits ecosystem services, the intensive exploitation of land resources from the natural environment can accelerate ecosystem degradation. In particular, the adverse effect of LULC change on ecosystem services would be intensified in the areas with a drying trend (Fig. 7).

LULC is closely related to soil properties (Feng et al., 2022) and dominates the change of the NPP (Ma et al., 2022). Although climate change generally has a greater effect on water supply than LULC change (Fu et al., 2017; Bai et al., 2019; Clerici et al., 2019; Ma et al., 2022), in warm-temperate semi-arid continental climate regions, LULC change also has a significant impact on water supply and vegetation restoration is beneficial to the increase of water yield (Li et al., 2021). Rational land use development, such as the conversion of cropland to forest land and grassland, could reduce water consumption and improve carbon storage and soil retention (Li et al., 2022; Rafiei-Sardooi et al., 2022). Conversely, unreasonable land resource development can affect the regulating and supporting capabilities of ecosystems. For example, the decrease of soil nutrient levels and other soil performance metrics can increase soil degradation and soil erosion (Covaleda et al., 2011). A more specific example is urbanization, which can increase the impervious surface area in a given region, hamper environmental sustainability, and reduce ecological integrity (Tao et al., 2015; Keeler et al., 2019; Liu et al., 2021).

4.2 Implications for the development and utilization of natural resources in Central Asia

Water shortages and the uneven distribution of water resources have been a long-term challenge in Central Asia because of its dry climate and complex terrain (with high mountainous regions in the east and low plain regions in the west) (Yang et al., 2017). Although there is a large area of plains in Central Asia, low precipitation and unreasonable land resource utilization have limited the sustainable development of ecosystems and decreased ecosystem services. For example, the expansion of irrigated cropland concentrated in the Amu Darya River Basin and the Syr Darya River Basin decreased the water flowing to the Aral Sea, which caused the shrinkage of the Aral Sea and resulted in the great environmental damage (Chen et al., 2013). Based on the results of this study, the sustainable development and utilization of resources must be linked with environmental protection, rational land use management strategies, and a deep understanding of climate change effect (Ma et al., 2022).

The AFR and AMR are the key water source regions in Central Asia. These two regions also contain abundant vegetation. However, urbanization in these regions is rapid, accompanied by the reduction of grassland area. Considering the synergistic effect of the drying climate trend in the AFR and AMR, social and economic development must protect natural forests and grassland (Ma et al., 2022) and minimize the occupation of ecologically important lands by urban expansion (Wang et al., 2021). In this way, land degradation and plant diversity reduction caused by human activities can be avoided. The degradation of grassland in the TSR was remarkably serious. In order to avoid vegetation degradation and the decline of soil fertility and productivity, while satisfying the demand of crop production, it is necessary to plant appropriate crops according to local climate and soil conditions and prohibit overgrazing (Jilili and Ma, 2015). Moreover, this implementation should prioritize the western TSR, where ecosystem services have decreased remarkably, and unreasonable land resource development would aggravate this tendency under a drying climate trend (Figs. 5–7). In the DSR and DR, there are large areas of sparse grassland and bare land with scarce precipitation. Although ecosystem services in 2015 increased to some degree compared with 2000, the long-term NPP change in the DR showed a significant downward trend. Thus, urbanization and irrigated cropland expansion in these two regions (DSR and DR) are also worthy of attention. If urbanization and cropland expansion are not curbed, this will lead to the decreases of soil quality and ecosystem services (Qiu et al., 2012). Therefore, it is important to strengthen the protection of grassland and inhibit the desertification and soil erosion. Vegetation restoration measures, such as planting species resistant to salt, alkaline conditions, and drought, should be taken in degraded ecological areas. In addition, it will be important to establish high-standard cropland and develop ecological agriculture methods, such as improved irrigation technology and enhanced water resource utilization efficiency (Pereira et al., 2009; Akpoti et al., 2021). This would also benefit the ecosystem restoration of the LR, which is located in the downstream of the river basins.

4.3 Limitations

In this study, changes of the NPP, water yield, and soil retention during the period of 2000–2015 were calculated for the whole Central Asia and for the six biomes in Central Asia. The relative importance and combined effect of LULC change and climate change on ecosystem services were demonstrated. In addition, the effects of the spatial differences in temperature and precipitation on ecosystem services, as well as the correlations between climate factors and ecosystem services on a temporal scale, were analyzed. The results can help researchers to identify the most important climate factor affecting the spatial distribution of ecosystem services. Combined with the analysis of the effects of LULC change and climate change on ecosystem services, this study can provide effective suggestions for reasonable natural resource development and utilization according to the climate and LULC characteristics on the biome scale.

However, this study has limitations. There are complex interactions between LULC change and climate change (Jia et al., 2019), but this study ignored the influences of those interactions. This may have caused some deviations in the results. For example, LULC change can affect surface temperature through non-radiative processes, such as the hydrological cycle (Jia et al., 2019); precipitation change can not only affect the distribution of vegetation (Mo et al., 2019; Wu et al., 2020), but also increase soil erosion in some extreme occasions (Zhou et al., 2016); and high temperature and drought can result in the degradation of ecosystems and land functioning (Trumbore et al., 2015; Lesk et al., 2016), thereby affecting LULC types. Another limitation is related to the ecosystem service algorithms. First, the formula used to calculate soil retention does not include temperature. Second, solar radiation and ET_0 in the CASA and InVEST models are related to temperature and precipitation. These factors may cause difficulty in quantifying the relative contributions of temperature and precipitation to ecosystem services, which need to be considered in the future.

5 Conclusions

Ecosystem services are important links between natural ecosystem and human well-being. Based on the CASA, InVEST, and RUSLE models, this study revealed the spatiotemporal patterns of three ecosystem services (the NPP, water yield, and soil retention) in Central Asia during the period of 2000–2015. The effects of LULC change and climate change on ecosystem services were also discussed using various analysis methods. The results showed that ecosystem services decreased from forest land to grassland, and were lowest in the desert of Central Asia. During the period of 2000–2015, ecosystem services showed fluctuant trends, and significant decreases were mainly found in the southeast mountainous area and northwest of Central Asia. Climate factors (temperature and precipitation) had a greater effect on water yield and soil retention, but the NPP was more strongly influenced by LULC change. In addition, precipitation was strongly and positively correlated to ecosystem services, while the relationship between temperature and ecosystem services was weaker. The conversion of bare land to grassland and cropland, as well as the increase of forest land, improved ecosystem services. However, urbanization and the transformation of grassland to cropland decreased ecosystem services. Despite the limitations of this study, the findings could provide practical information for reasonable land-use planning, as well as ecosystem protection and restoration in Central Asia.

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