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Spatiotemporal changes of ecosystem service trade-offs under the influence of forest conservation project in Northeast China

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Trade-offs between ecosystem services are measures of the degree to which the changing differences between the individual ecosystem services. Although changes in ecosystem service trade-offs are critical for forest ecosystem management, spatiotemporal changes in trade-offs are currently less studied, especially under the influence of ecological engineering implementation. Therefore this study explored the spatiotemporal changes and drivers of ecosystem service trade-offs in various forest types following the implementation of the natural forest conservation project (NFCP), with the example of the Greater Khingan Mountains. Spatial analyses, and root mean square error (RMSE) were applied to investigate spatiotemporal changes in trade-offs, and geodetector was employed to assess their driving factors. The results indicated that among all ecosystem service pairs from 1990 to 2020, the trade-offs between habitat quality and net primary productivity (NPP), NPP and soil conservation showed a growing trend. However, the trade-offs between habitat quality and water conservation, NPP and water conservation, and soil conservation and water conservation showed a declining trend. The ecosystem service trade-offs of coniferous (0.47) were higher than either broad-leaved (0.37) or shrubs (0.28). Moreover, changes in the ecosystem service trade-offs of all kinds of forests were spatially heterogeneous. The drivers with the greatest explanatory power in coniferous, broad-leaved, and shrubs were land use (22.68%), land use (15.19%), and NDVI (20.63%), respectively. Environmental factors contributed great mean explanatory power (62.27–71.67%) to the trade-offs than anthropogenic

activity factors. Therefore, spatiotemporal changes and drivers of trade-offs in different forests should be contemplated when conducting subsequent ecological restoration programs in the future.

KEYWORDS

natural forest conservation project, forest ecosystem service, trade-off, spatiotemporal changes, driving factors

Introduction

Forests are the largest natural ecosystems on Earth (FAO, 2020). They provide natural environment for humans by delivering numerous ecosystem services (Nkem et al., 2007; Mbow et al., 2014). Global climate change and increased human activities have resulted in environmental devastation and forest deterioration, such as soil erosion, water shortage, and habitat degradation (Foley et al., 2005). Habitat degradation and supply decreases in ecosystem services threaten ecosystem balance and thus human welfare (Wang et al., 2017). To tackle this issue and ensure the sustainable development of forest ecosystems, China has implemented several successively ecological projects, for instance, the natural forest conservation project (NFCP) since 2000 (Mao et al., 2019). Restoration programs have greatly improved habitat quality and ecosystem services in forest ecosystems (Benayas et al., 2009). Assessing forest ecosystem services after restoration can provide insights into future ecological projects' implementation to maximize ecosystem service benefits (Tallis et al., 2008).

Trade-offs between ecosystem services measure the degree to which the changing differences between the individual ecosystem services (Bennett et al., 2009; Qiu et al., 2021). Trade-off interactions between forest ecosystem services may enhance or weaken by spatiotemporal changes in ecosystem services (Bennett et al., 2009). They are closely connected with spatiotemporal dynamics of ecological processes, and are spatiotemporally heterogeneous (Liu et al., 2019; Qiao J. M. et al., 2019; Qiu et al., 2021; Zhao et al., 2021). With global warming and human activities increasing, the spatiotemporal dynamic property of trade-offs makes their management more unsure and challenging (Gonzalez-Ollauri and Mickovski, 2017; Dong et al., 2020). However, most related studies were mainly focused on spatiotemporal changes in forest ecosystem services. For instance, ecosystem services provided by different forest types were significantly improved after dam construction in the Three Gorges reservoir area (Chu et al., 2019). The spatial variations of forest ecosystem services were closely connected with land use patterns (Aznar-Sánchez et al., 2018). Spatiotemporal changes in trade-offs among different forest ecosystem services can affect the increase or decrease of different ecosystem services, and thus change the

ecosystem overall benefits. Comprehending the spatiotemporal disparities in trade-offs among different forest ecosystem services is relatively limited, especially the spatiotemporal changes after the ecological project implementation. Therefore, a greater comprehension of the spatiotemporal changes in forest ecosystem service trade-offs is necessary to provide an effective policy basis for forest ecosystem management.

Explicating the drivers of trade-offs is crucial for confirming corresponding solutions to alleviate trade-offs and improve ecosystem services (Power, 2010). Numerous studies indicated that the spatiotemporal dynamics of trade-offs between forest ecosystem services depended on natural factors (i.e., precipitation, elevation, slope, etc.) and anthropogenic activity factors (i.e., land use, population distribution, etc.) (Lyu et al., 2019; Peng et al., 2019). Although these studies focused on the effects of environmental factors and anthropogenic activity factors, there is still a lack of comprehensive comparison of driving factors. In addition, most of these studies used traditional correlation or regression analysis that focused on driver effects from a numerical perspective, but ignored the spatial heterogeneity of drivers themselves. Geodetector is a new tool for geographic research that can effectively analyze spatial differentiation in geographic phenomena and assess how the factors influence spatial differentiation (Han et al., 2015). The core assumption of geodetector is that if the independent variable X and the dependent variable Y have a virtual spatial correlation, they are linked (Wang et al., 2010). This approach has been progressively applied to identify the spatially stratified characteristics of land use and landscape patterns. It detects spatial differences and principal causes efficiently in geographic phenomena and can be applied to analyze the driving factors of trade-offs.

As the mainstay of the natural ecosystem in northern China, forests play a critical part in maintaining regional climate and environmental protection. The Greater Khingan Mountains are boreal forests and are necessary ecological barriers in northern China. They also play an essential role in net primary productivity (NPP), soil conservation, water conservation, and habitat quality (Mao et al., 2019; Zhang et al., 2022). To protect the ecological environment, the Chinese government has implemented the NFCP since 2000. The first phase of the NFCP ended in 2010, and the second round of the NFCP started

in 2011. The effect of the NFCP on ecosystem services could guide subsequent ecological engineering. The Greater Khingan Mountains were the main area for NFCP implementation in Northeast China. Therefore, taking the Greater Khingan Mountains as an example, this paper aims to: (1) evaluate the spatiotemporal changes of forest ecosystem services in the Greater Khingan Mountains from 1990 to 2020; (2) investigate the spatiotemporal changes in ecosystem service trade-offs and their differences among various forest types; (3) measure the influence of drivers on forest ecosystem service trade-offs among various forest types using geodetector.

Materials and methods

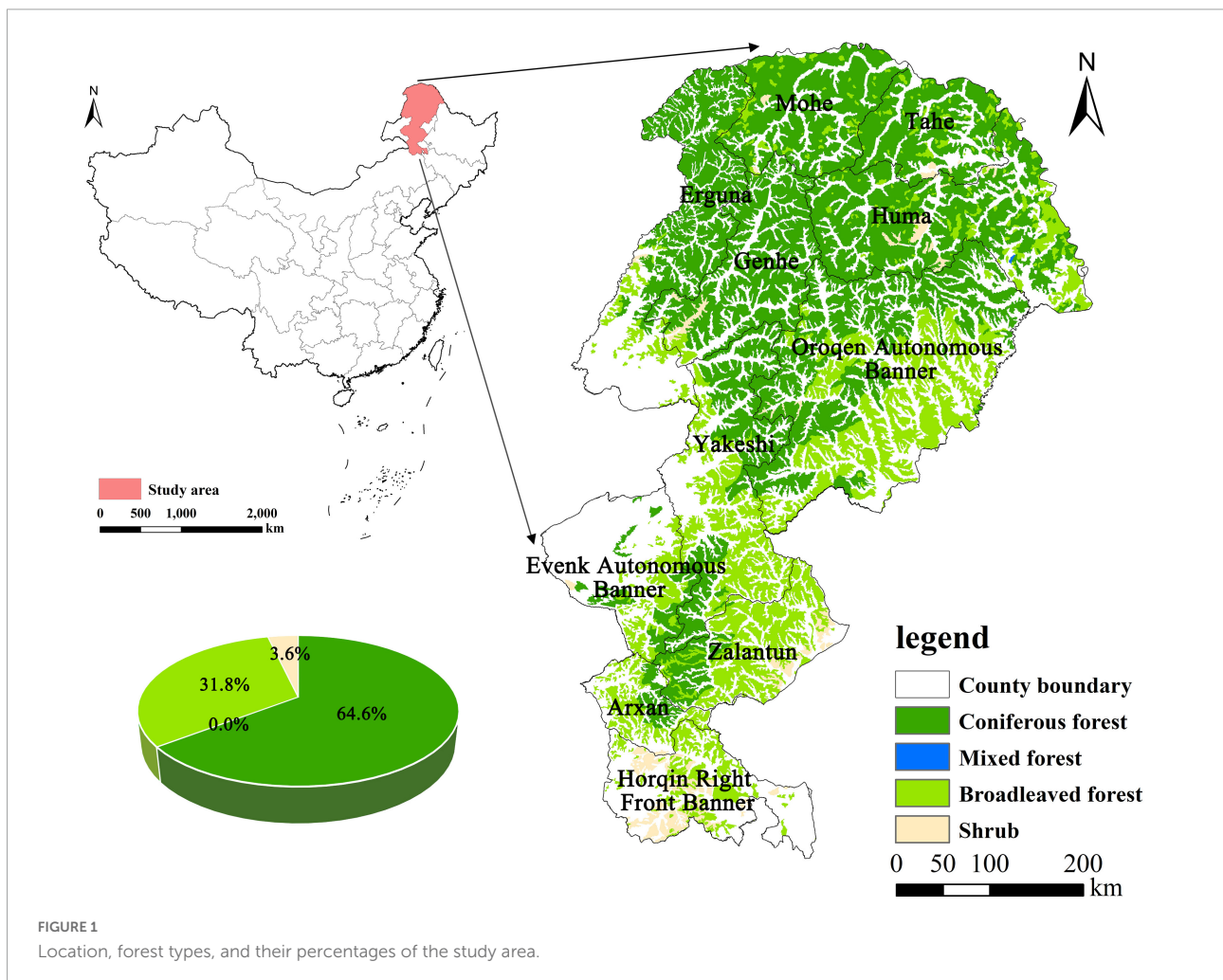
Study area

The Greater Khingan Mountains are located at 118°14'~127°44'E, 45°13'~53°56'N (Figure 1). Their administrative scope includes the Hinggan League of Inner

Mongolia Autonomous Region, Hulunbuir City, and the Greater Khingan Mountains area of Heilongjiang Province, with an area of about 260,000 km². It has a temperate continental climate characterized by long, cold winters and short, rainy summers. It is rich in solar radiation resources, with a mean average temperature of -2.5 to 6.8°C and a mean annual rainfall of 310–750 mm. The vegetation types in this region are mainly coniferous, coniferous and broad-leaved mixed, broad-leaved, and shrubs. Since the areas of coniferous and broad-leaved mixed were too small, three types of forest types including coniferous, broad-leaved, and shrubs were selected in this study. The spatial patterns of the forests were digitized using the Vegetation Atlas of China (Editorial Committee for Vegetation Atlas of China, 2001).

Data sources and processing

The datasets employed incorporated land use, NDVI, meteorological, elevation, soil data, GDP per land area and,



population density in this paper. The specifics were shown in **Table 1**. Land use was used to estimate habitat quality. NDVI was used to retrieve the absorbed photosynthetic active radiation (APAR) when estimating NPP. Rainfall data were used to estimate the rainfall erosion factor. Slope, slope length, and topography factor were calculated using the elevation. Soil data were used to estimate the soil erodibility factor. All data were rescaled to 300 m to satisfy the calculation requirements.

Quantification of forest ecosystem services

In recent decades, many ecological problems have been arisen in the Greater Khingan Mountains, such as soil erosion, water shortage, and habitat degradation (Mao et al., 2014). Based on previous studies and field research, we chose 4 key forest ecosystem services: NPP, soil conservation, water conservation, and habitat quality, which are highly relevant to the stakeholders in this area (Mao et al., 2019; Zhang et al., 2022).

Net primary productivity

We adopted the Carnegie-Ames-Stanford-Approach (CASA) model to estimate NPP at the grid cell scale (Potter et al., 1993). The specific calculation was as follows:

$$NPP(x, t) = APAR(x, t) \times \epsilon(x, t)$$

where net primary productivity (x, t) denotes the net primary productivity at points x and t , $APAR(x, t)$ denotes the incident solar radiation received by the canopy at a particular time period ($MJ \cdot m^{-2}$), and $\epsilon(x, t)$ denotes the light energy utilization rate ($gC \cdot MJ^{-1}$). More information about the model can be available in the **Supplementary Table 1**.

Soil conservation

We employed the RUSLE model to simulate the soil conservation amount. Soil conservation was the discrepancy

between potential and actual soil erosion in an ecosystem process (Ausseil et al., 2013). It was calculated using the following equation:

$$SC = R \times K \times LS \times (1 - P \times C)$$

where SC denotes the soil conservation amount, and unit is $t/(km^2 \cdot a)$, R denotes the rainfall erosion force factor [$MJ \cdot mm/(km^2 \cdot h \cdot a)$] (Fournier, 1960), K denotes the soil erodibility factor [$t \cdot km^2 \cdot h/(km^2 \cdot MJ \cdot mm)$] (Williams et al., 1983), LS denotes the topography factor, C denotes the cropping management factor (Cai et al., 2000), and P denotes the engineering measure factor (You and Li, 1999). More details about the model can be available in the **Supplementary Table 1**.

Water conservation

The water conservation module in InVEST model is grounded on the Budyko hydrothermal coupling water balance hypothesis (Budyko, 1974; Donohue et al., 2012). Taking into account the average annual rainfall and actual evapotranspiration (Zhang et al., 2001), the water yield was calculated as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x)$$

where $Y(x)$ denotes the water yield in grid cell x (mm), $AET(x)$ denotes the practical evapotranspiration in grid cell x , and $P(x)$ denotes the annual rainfall in grid cell x (mm). More details about the model can be available in **Supplementary Table 1**.

Habitat quality

Habitat quality was considered as an indicator of biodiversity (Feng et al., 2018), and it was calculated as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xy}^z}{D_{xy}^z + k^z}\right)\right]$$

where Q_{xj} denotes the habitat quality at grid cell x of land use type j . D_{xy} and H_j are overall threat degree and habitat

TABLE 1 Data sources used in this paper.

Data set	Data sources and descriptions	Resolution
Land use	Land use data in 1990, 2000, 2010, and 2020 were taken from Copernicus Climate Change Service (https://cds.climate.copernicus.eu/).	300 m
NDVI	Data for 1990 were obtained from GIMMS-NDVI dataset (https://climatedataguide.ucar.edu/climate-data/ndvi-normalized-difference-vegetation-index-3rd-generation-nasagfsc-gimms), Data for 2000, 2010, and 2020 were derived from MOD13A3 NDVI dataset (https://search.earthdata.nasa.gov/).	8,000 m, 1,000 m
Meteorological	The meteorological data, including month temperature and precipitation, were obtained from the China Meteorological Data Service Center (http://www.cma.gov.cn/)	1,000 m
DEM	NASA/USGS published of SRTM Global DEM (https://lpdaac.usgs.gov/)	90 m
Soil data	The soil data, including clay content, silt content, sand content, and organic matter content, were derived from the Chinese soil dataset based on the Harmonized World Soil Database (HWSD) (v1.1) (http://bdc.casnw.net/)	1,000 m
GDP per land area	Acquired from the Resource and Environment Science and Data Center (http://www.resdc.cn/).	1,000 m
Population density	Acquired from the Resource and Environment Science and Data Center (http://www.resdc.cn/).	1,000 m

suitability, respectively. z is set as 2.5, and k is the half-saturation constant, which has been set as 0.5. In this paper, we took farmland, urban land and highways as threats sources. More details about the model can be available in the [Supplementary Table 1](#).

Measurement of the forest ecosystem service trade-offs

Root mean square error (RMSE) was used to quantify the trade-offs between each two ecosystem services (Bradford and D'Amato, 2012; Feng et al., 2017). It calculates trade-offs as the distance from point to line (Figure 2). The further the distance is, the greater the trade-off is. Whereas, the shorter the distance is, the more it tended to be synergistic. RMSE is a simplistic and efficient approach to express the extent of trade-offs between any two ecosystem services, regardless of their correlation. Data normalization was conducted to remove the impacts of grid cells on each ecosystem service before RMSE calculation as follows:

$$ES_{std} = \frac{(ES_{obs} - ES_{min})}{(ES_{max} - ES_{min})}$$

where ES_{std} denotes the normalized value of ecosystem services, ES_{obs} denotes the observed value of ecosystem services, ES_{min} and ES_{max} are the minimum and maximum observed value of ecosystem services, correspondingly. The value range of ES_{std} is 0–1.

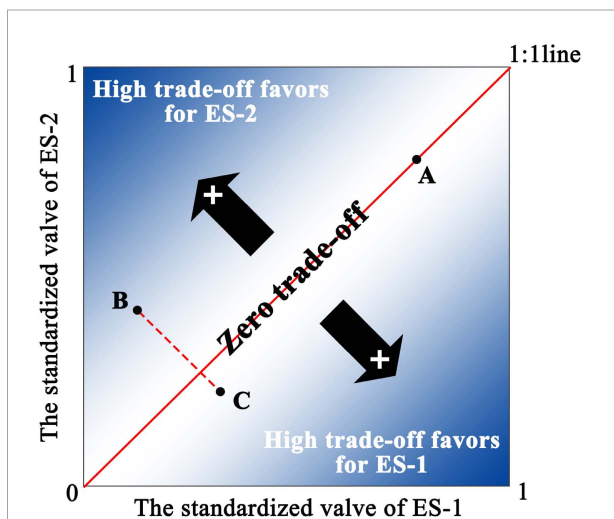


FIGURE 2
Illustration and example of the trade-offs between two ecosystem services. The RMSE is the distance between an ecosystem service pair's coordinates and line 1:1, where the two ecosystem services are equal. Take [Figure 2](#) as an example, the trade-off value at point A is 0; the trade-off value at point B is higher than that at C. Moreover, at point B the trade-off favors ES2, but at point C the trade-off favors ES1. The graph was revised based on previous studies (Bradford and D'Amato, 2012; Lu et al., 2014).

Then, RMSE was calculated as follows:

$$RMSE = \sqrt{\frac{1}{n-1} \times \sum_{i=1}^n (ES_i - \widehat{ES})^2}$$

where ES_i denotes the normalized value of ecosystem services i , and \widehat{ES} denotes the expected value of the i number of ecosystem services, n denotes the number of ecosystem service types. \widehat{ES} is the mean value of the i number of ES_i (Bradford and D'Amato, 2012). The RMSE denotes the mean disparity between each ES_{std} and mean ES_{std} , and it characterizes the amplitude of scattering from the mean (Feng et al., 2017; Han et al., 2020; Xu et al., 2020). The RMSE value is between 0 and 1.

Identification of the key drivers

Nine driving factors were chosen from published studies (Lyu et al., 2019; Peng et al., 2019; Qiu et al., 2021), and they were categorized into environmental factors and anthropogenic activity factors. Environmental factors include NDVI, temperature, precipitation, elevation, slope, and soil types. Anthropogenic activity factors include land use, population density, and GDP density.

GeoDetector has particular benefit in the treatment of spatially stratified heterogeneity and categorical variables (Wang et al., 2010; Chen et al., 2020). Geodetector was applied to quantitatively identify the explanatory power of drivers for forest ecosystem service trade-offs, the value was measured by the q -value. The calculation equation is as follows:

$$q = 1 - \frac{1}{n\sigma^2} \sum_{h=1}^L n_h \sigma_h^2$$

where q denotes the explanatory power of the driving factor, n denotes the sum of sample points, σ^2 denotes the sum regional variance, $h = 1, 2, 3, \dots, L$ denotes the layer of factor X , n_h and σ_h^2 denote the number of sample points and variance of layer h . The q -statistic is between 0 and 1. The larger the q -statistic, the greater the explanation of ecosystem services by the influencing factors.

Results

Spatiotemporal changes in forest ecosystem services after natural forest conservation project implementation

From 1990 to 2020, all NPP, soil conservation, water conservation, and habitat quality in the Greater Khingan Mountains gradually increased. The spatial distribution of the four ecosystem services decreased from northern to southern in

the Greater Khingan Mountains (Figure 3 and Table 2). Habitat quality was relatively uniform across the area. The mean value of habitat quality fluctuated between 0.57 and 0.58. The mean

values of different forest types were significantly different, with values of 0.73, 0.58, and 0.42 for coniferous, broad-leaved, and shrubs, respectively. In 2000, the highest habitat quality was

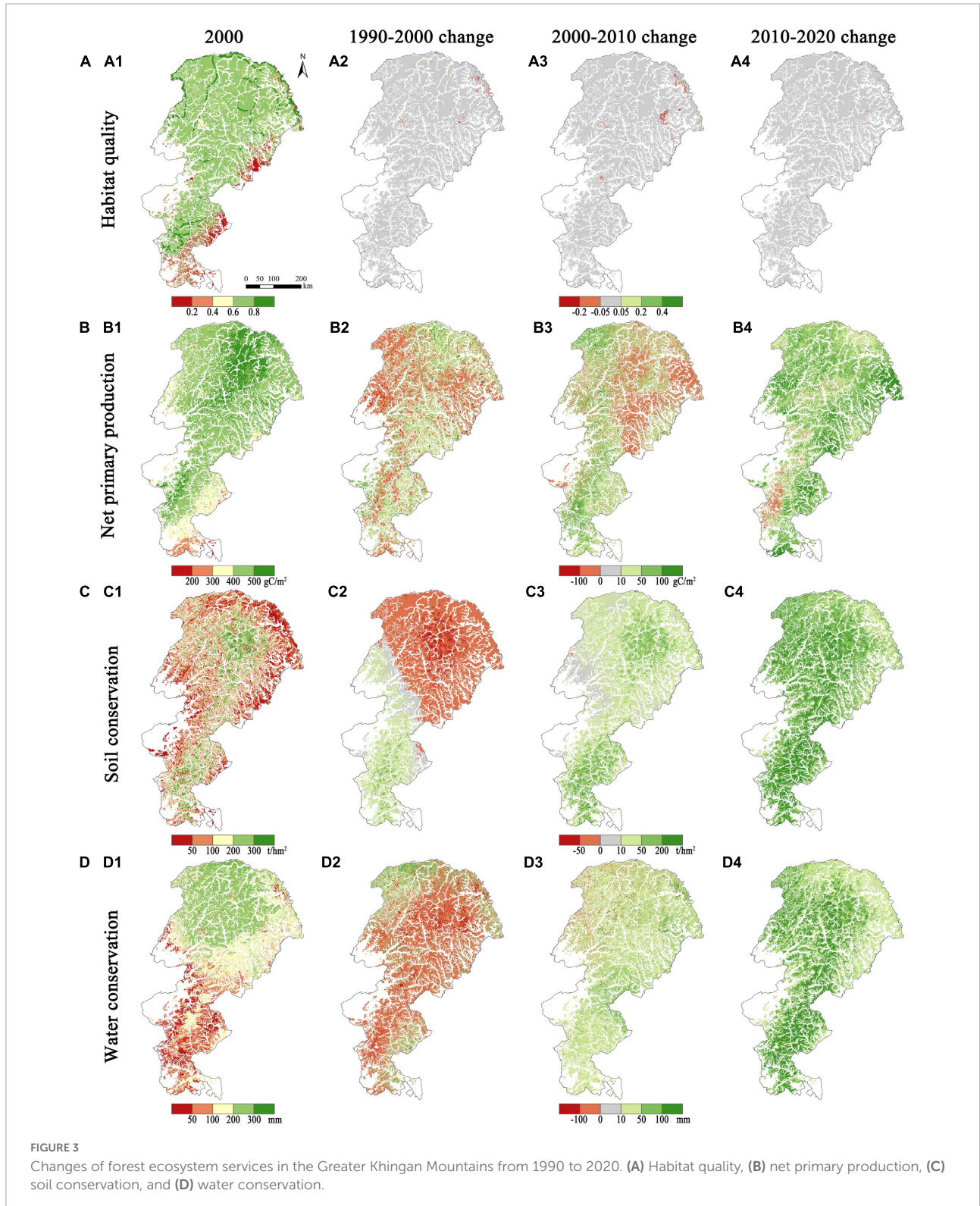


TABLE 2 Temporal changes of forest ecosystem services in the Greater Khingan Mountains from 1990 to 2020.

	NPP (gC/m ²)			Soil conservation (t/hm ²)			Water conservation (mm)			Habitat quality		
	CF	BF	SH	CF	BF	SH	CF	BF	SH	CF	BF	SH
1990	460.25	407.997	338.212	141.293	106.319	95.706	208.921	124.745	135.377	0.739	0.576	0.408
2000	465.297	421.755	345.482	129.141	114.19	104.195	187.053	106.104	121.714	0.742	0.581	0.423
2010	485.521	448.41	381.733	161.322	156.638	152.413	245.926	178.67	180.26	0.73	0.584	0.426
2020	546.474	512.918	457.726	310.28	325.507	288.577	394.884	347.539	316.424	0.725	0.589	0.427
1990–2000	5.047	13.758	7.27	−12.152	7.871	8.489	−21.868	−18.641	−13.663	0.003	0.005	0.015
2000–2010	20.224	26.655	36.251	32.181	42.448	48.218	58.873	72.566	58.546	−0.012	0.003	0.003
2010–2020	60.953	64.508	75.993	148.958	168.869	136.164	148.958	168.869	136.164	−0.005	0.005	0.001

CF, BF, and SH represent coniferous forest, broad-leaved forest and shrub.

in the northwestern portion, and the lowest mainly focused on the southeast (Figure 3A1). In terms of temporal variation, habitat quality was relatively stable from 1990 to 2020, with small interannual variation. The mean value of habitat quality in coniferous showed a small downward trend, but small increased trends in both broad-leaved and shrubs. The stable zone (i.e., variations between −0.05 and 0.05) of habitat quality accounted for 93–98% (Figures 3A2–4). Habitat quality changed in a very small space and was less influenced by land use and threatened source changes.

The NPP showed a gradually increasing trend under various forest types. The average NPP in 1990, 2000, 2010, and 2020 were 402.15, 410.84, 438.55, and 505.71 gC/m², respectively. The average NPP increased by 67.15 gC/m² in 2010–2020, which was significantly higher than that in 1990–2000 (8.69 gC/m²) and 2000–2010 (27.71 gC/m²). Moreover, the increased NPP of shrubs (75.99 gC/m²) was significantly higher than that of coniferous (60.95 gC/m²) and broad-leaved (64.50 gC/m²) in 2010–2020. The average NPP of coniferous was higher than that of broad-leaved, higher than that of shrubs between 1990 and 2020. For spatial distribution, NPP gradually decreased from northeastern to southwestern in 2000. Compared with 1990–2000, the NPP in 2010–2020 increased more in the northwestern and southeastern Greater Khingan Mountains, with an increasing percentage of 48–76%, respectively.

In terms of temporal variation, soil conservation decreased and then increased from 1990 to 2020. It slightly decreased in 1990–2000, slightly increased in 2000–2010, but significantly increased in 2010–2020. The soil conservation in various forest types changed different showed different trends. Soil conservation of coniferous decreased and then increased, while soil conservation of broad-leaved and shrubs constantly increased from 1990 to 2020. In terms of spatial distribution, the highest soil conservation was in the northwestern Greater Khingan Mountains, and the lowest primarily focused on the peripheral areas in 2000. From 1990 to 2000, the proportions of the area where the soil conservation increased and decreased were 62 and 38%, respectively. The increased areas of soil conservation during 2000–2010 and 2010–2020 accounted for

83 and 92%, respectively. The increased soil conservation was associated with the NFPC implementation.

Water conservation significantly decreased and increased from 1990 to 2020 (Figure 3D). The mean value of water conservation slightly decreased from 1990 to 2000, gradually increased from 2000 to 2010, and significantly increased from 2010 to 2020. Water conservation under different forest types showed consistent temporal variations from 1990 to 2020. Among them, water conservation of coniferous had the highest average value. Water conservation of broad-leaved had the fastest growth. The highest water conservation was found in the coniferous in the northern Greater Khingan Mountains, whereas the lowest water conservation was found in the shrubs in the southwest. From 1990 to 2000, the area of decreased water conservation accounted for 68% of the region, while in 2000–2010 and 2010–2020, the area of increased water conservation accounted for 82 and 86%, respectively.

Spatiotemporal changes in forest ecosystem service trade-offs after natural forest conservation project implementation

In this paper, we used the forest ecosystem service trade-offs in 2000 as a reference to compare the trade-off changes after NFPC implementation (Figure 4). From 1990 to 2020, the trade-offs between habitat quality and NPP, NPP and soil conservation, and soil conservation and water conservation increased, while the trade-offs between habitat quality and water conservation, NPP and water conservation decreased. The trade-off between habitat quality and soil conservation were relatively stable before and after NFPC implementation. Moreover, all the trade-offs of three forest types showed clear stratifications. The RMSE of coniferous (0.47) was higher than that of broad-leaved (0.37), was higher than that of shrub (0.28). The trade-off between habitat quality and soil conservation in coniferous and broad-leaved decreased by 0.06 and 0.07 from

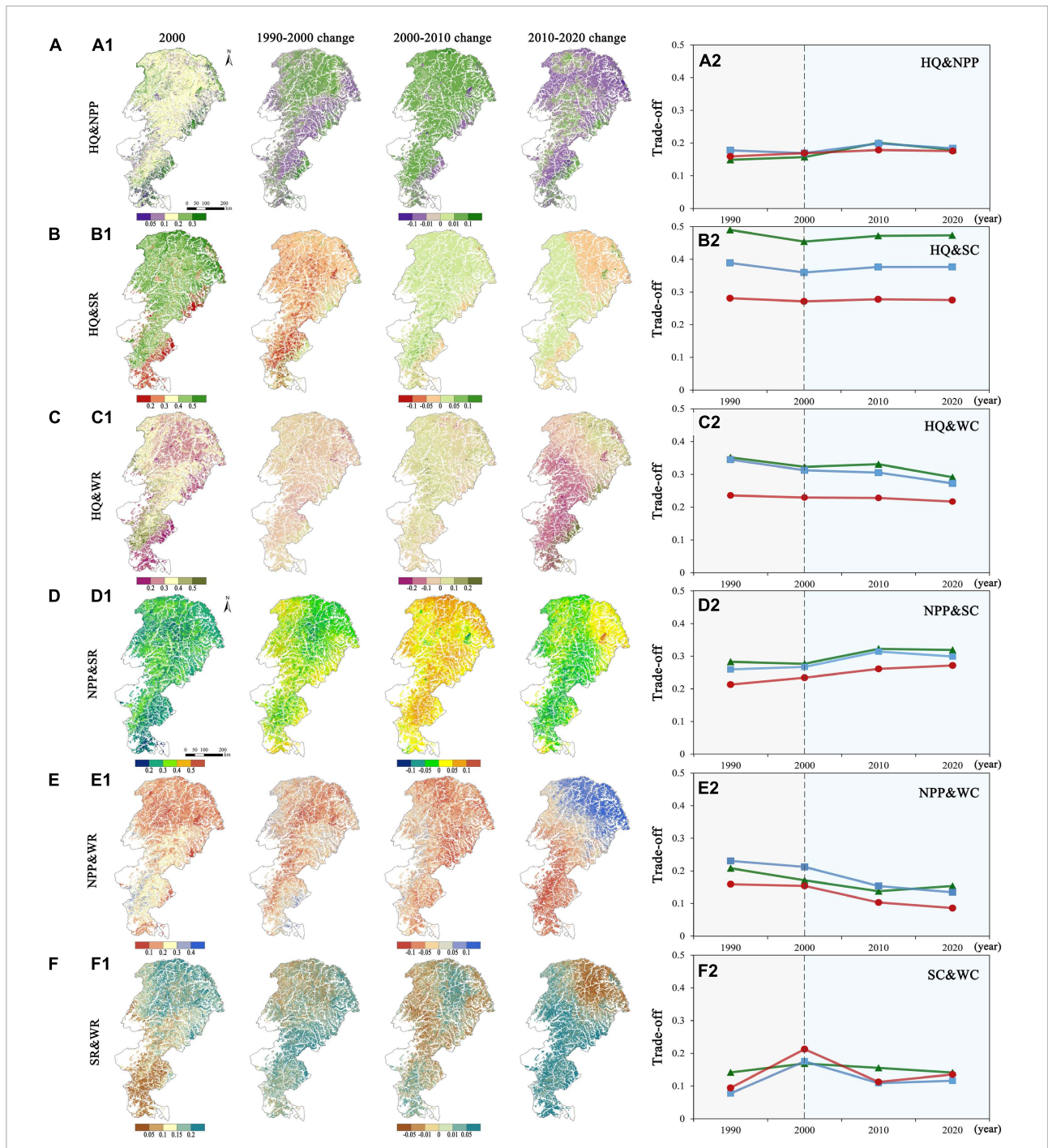


FIGURE 4 Spatial variations of forest ecosystem service trade-offs in the Greater Khingan Mountains from 1990 to 2020, and temporal variations in trade-offs of different forest types from 1990 to 2020. (A) HQ and NPP, (B) HQ and SC, (C) HQ and WC, (D) NPP and SC, (E) NPP and WC, (F) SC and WC. HQ, SC, and WC represent habitat quality, soil conservation, and water conservation.

1990 to 2020, respectively. While the trade-off between habitat quality and soil conservation in shrubs remained essentially unchanged. Both the NPP and soil conservation trade-offs in 1990–2000 and in 2000–2020 increased. The trade-off between NPP and soil conservation in shrubs increased by 0.06 over

30 years, which was higher than in coniferous and broad-leaved. The soil conservation and water conservation trade-offs increased and then decreased from 1990 to 2020. The trade-offs between soil conservation and water conservation decreased after NFP implementation.

In terms of spatial distribution, the trade-offs between pairs of ecosystem services showed significant spatial heterogeneity in the three forest types. From 2000 to 2010, the trade-off between habitat quality and NPP increased in the 84% areas of the Greater Khingan Mountains. The trade-off between habitat quality and soil conservation in 2000 decreased from northern to southern. The highest values were found in northern coniferous, while the lowest values were in the southeastern shrubs. The trade-off between habitat quality and water conservation decreased in the 71% areas of the region from 2010 to 2020. The trade-offs between NPP and soil conservation increased in 64, 92, and 53% areas of the region during 1990–2000, 2000–2010, and 2010–2020, respectively. The spatial heterogeneity trade-offs between soil conservation and water conservation from 1990 to 2020 were higher than that between any other two ecosystem services. It suggested that the trade-offs between soil conservation and water conservation were more affected by the NFCP than between other ecosystem services.

The trade-offs between each two ecosystem services were considerably different among the three forest types (**Figure 5A**). In the histogram, the trade-offs in coniferous were significantly higher than either in broad-leaved or in shrubs (**Figure 5B**). The points in the soil conservation-water conservation scatter plot mostly fell on the 1:1 line, indicating a slight trade-off between soil conservation and water conservation (0.13). Moreover, the points in the soil conservation-water conservation scatter plot of shrubs were relatively far away from the 1:1 line, showing high trade-offs between soil conservation and water conservation in shrubs. In addition, the trade-offs between NPP and water conservation were low (0.15). The points in the NPP-soil conservation, and habitat quality-water conservation scatter plot were somewhat away from line 1:1, suggesting appropriate trade-offs (0.28 and 0.29, respectively). The trade-offs between habitat quality and soil conservation (0.37) were significantly higher than the trade-offs between any other two ecosystem services. RMSE between habitat quality and soil conservation in coniferous and broad-leaved exceeded 0.4.

Influence of drivers on forest ecosystem service trade-offs

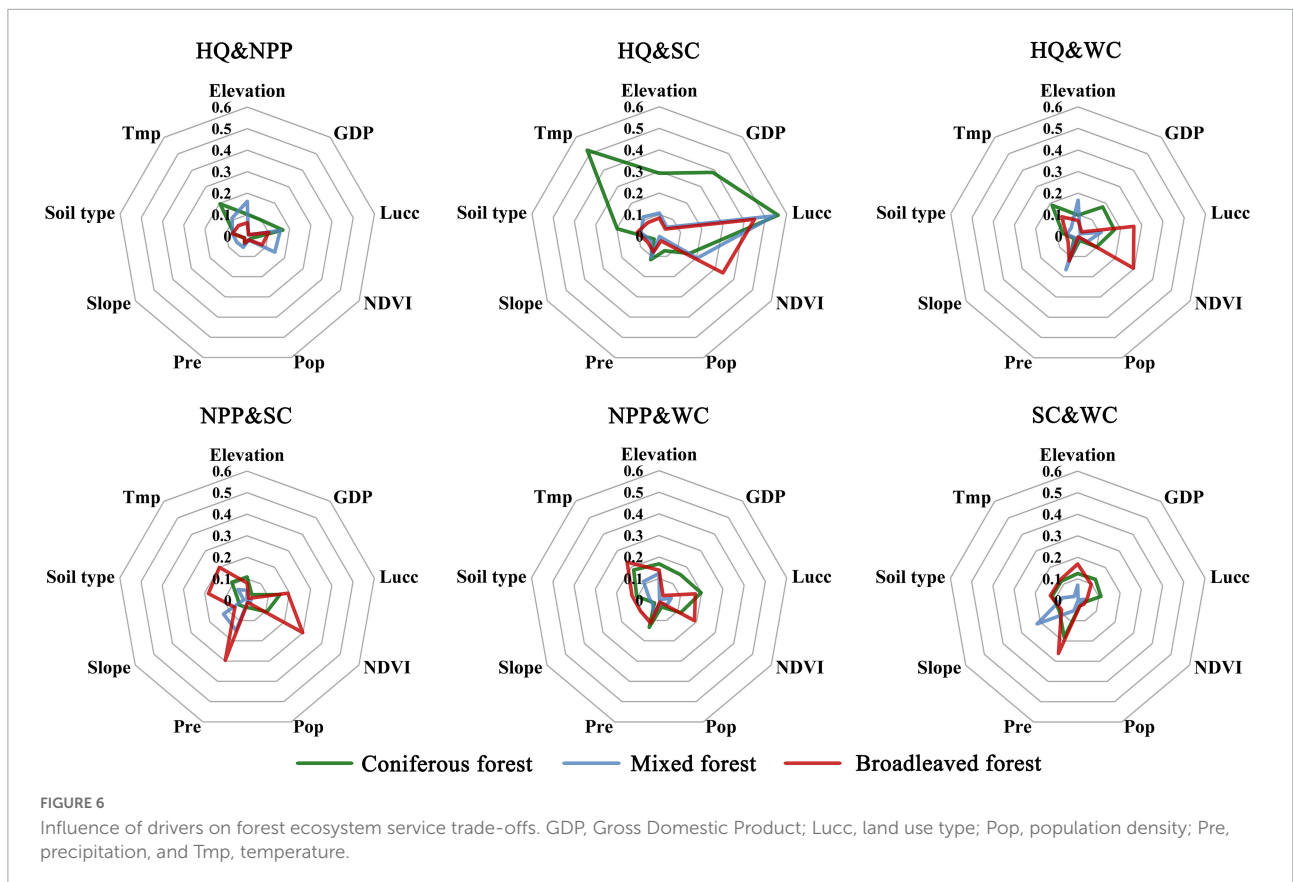
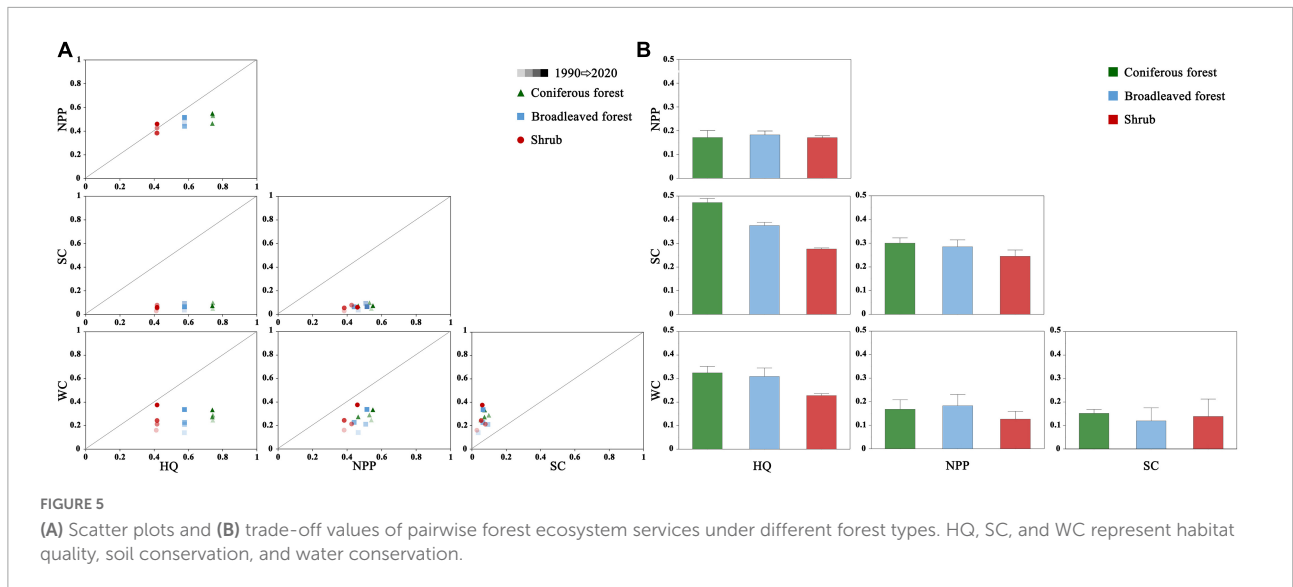
Overall, the effects of the drivers differed significantly among the three forest types (**Figure 6**). In coniferous, the explanatory power of temperature and land use on habitat quality and soil conservation trade-offs were significantly higher than other factors (52 and 55%, respectively). In broad-leaved, land use influenced habitat quality-soil conservation trade-offs most (54%). In shrubs, land use and NDVI influenced habitat quality-soil conservation tradeoffs more than the other factors (44 and 34%, respectively). The explanatory power of land use on habitat quality-soil conservation trade-offs (45%), habitat quality-water conservation trade-offs (32%),

NPP-soil conservation trade-offs (29%), and NPP water conservation trade-offs (31%) were higher than the other factors. Precipitation could explain 15, 30, and 26% of habitat quality-soil conservation, NPP-soil conservation, and soil conservation-water conservation trade-offs, respectively. It was noteworthy that habitat quality-NPP trade-offs were less influenced by the drivers. It might be related to the low trade-offs between them.

The average explanatory power of anthropogenic activities factors on ecosystem service trade-offs was 10%. This indicated a low influence of anthropogenic activities on forest ecosystem services. For environmental factors, the explanatory power of NDVI on trade-offs differed significantly among coniferous (9%), broad-leaved (8%), and shrubs (20%). The explanatory power of temperature on habitat quality-soil conservation trade-offs (52%) was considerably higher than on any other two ecosystem services. Moreover, soil type was of little importance to trade-offs. The result indicated that the influence of environmental factors on forest ecosystem service tradeoffs was regular and high variation from 1990 to 2020.

Discussion

Generally, ecosystem services in the Greater Khingan Mountains increased after NFCP implementation. This result was in line with the published research, which also indicated a crucial increase in forest ecosystems after the implementation of the NFCP (Wang et al., 2017; Mao et al., 2019). But soil conservation and water conservation decreased and then increased from 1990 to 2020. These two ecosystem services were more affected by rainfall factors (Wang and Dai, 2020). The rainfall instability exacerbated the change magnitude in these two ecosystem services before and after the NFCP implementation. The ecosystem services of the three forest types showed different degrees of increase after the NFCP implementation in this study. It increased more in broad-leaved than in the other two forest types, which may be related to spatial distribution and area of broad-leaved. The spatial distribution, interrelationships and, drivers of ecosystem services were impacted by spatial scale nature (He et al., 2019; Sun et al., 2020). It was notable that the trade-offs during the second phase of the NFCP increased more than during the first phase. The forest ecosystem gradually entered a period of rapid growth after the first decade of recovery, which was in line with the trend of secondary ecosystem evolution. In addition, the Chinese government paid more attention to forest protection in recent years. It launched several ecological restoration programs, for instance, the grain to green project, the three north shelter forest system project, and the national nature reserves (Mao et al., 2019). Moreover, great promotions of ecological civilization and increased public awareness of environmental protection were also important in promoting



the continuous improvement of forest ecosystems during the second phase (Zhao et al., 2017; Dong et al., 2021; Yang et al., 2021).

The forest ecosystem service trade-offs in coniferous and broad-leaved was higher than in shrubs. Published research has explored the ecosystem service's interrelationships in terms of spatiotemporal variations (Qiao X. et al., 2019; Qiu et al., 2021).

Nevertheless, few research investigated their discrepancies among different forest types. The results of this study indicated that the trade-offs in coniferous were higher than both in broad-leaved and shrubs. It may be due to their large distribution area and relatively low intensity of anthropogenic activities in coniferous. Coniferous was the highest total of ecosystem services than broad-leaved and shrubs. The high trade-offs in

coniferous were detrimental to the sustainability of ecosystem benefits (Bradford and D'Amato, 2012).

Ecosystem service trade-offs in various regions changed spatiotemporally after the ecological project implemented (Li et al., 2018; Qiao X. et al., 2019). The trade-offs between different ecosystem services were different in the Greater Khingan Mountains during 1990–2020. The trade-off relationships involving NPP increased, while the trade-offs related to water conservation decreased from 1990 to 2020. It has shown that understanding trade-off mechanisms requires an integrated consideration of multiple ecosystem services in one ecosystem (Bradford and D'Amato, 2012; Lu et al., 2014). The change rates of ecosystem services were not the same between 1990–2000 and 2000–2020 (Figure 3). Similar findings were reported for the spatiotemporal variances in other ecosystem services after ecological projects (Wang et al., 2021). Uneven changes in forest ecosystem services at different project phases might be the main reason for spatiotemporal variations of trade-offs.

The ecosystem service trade-offs were closely related to climatic factors (Runting et al., 2017; Qiu et al., 2021). Topographical and soil type factors also affected trade-offs to some extent (Feng et al., 2017). This study showed that the influence of environmental factors on trade-offs were more than anthropogenic activities in the Greater Khingan Mountains. This might be related to the different sensitivity of ecosystem service trade-offs to drivers in the Greater Khingan Mountains. The result was in line with published research (Wang et al., 2021; Chen et al., 2022). Generally, changes in forest ecosystems after the project were mainly influenced by environmental factors, rather than anthropogenic activities. However, certain anthropogenic activity factors had a crucial influence on trade-offs. For instance, land use was the most important factor on the trade-offs from 1990 to 2020. It was owing to the prominent effects of land use on four ecological services. The rapid spread of urbanization was an important reason for forest ecosystem destruction, and the transformation of land use types was closely connected with the rapid urbanization (Yang et al., 2020; Han et al., 2021). In addition, population density and GDP density were also significant driving factors in the trade-offs, which was consistent with previously published studies (Yang et al., 2017; Zhang et al., 2020).

Several limits ought to be recognized in this study. Firstly, although NPP, soil conservation, water conservation, and habitat quality were considered as the forest ecosystem services in the Greater Khingan Mountains, wood production was not involved. Because of corresponding data missing and inconsistent statistical calibration standards across provinces. There are some challenges to the rasterization of statistical data because the study area was not a complete administrative region. Secondly, due to the constraints of data collection, it is not possible to simulate ecosystem services with high accuracy due to the constraints of data collection. Finally, the RMSE approach could not accommodate the issue of non-linear interactions and

thresholds between forest ecosystem services (Qiao J. M. et al., 2019; Wang et al., 2021). Thus, inflection points and thresholds of ecosystem trade-offs should be investigated for the guidance of ecosystem management in the future.

Conclusion

The study evaluated the spatiotemporal changes of forest ecosystem service trade-offs and their drivers in the Greater Khingan Mountains after NFCP implementation. All of the ecosystem services in the three forest types increased after the project. The trade-offs between habitat quality and NPP, NPP and soil conservation increased, while the trade-offs between habitat quality and water conservation, NPP and water conservation, and soil conservation and water conservation decreased after the project. The ecosystem service trade-offs in coniferous was higher than in broad-leaved and shrubs. The explanatory power of the drivers (except for soil type) was significant different among the three forest types. The most important drivers for the trade-offs in coniferous and broad-leaved regions were land use, while the most important drivers were NDVI and precipitation in shrubs. Environmental factors affected the ecosystem service trade-offs more than anthropogenic activities in the Greater Khingan Mountains. Among all anthropogenic activity factors, land use was the most important one. Overall, exploring the ecosystem service trade-off changes after NFCP provides valuable insights for future policy development and subsequent ecological project implementation.

Data availability statement

The original contributions presented in this study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding author.

Author contributions

WC conceived the article. GJ and YD wrote the first draft. WC and SZ edited subsequent drafts. All authors contributed to the manuscript and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2022.978145/full#supplementary-material>

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