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Analyzing spatial patterns and driving factors of cropland change in China's National Protected Areas for sustainable management

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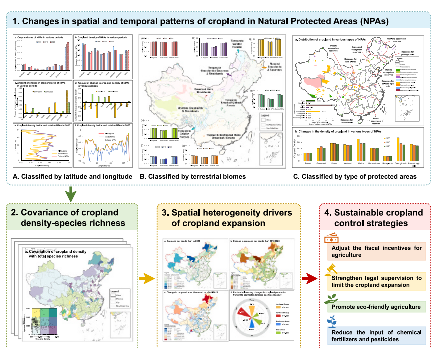
HIGHLIGHTS

- Changes in cropland area and density, along with regional driving factors in China's protected areas are examined.
- Cropland in China's National Protected Areas has increased consistently over the past two decades.
- High cropland densities are associated with dense populations and low rural education and income.
- The expansion of cropland in the Northeast and Northwest exacerbates biodiversity loss.
- Adverse natural conditions and deficient agricultural infrastructure drive cropland expansion in the Southwest.

GRAPHICAL ABSTRACT



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ABSTRACT

Farming in protected areas frequently challenges ecological conservation goals while supporting local livelihoods. To balance protection and agriculture, a comprehensive understanding of cropland dynamics in protected areas is of paramount importance. However, studies addressing this trade-off are relatively scarce, especially considering explicit Chinese government regulations on population relocation and cropland retirement in National Protected Areas (NPAs). Our study examined the spatial and temporal pattern of cropland in NPAs and explored the covariance between cropland density and species richness. Concurrently, the driving factors of cropland development in NPAs were analyzed using Multiple Linear Regression. The results indicate that the cropland area in NPAs continued to expand, growing from 1.93 to 2.34 million hectares in 2000–2020, with a cropland density of approximately 0.4. Cropland expansion in the northern NPAs, particularly in the resource-rich Northeast (28.12 %) and the Northwest with high marginal agricultural returns (38.26 %), have encroached upon species habitats and aggravated biodiversity loss. Moreover, cities with higher cropland densities in NPAs are usually located at borders, possibly due to decentralized management. The Multiple Linear Regression results show that high cropland density is usually associated with a high population density ($\beta = 0.156$) and lower levels of rural education ($\beta = -0.101$) and income ($\beta = -0.122$). To mitigate the issue of cropland development in NPAs, it is crucial to avoid one-size-fits-all management strategies, strengthen regional legal supervision, adjust fiscal incentives, and promote eco-friendly agriculture. In the north regions, the expansion of cropland in NPAs should be strictly controlled. For the southwest, the positive role of preserving

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cropland in NPAs for alleviating human-nature conflict and maintaining social stability should be emphasized. This study provides research support for China's exploration of geographically suitable strategies for controlling cropland in NPAs. Moreover, the findings could serve as a reference for the governance of NPAs in other countries.

1. Introduction

Since the Industrial Revolution, agricultural expansion has put a vast number of species at risk of extinction (Kehoe et al., 2017; Phalan et al., 2016). Tireless efforts have been made by the international community to preserve biodiversity. Aichi Biodiversity Targets 11 proposed to designate 17 % of global land as protected areas by 2020 (CBD, 2011). The United Nations Sustainable Development Goals (SDGs) 15 demand the protection, restoration and promotion of terrestrial ecosystems to address the issue of biodiversity loss (UN, 2015). Protected areas not only serve as refuges for threatened and endangered species (Coad et al., 2019; Laurance et al., 2012), but also provide ecosystem services such as climate regulation (Zabel et al., 2014), and tourism (Watson et al., 2014). However, in practice, protected areas may restrict the livelihood of local indigenous people and suffer threats from illegal cultivation, deforestation, and poaching (Ghimire and Pimbert, 1997; Liu et al., 2012). Balancing ecological conservation with cropland utilization in National Protected Areas (NPAs) is a complex issue (Vijay and Armsworth, 2021), with the core tension lying between global ecological product benefits and local residents' welfare (Xu et al., 2006). On one hand, cropland may be an essential guarantee for the survival of the indigenous residents in the protected areas (Vijay and Armsworth, 2021). On the other hand, land cultivation and chemical inputs could pose a severe threat to biodiversity (Silva et al., 2005; Alkan, 2009), leading to soil degradation, water pollution, and other environmental impacts. Exploring sustainable management strategies and balancing genuine ecological protection goals with local survival and developmental needs (Zhang et al., 2017) holds significant implications for achieving the objectives of protecting and restoring natural habitats outlined in the Millennium Development Goals and the UN Decade on Ecosystem Restoration.

The widespread existence of cropland in protected areas is a universal and difficult to eradicate global phenomenon. The extent of protected areas is about 21.66 million km^2, which accounts for 16.05 % of the global terrestrial land area (UNEP-WCMC and IUCN, 2023). As of 2018, there are approximately 6 million km^2 of protected areas worldwide with intensive human activities (Jones et al., 2018), posing significant obstacles to the achievement of the Convention on Biological Diversity's protection targets. The cropland area in these protected zones is around 1.4 million km^2 (Phalan et al., 2016). The total area of NPAs of China is about 0.98 million km^2 by 2020, with an internal cropland ratio of 2.4 %. Environmental goals are often squeezed by livelihood targets (He et al., 2018; Wu et al., 2011) due to the lack of quantitative assessment of cropland demand and carrying capacity of NPAs, imperfect management systems, and emphasis on operation over protection (Han, 2000). This problem manifests spatial heterogeneity due to the large number and scattered distribution of NPAs in China, intensifying management difficulty. Four possible reasons for the presence of cropland in protected areas were identified through a meta-analysis of multiple studies: (i) Cropland predates the establishment of the protected areas, with some initially designed specifically for cropland landscapes, making it difficult to move (Phalan et al., 2016). (ii) Corruption or poor management leading to inefficient protected area management (Watson et al., 2016). (iii) Owing to the lack of local finance and inadequate ecological compensation, residents are forced to cultivate cropland due to survival pressure (Han, 2000). (iv) Land ownership right is ambiguous, so residents consider the protected areas to be community resources that they have the right to cultivate (Phalan et al., 2016).

Agronomists, economists, and ecologists have studied agricultural expansion in protected areas from different perspectives. Desquilbet et al. (2017) have attempted to explain the motivation for farmers to cultivate land in protected areas using the Land Sparing and Land Sharing (LSS) framework, suggesting that extensive agriculture can alleviate agricultural pressure in protected areas. Vijay and Armsworth (2021) quantified the extent and influencing factors of agriculture in terrestrial protected areas globally, suggesting that changes in species and land use in protected areas should be given attention. Phalan et al. (2013) estimated the extent and potential of cropland in priority areas for tropical biodiversity conservation, recommending the stabilization of agricultural boundaries around protected areas through strengthened land-use planning and regulation. In addition, scholars have embarked on an exploration into various aspects such as the classification system of NPAs (Tang et al., 2019; Wang et al., 2004), species distribution (Hu et al., 2017; Zhang et al., 2020), human activities (Wan et al., 2015; Zhu et al., 2019), management effectiveness (Cheng and Ma, 2008; Quan et al., 2009; Xu et al., 2019a), and developmental contradictions (Huang et al., 2018; Liu et al., 2010; Xu et al., 2019b) of NPAs in China. However, most of the pertinent studies focus on the analysis of management practices in typical protected areas, with fewer involving empirical analysis of the global temporal and spatial processes of cropland in protected areas at the national scale, as well as their driving factors.

The aim of this study is to examine the spatial and temporal pattern and driving factors of cropland in NPAs, and to explore regional heterogeneities. Initially, a 1 km grid cropland density dataset was constructed by performing an upscaling conversion of GlobeLand30 dataset, with a 30-m resolution for 2000, 2010, and 2020. The changes in the spatial and temporal pattern of cropland within NPAs were then analyzed. Next, Pearson correlation coefficient was used to compare the relationship between cropland densities inside and outside NPAs of predominantly mountainous and plain cities. The covariate of cropland density and species richness was then evaluated. Finally, multiple linear regression was employed to simulate the combined driving effects of agricultural foundations, natural and social conditions on the cropland density in NPAs. The outcomes of this study can provide references for formulating regionally suitable cropland control policies in NPAs in terms of the balance between food demand and ecological conservation, and the causes of cropland development.

2. Materials and methods

2.1. Data and study area

The study involves three types of data (Table 1). The first category of data pertains to cropland. Cropland area data comes from the GlobeLand 30 surface cover dataset with a resolution of 30 m for the periods 2000/2010/2020 (Chen et al., 2016; Jun et al., 2014). The data quality of GlobeLand 30 is outstanding, particularly in its widely recognized high accuracy in cropland identification (Brovelli et al., 2015; Yang et al., 2017). Cropland density is characterized by the proportion of cropland area in the kilometer grid (Fritz et al., 2015; Yu and Lu, 2018; Ye et al., 2022a). The cropland density raster dataset is constructed by upscaling the cropland raster in the GlobeLand30 dataset, with the raster attribute value being the cropland area within the grid *(see Appendix Method)*.

The second category relates to ecological data. Map of terrestrial biomes originate from the Ecoregions 2017 © Resolve dataset (Dinerstein et al., 2017; Olson et al., 2001). The BiodiversityMapping database includes the species richness grid data of three types of vertebrates (birds in 2019, mammals in 2018, and amphibians in 2017) at a global resolution of 10 km (Jenkins et al., 2013; Pimm et al., 2014). The species richness raster dataset is generated by aligning and summing these three categories of vertebrate raster, with each grid cell representing the total count of birds, mammals, and amphibians.

The third category involves the analysis of factors influencing cropland density in NPAs in each province. Table 1 presents indicators representing the development levels in the social, economic, and agricultural sectors, such as population density and Gini coefficient (National Bureau of Statistics of China, 2021a, 2021b). Here, 1 km resolution grid data on cropland production potential is derived from a combination of datasets related to cropland distribution, soil properties, and elevation DEM in China. The estimation process employs the GAEZ model, which comprehensively accounts for multiple factors including sunlight exposure, temperature, moisture and topography (Fischer et al., 2021; Xu and Liu, 2017). Since the statistical data for the year 2000 is incomplete, missing data are replaced with data from adjacent years. The food self-sufficiency rate equals the ratio of total grain consumption to total grain production, where total grain consumption is estimated by multiplying the population by the per capita grain possession in China (400 kg/year·person) (Fig. 1).

2.2. Pearson correlation coefficient (PCC)

Pearson correlation coefficient (PCC) is selected to calculate the correlation of cropland density inside and outside NPAs, thereby exploring the driving force of external croplands on the degree of cropland development within NPAs. Pearson correlation coefficient is a method proposed by British statistician Karl Pearson in the 20th century to reflect the correlation between variables (Pearson, 1920; Lee Rodgers and Nicewander, 1988; Ren et al., 2023). Suppose there are two variables X and Y, and their linear correlation can be expressed by Pearson correlation coefficient $\rho_{X,Y}$, as shown in Eq. (1). Here, $\rho_{X,Y}$ ranges from -1 to 1, where $\overline{X}$ and $\overline{Y}$ stands for the mean values of the variables X and Y, respectively.

$$\rho_{X,Y} = \frac{\sum (X-\overline{X})(Y-\overline{Y})}{\sqrt{\sum (X-\overline{X})^2 \sum (Y-\overline{Y})^2}} \tag{1}$$

2.3. Multiple linear regression (MLR)

Multiple linear regression (MLR) is used to analyze the factors influencing the cropland density in NPAs in each province in 2000,

Table 1
Indicators and data sources.

Categories	Indicators	Explanations	Datasets	Data type	Year
cropland-related data	*CA*	cropland area	GlobeLand 30 surface cover dataset (Chen et al., 2016; Jun et al., 2014)	30 m raster	2000/2010/2020
	CD	cropland density	cropland density dataset (Ye et al., 2022a)	1 km raster	2000/2010/2020
	–	land use change	GlobeLand 30 surface cover dataset (Chen et al., 2016; Jun et al., 2014)	30 m raster	2000/2010/2020
	–	DEM (digital elevation model)	SRTM DEM dataset (NASA, 2000)	250 m raster	–
ecology-related data	–	boundaries of NPAs	China Nature Reserves Biological Specimen Resources Sharing Platform (www.papc.cn)	vector	2000/2010/2020
	–	biomes	Ecoregions 2017 © Resolve database (Dinerstein et al., 2017; Olson et al., 2001)	vector	2017
	–	species richness	BiodiversityMapping database (Jenkins et al., 2013; Pimm et al., 2014)	10 km raster	Birds 2019 Mammals 2018 Amphibians 2017
explanatory Variables: data related to influencing factors	*CPP*	cropland production potential	Resource and Environmental Science Data Center (Xu and Liu, 2017)	1 km raster	2010
	PD	population density	Resource and Environmental Science Data Center (Xu, 2017)	1 km raster	2000/2010/2019
	PD_{NPA}	population density in NPAs	Resource and Environmental Science Data Center (Xu, 2017)	1 km raster	2000/2010/2019
	GDP	per capita GDP in rural areas	China Statistical Yearbook (National Bureau of Statistics of China, 2021a)	province	2000/2010/2020
	SSR	grain self-sufficiency rate	China Statistical Yearbook (National Bureau of Statistics of China, 2021a)	province	2000/2010/2020
	GI	Gini coefficient	China Statistical Yearbook (National Bureau of Statistics of China, 2021a)	province	2000/2010/2020
	AW	per capita agricultural water usage	China Statistical Yearbook; China City Statistical Yearbook (National Bureau of Statistics of China, 2021a, 2021b)	province; city	2002/2010/2020
	RE	per capita electricity usage in rural areas	China Statistical Yearbook; China City Statistical Yearbook (National Bureau of Statistics of China, 2021a, 2021b)	province; city	2000/2010/2020
	FI	per capita income of farmers	China Statistical Yearbook; China City Statistical Yearbook (National Bureau of Statistics of China, 2021a, 2021b)	province; city	2000/2010/2020
	EY	year of education in rural areas	China Statistical Yearbook; China City Statistical Yearbook (National Bureau of Statistics of China, 2021a, 2021b)	province; city	2001/2010/2020
	AG	agricultural GDP share	China Statistical Yearbook; China City Statistical Yearbook (National Bureau of Statistics of China, 2021a, 2021b)	province; city	2000/2010/2020
	TR	terrain relief	China 1:1million DEM dataset (Feng et al., 2007)	province; city	–
	GI_{Rural}	Gini coefficient in rural areas	China City Statistical Yearbook (National Bureau of Statistics of China, 2021b) DMSP & VIRRS dataset (Lv and Cui, 2020)	city	2020
	GDP_{City}	per capita GDP in cities	China City Statistical Yearbook (National Bureau of Statistics of China, 2021b)	city	2020
	YE	average establishment year of NPAs	China Nature Reserves Biological Specimen Resources Sharing Platform (www.papc.cn)	province; city	1956–2020

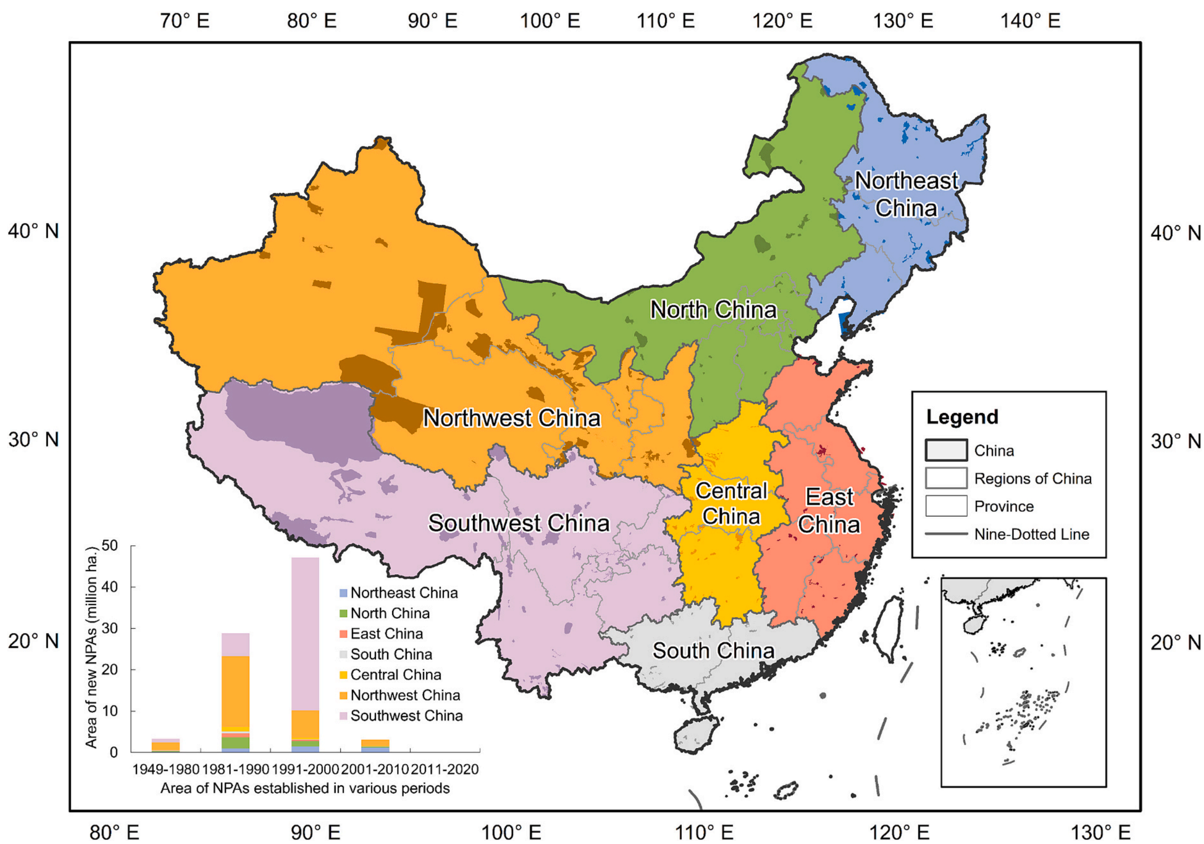

Fig. 1. Spatial distribution of NPAs divided by geographical region in China. The darker-colored shapes within each region represent the boundaries of NPAs. China's NPAs were mainly distributed in the Southwest (53 %) and Northwest (33 %) in 2020. NPAs established in the 1980s accounted for 35 % of the total area, primarily attributed to the establishment of the Lop Nur Bactrian Nature Reserve and the Altunshan Nature Reserve in Xinjiang Province. NPAs established in the 1990s accounted for 57 % of the total area, largely due to the establishment of the Chang Tang Nature Reserve in Tibet Autonomous Region and the Hoh Xil Nature Reserve in Qinghai Province in the Southwest.

2010, and 2020 (Aiken et al., 2003; Jin et al., 2024). The basic form of multiple linear regression is shown in Eq. (2). Here, y indicates the dependent variable and $x_1, x_2, \dots, x_n$ are the independent variables. β_0, $\beta_1, \beta_2, \dots, \beta_n$ are the regression coefficients, and ε is the error term.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \varepsilon \tag{2}$$

The least squares method allows estimating the regression coefficients to minimize the sum of squares of the errors, as shown in Eq. (3). where $\widehat{y_i}$ is the predicted value obtained by the linear combination of the independent variables $x_1, x_2, \dots, x_n$.

$$\sum_{i=1}^{n} (y_i - \widehat{y_i})^2 = \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_{i1} - \beta_2 x_{i2} - \dots - \beta_n x_{in})^2 \tag{3}$$

The regression coefficients in the multiple linear regression model can be solved using matrix methods. X stands for an $n \times (m+1)$ matrix where n denotes the number of samples, and m denotes the number of independent variables. The i-th row of X is $(1, x_{i1}, x_{i2}, \dots, x_{im})$, and Y is an $n \times 1$ vector of dependent variables. Thus, the multiple linear regression model can also be expressed as follows in Eq. (4). where β is the vector of regression coefficients for $(m+1) \times 1$ and ε is the error vector for $n \times 1$.

$$Y = X\beta + \varepsilon \tag{4}$$

The least squares solution for β can be solved using matrix methods, as shown in Eq. (5). Where X^T is the transpose matrix of X. If $X^T X$ is invertible, then a least squares solution exists and is unique.

$$\beta = (X^T X)^{-1} X^T Y \tag{5}$$

In this study, 14 potential explanatory factors that influence the cropland density CD_{NPA} in NPAs in each province are identified, thus resulting in 2^{14} possible models. The model containing all potential explanatory variables is shown in Eq. (6). Here, *CD* and *PD* are the cropland density and population density of a province. *AG* represents the agricultural GDP share. *AW* represents the per capita agricultural water usage. *CPP* is the cropland production potential. *EY* is the year of education in rural areas. *FI* is the per capita income of farmers. *GDP* is the per capita GDP in rural areas. *GI* is the Gini coefficient. *RE* is the per capita electricity usage in rural areas. *SSR* is the grain self-sufficiency rate. *YE* is the average establishment year of the NPAs. *TR* is the average terrain relief.

$$\begin{aligned} lnCD_{NPA} = {} & \beta_0 + \beta_1 lnCD + \beta_2 lnPD + \beta_3 lnPD_{NPA} + \beta_4 AG + \beta_5 AW + \beta_6 CPP \\ & + \beta_7 EY + \beta_8 FI + \beta_9 GDP + \beta_{10} GI + \beta_{11} RE \\ & + \beta_{12} SSR + \beta_{13} YE + \beta_{14} TR \end{aligned} \tag{6}$$

To measure the goodness of fit of each model, the *AIC* (Akaike, 1974; Anderson, 2008) of the 2^{14} models are calculated, and the model corresponding to the smallest *AIC* value is the best model *(see Appendix Method)*. Population density and cropland density in provinces and NPAs are performed logarithmic transformation. To ensure the normality of the data distribution and comparability among variables, Z-score standardization on other potential influencing factors except cropland density are carried out.

3. Results

3.1. Changes in spatial and temporal patterns of cropland in NPAs

The temporal and spatial patterns of cropland in NPAs of mainland China, classified by various natural geographic partitions, and the cropland density inside and outside of the NPAs divided according to longitude and latitude are analyzed. The cropland area in NPAs continuously expanded (Fig. 2c), rising from 1.93 million hectares to 2.34 million hectares during 2000–2020 (Fig. 2a, and *see Appendix Data* for detailed data). Over these two decades, cropland expansion was concentrated in Central and North regions, accounting for 99.61 % of the total increase (Fig. 2c). The total cropland area in NPAs exceeded 2 million hectares after 2010, with both the Northeast and Northwest regions surpassing 0.5 million hectares (Fig. 2a). The nationwide average cropland density within NPAs follows a pattern of initial decline, dropping from 0.40 in 2000 to 0.38 in 2010, and subsequently rebounding to 0.39 in 2020 (Fig. 2b, d). The cropland densities in NPAs in the Northeast (>0.50) and Northwest (>0.40) remained the highest from 2000 to 2020, consistently exceeding the national average, whereas the lowest cropland densities were in Southwest and South China (0.30). From 2000 to 2010, the cropland density in NPAs in all regions, except Central China, decreased. From 2010 to 2020, the cropland density in NPAs in North China (0.037), East China (0.026), and South China (0.022) increased more significantly. The cropland density inside and outside of NPAs, as accounted for by longitude and latitude, is shown in Fig. 2e, f. Results reveal substantial spatial disparities in cropland density. The cropland density outside NPAs is

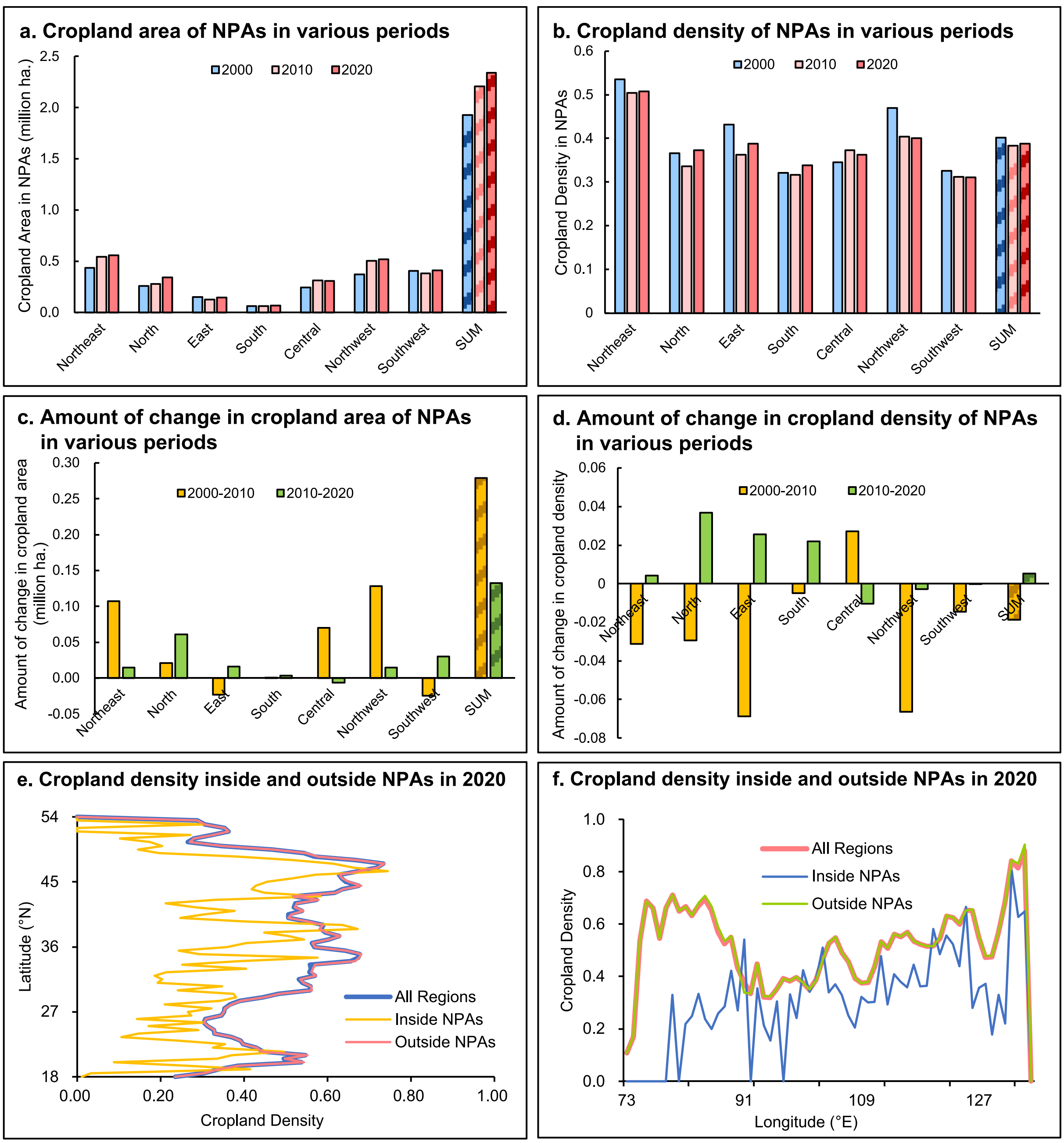

Fig. 2. Spatial and temporal pattern of cropland in China's NPAs. (a) cropland area; (b) cropland density; (c) change in cropland area; (d) change in cropland density; (e) change in cropland density across different latitude intervals, span of 0.5°; (f) change in cropland density across different longitude intervals, span of 1°. Darker bars in Fig. (a)-(d) represent national averages.

roughly equivalent to the overall and is generally higher than that inside NPAs (Fig. 2e, f). The differences in cropland density between the inside and outside of NPAs in the north (32°-54°N) and east (90°-135°E) are relatively small. However, in the south (18°-32°N) and west (73°-90°E), the cropland density inside NPAs is markedly lower than outside. The highest cropland density appears at the border of Inner Mongolia Autonomous Region and Jilin Province at 47°N (Fig. 2e) and in the eastern part of Heilongjiang Province at 132°E (Fig. 2f).

Across all biomes, the cropland density outside NPAs is roughly equivalent to the overall and is higher than that inside NPAs. Spatially, cropland density in NPAs exhibits a latitudinal zonality, decreasing progressively from north to south (Fig. 3). Within the biomes of North China, the cropland densities of NPAs are usually high, which is an evident sign of agricultural expansion issues (Liu et al., 2019). Due to the high cropland density in flooded grasslands & savannas and deserts & xeric shrublands (0.68 and 0.61, respectively), these two biomes emerge as pivotal zones for future ecological restoration and cropland management. In contrast, NPAs in forest biomes exhibit generally lower cropland densities. This stems from the rigorous management measures directed towards forest protected areas by the state, making the cost of land development in NPAs significantly higher in relation to grasslands and wetlands (Xu et al., 2016). Over time, NPAs located in desert & Xeric shrublands have seen an initial increase, followed by a decrease in cropland density, with a slight variation of 0.018 (Fig. 3). The cropland densities of NPAs in all other biomes fluctuate in synchrony with changes outside their boundaries. Two coastal biomes, tropical & subtropical moist broadleaf/forests (−0.017) and temperate broadleaf & mixed forests (−0.031), have witnessed a consistent reduction in cropland density year over year. Cropland densities within other biomes have first seen a reduction and then an increase.

Protected areas represent an equilibrium of ecosystem, species, economy, population, and land use (Volis, 2018; Zhao et al., 2022). Cropland densities inside and outside NPAs, classified by NPA categories in China is displayed in Fig. 4. The result shows that it is necessary to

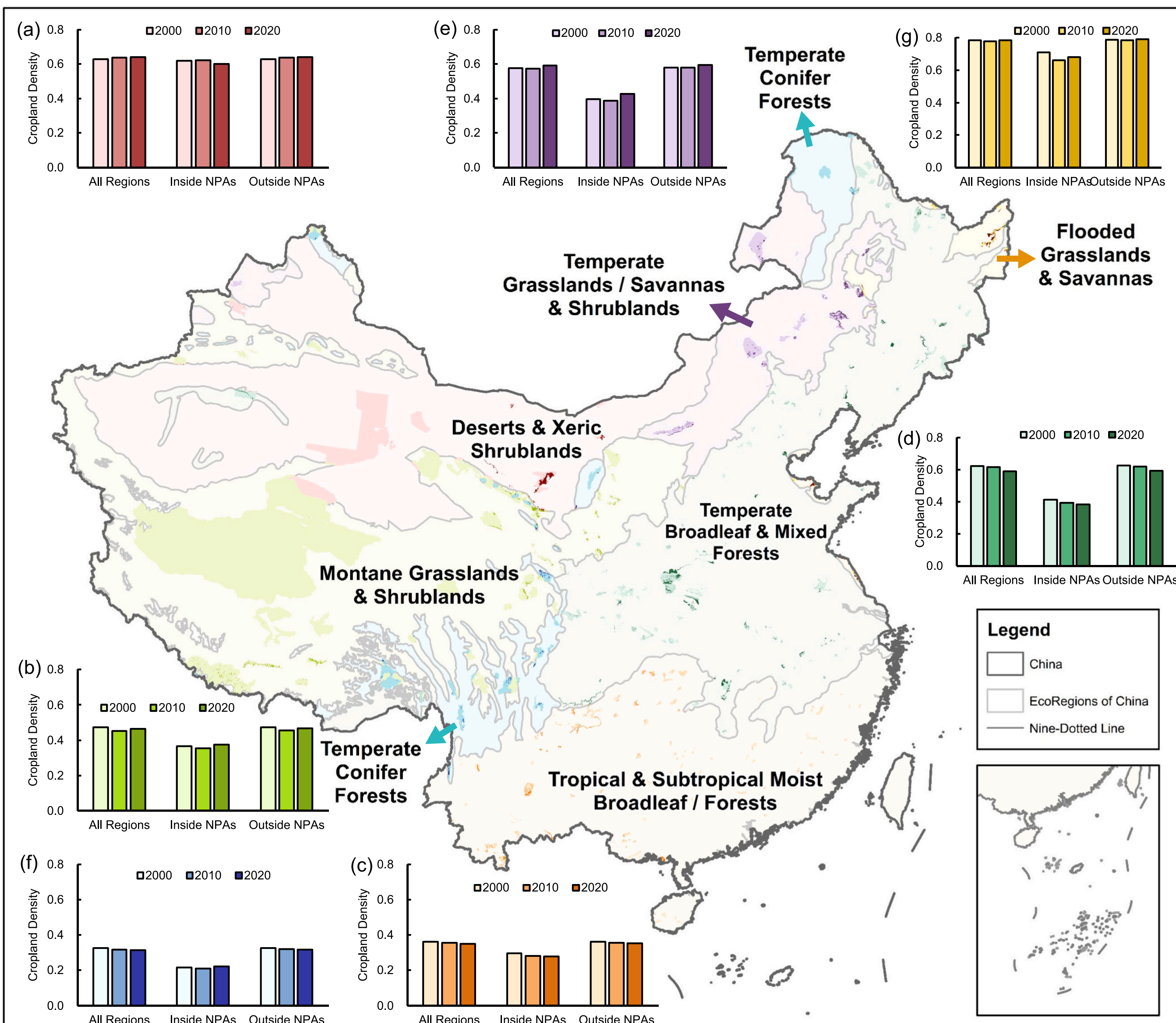

Fig. 3. Changes in Cropland Density in NPAs Across Different Terrestrial Biomes and Their Spatial Distribution. The 7 Terrestrial Biomes in China include: (a) Deserts & Xeric Shrublands, (b) Montane Grasslands & Shrublands, (c) Tropical & Subtropical Moist Broadleaf Forests, (d) Temperate Broadleaf & Mixed Forests, (e) Temperate Grasslands, Savannas & Shrublands, (f) Temperate Conifer Forests, (g) Flooded Grasslands & Savannas (Dinerstein et al., 2017). The lightest area represents terrestrial biomes, the darker area denotes NPAs, and the depth of color in NPAs indicates the internal cropland density.

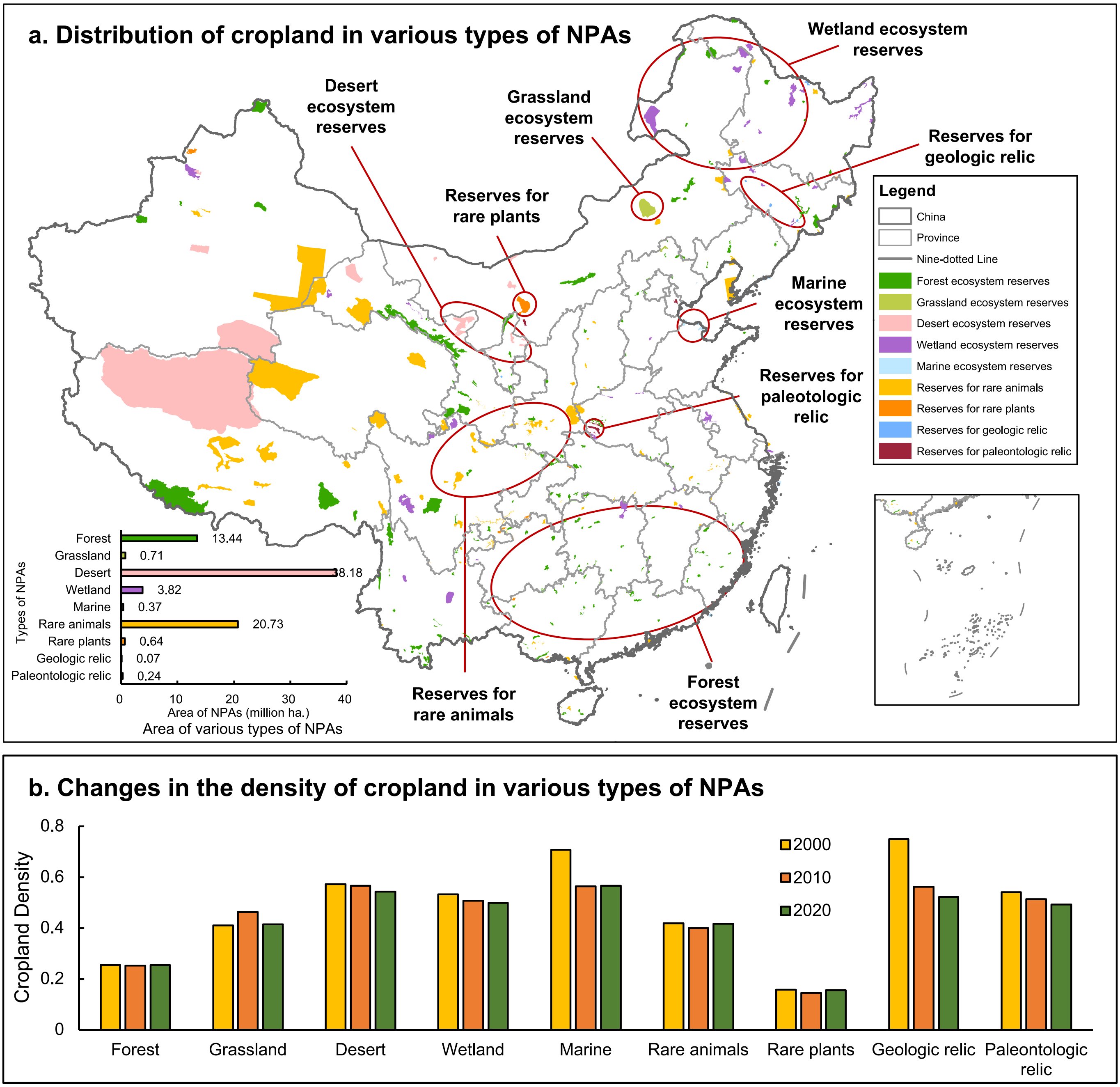

Fig. 4. Changes and Spatial Distribution in Cropland Density in Different Types of NPAs. China has three types of NPAs: (1) natural ecosystem reserves, including forest, grassland, desert, wetland, as well as marine, (2) reserves for wildlife, including rare animals and rare plants, and (3) reserves for natural heritage, including geological relic and paleontological relic (Wang et al., 2004).

develop cropland control systems for different types of protected areas. In the four categories of NPAs where protection laws or regulations are already established, cropland density remains <0.5 (Fig. 4b). While for categories lacking legal protection, such as deserts, marines, and wetlands, there is an urgent need for legislation to enhance cropland management measures. To be specific, presently, explicit rules have been laid out for the protection of Nature Reserves, Wild Plants, Forests, Grasslands, and Wild Animals (State Council, PRC, 1994, 1996; National People's Congress, PRC, 1984, 1985, 1988). Notably, West Erdos Nature Reserve, primarily protecting ancient endangered plants (Zhu et al., 1999), has a cropland density of 0.15 (Fig. 4a, in orange). NPAs for forest ecosystem have a cropland density of merely 0.25. Other NPAs with cropland densities consistently above 0.5 lack relevant protection regulations, but display a gradual downward trend (Fig. 4b). For instance, NPAs of paleontologic relic (0.75) and marine ecosystems (0.71) exhibited high cropland density in 2000. Over two decades, the cropland density in these two types of NPAs has decreased to <0.6. By 2020, regulations for the protection and management regulations for natural ecosystems such as wetlands, deserts, and marine zones are still lacking. Especially, the desert NPAs, accounting for 49 % of the total area of NPAs (Fig. 4a), face serious issues such as unsustainable agricultural practices and water security (Shaumarov et al., 2012) and have long been overlooked and inadequately protected. To achieve ecological governance and sustainable development for NPAs of all types, national-level management regulations which restrict the reclamation of cropland need to be improved and supplemented urgently.

3.2. The relationship between cropland density inside and outside NPAs

From 2000 to 2020, a statistic examination was conducted on cropland densities inside and outside NPAs for cities in China. Geographically, only a handful of cities have NPAs with higher cropland densities than the areas outside them (Fig. 5a-c). These cities are typically located along national borders or where three provinces intersect. This implies potential food security issues in these border cities, which can be attributed to two factors: (1) Tensions over human-nature relations. On one hand, the borders of China's provinces are often divided by mountain ranges and river directions. NPAs in border cities are typically located in remote mountainous regions with poor accessibility (Fan et al., 2022). On the other hand, NPAs located in peripheral regions face significant population pressure and development demands (Han, 2000). The siphon effect cause policy and capital resources to lean towards large cities (Yao et al., 2021). Furthermore, officials in border areas, driven by bureaucratic inertia or local protectionism, often lack long-term planning for local economies, thus exacerbating underdevelopment. (2) Inefficiency due to interdepartmental coordination. For NPAs managed jointly by several provinces, planning and management require close coordination among multiple government departments (Volis, 2018). Different regulatory standards across departments, conflicting interests, and a lack of effective communication result in unclear responsibilities and management chaos (He et al., 2018; Volis, 2018; Xie et al., 2014).

In terms of temporal changes, cropland has gradually been retired within the NPAs in Xinjiang Uyghur Autonomous Region and Qinghai Province over the past 20 years, while a high proportion of cropland has emerged in the NPAs in Tibet Autonomous Region. The ratio of cropland density inside and outside the NPAs in other regions has remained relatively stable. Several cities in Xinjiang Uyghur Autonomous Region had a certain amount of cropland in NPAs in 2000 (Fig. 5a). These croplands gradually disappeared, and cropland appeared in the NPAs at the border between Heilongjiang Province and Inner Mongolia Autonomous Region after 2010 (Fig. 5b). By 2020, cropland expansion had occurred in NPAs of all cities in Tibet Autonomous Region. Notably, the cropland densities in the NPAs of Chamdo (1.64) and Ngari (1.60) were significantly higher than outside (Fig. 5c). Research by Hua et al. (2022) also confirmed that NPAs in Tibet Autonomous Region are facing prominent issues of agricultural expansion. Moreover, cities like Dandong in Liaoning Province (1.87), Gannan in Gansu Province (1.52), Chizhou in Anhui Province (1.51), and Shangluo in Shaanxi Province (1.50) have significantly higher cropland densities inside the NPAs compared to outside. And the human-nature relations in these NPAs also need to be given due attention.

In order to investigate the impact of topography on cropland density inside and outside of NPAs, we conducted slope calculations based on DEM data. In accordance with the *Technical Regulations for Land Use Status Survey* (1984), an average slope of <6° is classified as flat cropland. We classified cities into two categories: those predominantly

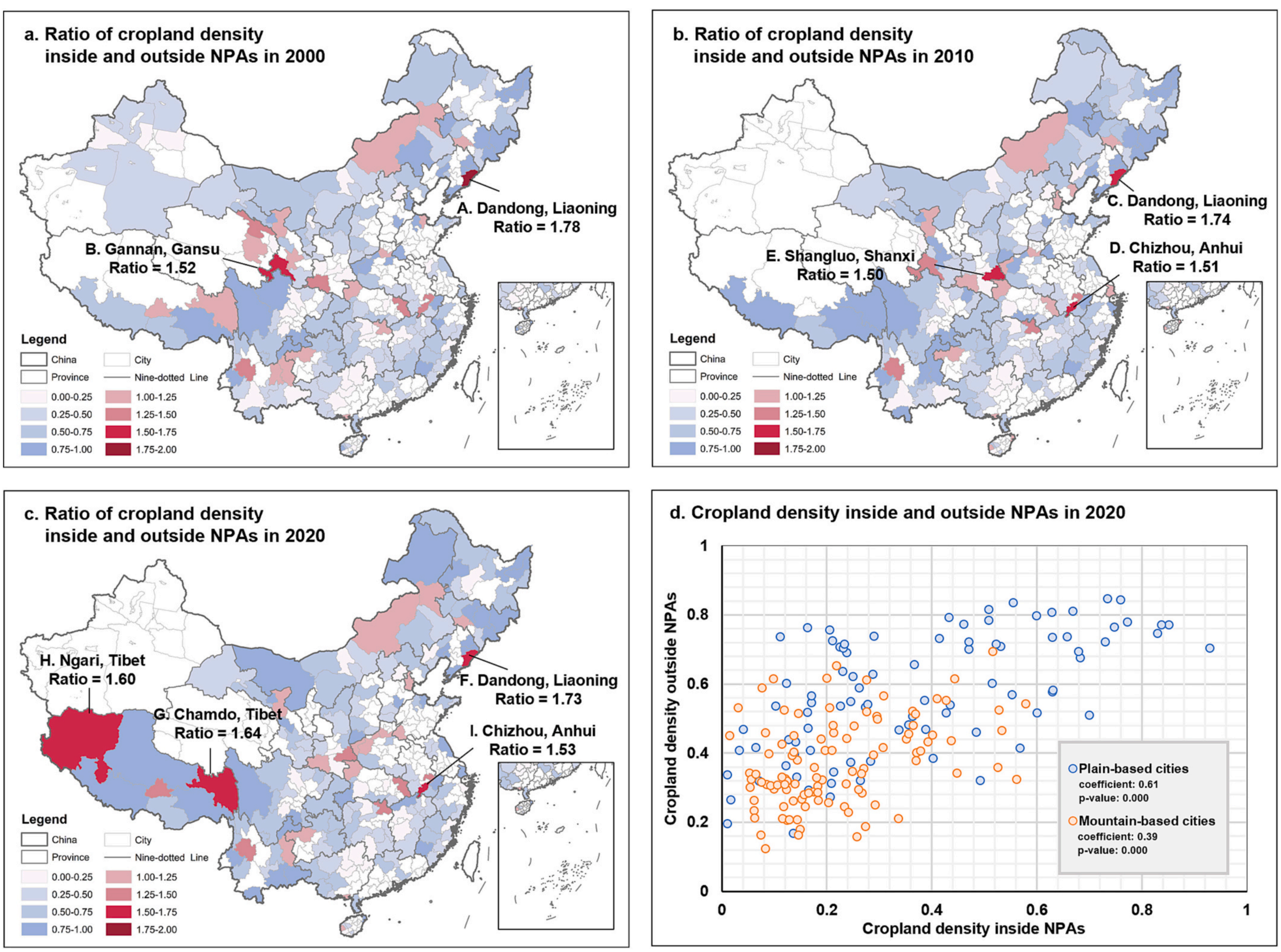

Fig. 5. Change in cropland density inside and outside NPAs. Fig. (a)-(c) show the ratio of cropland density inside and outside the NPAs during 2000–2020. The darker the color, the larger the ratio. Blue means the ratio is <1, while red means the ratio is >1. Blue dots represent plain cities, orange dots represent mountainous cities in Fig. (d).

located in plains and those mainly in mountains. Pearson correlation analysis was performed for the cropland density inside and outside of NPAs in 2020 for these two types of cities (Fig. 5d). The results show that the correlation between the cropland density inside and outside NPAs in plain cities ($r = 0.61$, $p < 0.001$) is higher than in mountainous cities ($r = 0.39$, $p < 0.001$). The flat terrain and superior natural endowments of plain cities result in higher connectivity and stronger interaction between inside and outside of NPAs. The difficulty of implementing protective measures to limit cropland is greater consequently. Conversely, NPAs in mountainous cities are less connected to the outside world due to rugged terrain and inconvenient transportation, and the correlation between internal cropland density and external factors is relatively small.

3.3. Covariance of cropland density-species richness in NPAs

To overlay the species richness of three vertebrate groups (birds, mammals and amphibians) on a 10 km grid, we obtain data for four classes of species richness. The results indicate a trade-off between food production and biodiversity conservation (Fig. 6a-d). The covariance between cropland density and total species richness has polarized characteristics (Fig. 6a). On one hand, NPAs located in the southwest, south, and northwest generally display low cropland density ($\leq$0.31) and high species richness (>232). The southwestern mountains, as important biodiversity hotspots in China (Xu and Wilkes, 2004), have a lower intensity of cropland utilization (Ye et al., 2022b), so agriculture poses less of a threat to protected species. On the other hand, NPAs in the eastern Inner Mongolia Autonomous Region and north exhibit high cropland density (>0.31) and low species richness ($\leq$232). Cropland cultivation in these areas often accompanies excessive use of chemical fertilizers and pesticides, leading to soil pollution and fragmentation of wetland landscapes (Zhao et al., 2013; Ren et al., 2022). Unreasonable cropland utilization behavior should be strictly controlled. Moreover, a few NPAs with high species richness (>232) display high cropland density (>0.62). For example, the northeastern region is rich in biological resources and hosts largest wetland group in China (Liu et al., 2004). However, long-term large-scale farming has disrupted the ecological balance (Wang et al., 2005). The conflict between wildlife and cropland in these areas is intense, and it's urgently needed to reduce the intensity of cultivation through eco-friendly agricultural methods (Ewers et al., 2009; Green et al., 2005; Zhang et al., 2017).

The covariance relationships between the species richness of three other classes and cropland density are showed in Fig. 6. The results indicate that the covariance relationship between threatened species

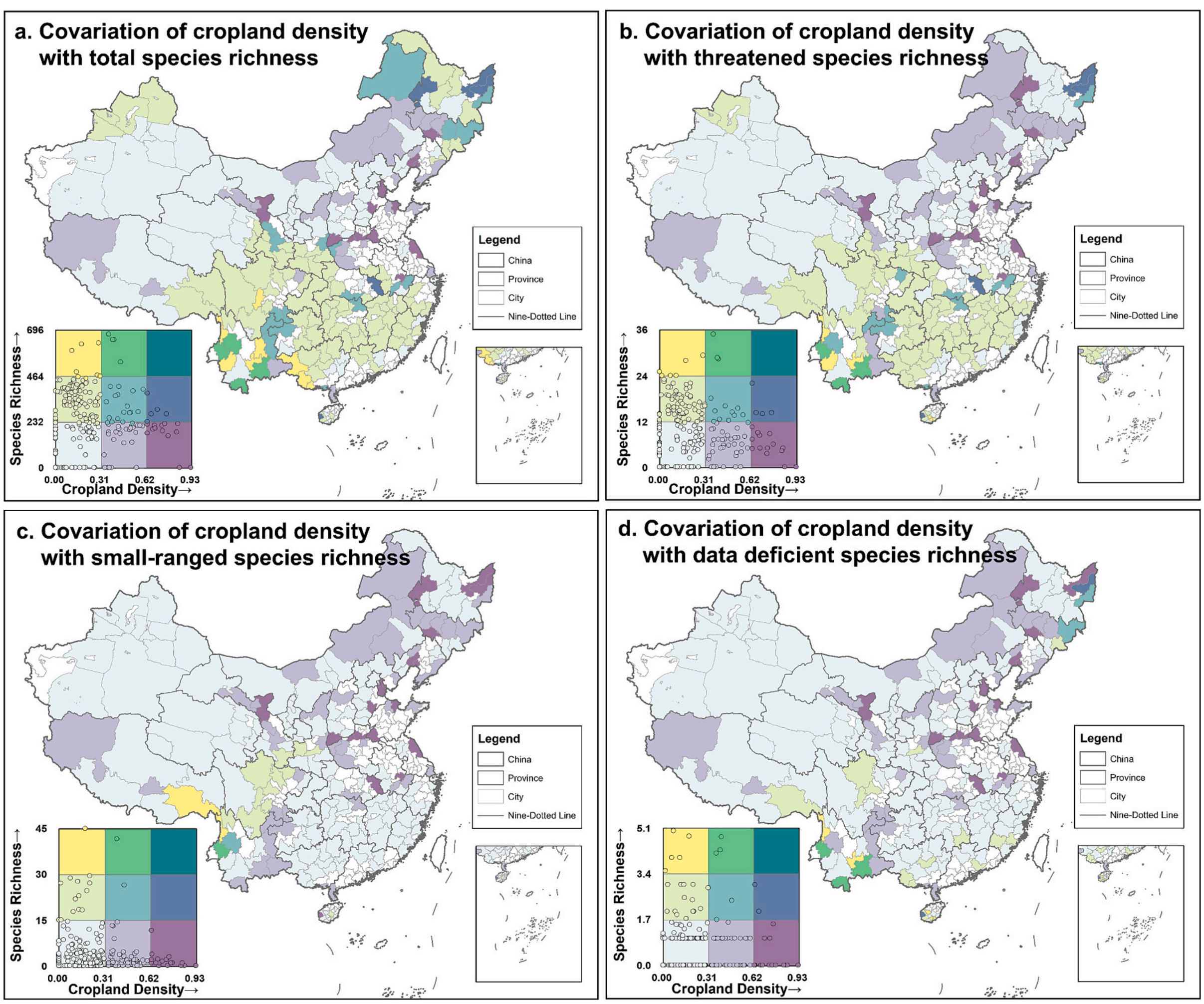

Fig. 6. Covariation of cropland density with species richness of three vertebrate species (birds, mammals and amphibians) in NPAs of China. The relationship between cropland density and (a) total species richness, (b) threatened species richness, (c) small-ranged species richness, and (d) data deficient species richness is respectively illustrated through maps and scatter plots. Threatened species are those considered vulnerable, endangered, or critically endangered in the International Union for Conservation of Nature's Red List (IUCN, 2010; Jenkins et al., 2013). Small-ranged species are those with a geographic range size smaller than the global median (i.e., the 50 % of species with the smallest ranges). Data deficient species are those with inadequate information to make a direct, or indirect, assessment of its risk of extinction based on its distribution and/or population status (Bland et al., 2017).

richness and cropland density (Fig. 6b) shows a distribution similar to that of total species richness (Fig. 6a). The covariance relationships between the species richness of the other two classes and cropland density generally present a high cropland density and low species richness pattern (Fig. 6c, d). This implies that habitats of small-ranged and data deficient species, particularly protected areas for wildlife, necessitate stricter and localized conservation measures. Otherwise, severe species extinction and biodiversity loss are imminent (Jenkins et al., 2013). Particular attention should be paid to the impact of croplands on local specialist species by designating priority conservation areas, rigorously limiting the scale of cultivation, and thoroughly assessing the effectiveness of conservation actions (Vijay and Armsworth, 2021).

3.4. The combined effect of natural-economic-social factors driving cropland density in NPAs

The contribution of 14 explanatory factors, including average cropland density and population density in each province, to the development of cropland density in the NPAs in 2000, 2010 and 2020 was analyzed by multiple linear regression. The results (Table 2) indicated that 10 explanatory factors were included in the final model, and all factors passed the significance test with $p < 0.05$. The cropland development density in NPAs is collectively driven by natural backgrounds, social conditions, and agricultural economic foundations.

China's resource endowments of high population and limited land, along with regional differentiation based on climate, terrain, economy, society, and culture, render the reasons for the extensive presence of croplands in NPAs more complex. On one hand, for provinces endowed with good cropland resources, that is, areas with high average cropland density ($\beta = 1.001$) and high potential for agricultural production ($\beta = 0.223$), cropland density tends to be higher in NPAs. This implies that cropland development in NPAs is primarily influenced by local natural endowments and cultural traditions. On the other hand, in impoverished regions with high Gini coefficients ($\beta = 0.063$) and low per capita farmer income ($\beta = -0.122$), local farmers will cultivate more cropland to secure basic livelihoods. This phenomenon is more prominent in areas with high population density in protected areas ($\beta = 0.156$). The exploitation of these croplands is often extensive, as indicated by the significant negative correlation between per capita agricultural water use ($\beta = -0.303$) and cropland density in protected areas. Therefore, increasing the educational level ($\beta = -0.101$) and per capita income of farmers, and reducing the population density in protected areas can help control the cropland development density in NPAs.

4. Discussion

4.1. Patterns of cropland expansion in NPAs

The establishment of protected areas aims to maximally safeguard natural ecosystems and biodiversity (Wade et al., 2020). Hence, local agricultural activities are usually stringently restricted, such as ecological retreat in core areas in NPAs (Zhang et al., 2017). However, this research shows that over 2 million hectares of cropland still exist in China's NPAs currently, and the trend is escalating, consistent with findings by Xu et al. (2016) and Zhao et al. (2013). Specifically, the NPAs in the northern biomes in China have a larger cropland density than those in the tropical and subtropical biomes of the south. Grain cultivation is not profitable in most areas, and only yields marginal profits in the northern regions. However, due to the relatively weaker economic development in the North, the opportunity cost of farming is lower. Consequently, farmers tend to irrationally expand their

Table 2
Analysis of the driving effect of different factors on cropland density in NPAs. Those marked in green are positive drivers, i.e. an increase in this factor promotes an increase in cropland density. Those marked in red are negative drivers, i.e. a decrease in this factor promotes an increase in cropland density. The coefficients (β) of all factors were standardized and passed the significance test of $p < 0.05$.

Explanatory Factors	Standardized Coefficient (β)	Standard Deviation	t-test	p-test
cropland density	1.001	0.113	8.87	0.000***
population density	-0.443	0.085	-5.23	0.000***
population density in NPAs	0.156	0.071	2.20	0.030*
cropland production potential	0.223	0.036	6.28	0.000***
Gini coefficient	0.063	0.026	2.42	0.018*
per capita income of farmers	-0.122	0.054	-2.27	0.026*
year of education in rural areas	-0.101	0.043	-2.33	0.022*
per capita GDP in rural areas	0.184	0.045	4.11	0.000***
per capita electricity usage in rural areas	0.154	0.038	-4.03	0.000***
per capita agricultural water usage	-0.303	0.119	2.55	0.013*

cultivated land area to increase their income (Ye et al., 2020). Severe cases of corn plantation encroachments have occurred in NPAs in Inner Mongolia Autonomous Region and Gansu Province (Xu et al., 2016). Moreover, NPAs such as deserts, wetlands, and coastal areas, which lack specific protection regulations, bear significant ecosystem functions and services. However, these NPAs often suffer from severe issues of landscape fragmentation and cropland expansion (Zhao et al., 2013). Therefore, adjusting financial incentives and establishing stringent control measures could be an effective means of curbing unregulated expansion of cropland in NPAs. The study by Varsha et al. has corroborated that the proportion of cropland in NPAs, as classified by IUCN, tends to be lower where management measures are more stringent (Vijay and Armsworth, 2021).

This research indicates that regions with higher cropland density in NPAs, often located at national borders or tri-provincial junctions, typically exceed that of surrounding cities. This may be the result of both the conflict between people and land caused by geographical location and inefficient implementation due to decentralized management. Furthermore, it seems that high cropland density and high species diversity struggle to coexist in NPAs. This suggests that biodiversity and food security often present a trade-off, a conclusion consistent with Varsha's research (Vijay and Armsworth, 2021). The combined characteristics of high species richness-low cropland density and low species richness-high cropland density show a polarized geographical divergence. The expansion of cropland in NPAs in the north has encroached on species habitats and exacerbated biodiversity loss compared to the south. In NPAs with high cropland density, employing breeding and biotechnology, reducing the input of fertilizers, pesticides, and insecticides, as well as enhancing crop efficiency in the usage of nitrogen, phosphorus, and water can mitigate these challenges. Additionally, managing soil organic matter and microbial communities to restore soil fertility (Tilman et al., 2001) could effectively reduce the negative externalities of cultivation. However, the factors influencing regional differences in cropland development in NPAs are multifaceted, driven by resource endowment characterized by large populations and small landholdings, along with regional disparities in climate, topography, economy, society, and culture (Liao et al., 2019). High cropland density is usually associated with higher population density and lower levels of rural access to education and income.

4.2. Regional cropland management measures should be developed

Investigating the complex causes and regional heterogeneities of cropland expansion in NPAs can facilitate the formulation of more effective land control policies for these areas. Per capita cropland might be a significant reference for adjusting the future allocation of population and cropland resources in NPAs (Cai et al., 2002). We classified the 31 provinces of mainland China into four groups and discussed the key drivers of per capita cropland area changes in NPAs for each group. Multiple linear regression was conducted using the change in per capita cropland area in the NPAs of cities from 2010 to 2020 as the dependent variable, and the explanatory variables of 2020 as independent variables

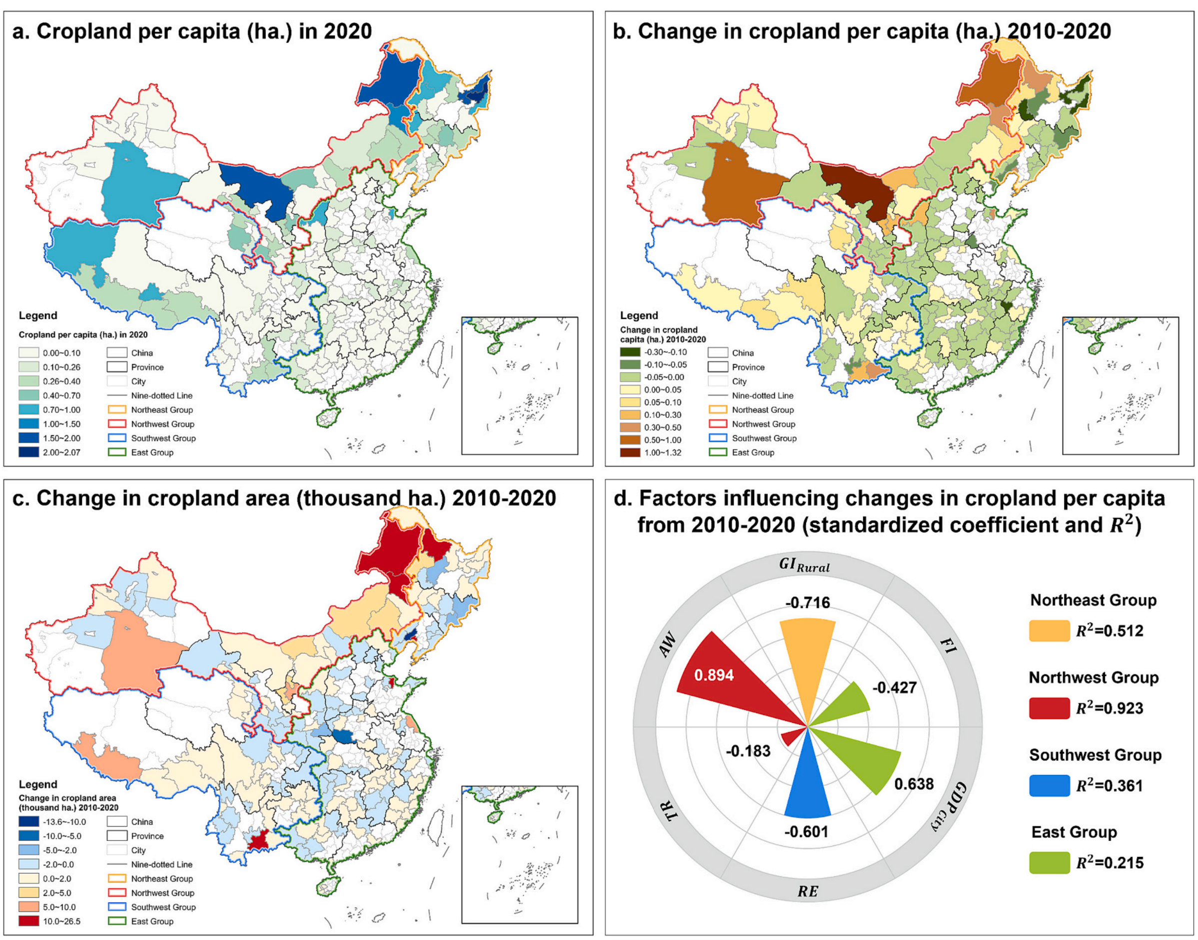

Fig. 7. Cropland patterns and factors influencing cropland expansion in the NPAs. (a) cropland area per capita in 2020, (b) amount of change in cropland area per capita 2010–2020, (c) amount of change in cropland area 2010–2020, (d) factors influencing change in cropland per capita by region. Here, *AW* represents the per capita agricultural water usage. GI_{Rural} is the Gini coefficient in rural areas. *FI* is the per capita income of farmers. GDP_{City} is the per capita GDP in cities. *RE* is the per capita electricity usage in rural areas. *TR* represents the average terrain relief.

(Table 1). Based on the results (Fig. 7d), we propose the following policy recommendations: (i) Guide the gradual withdraw of cropland from NPAs in the Northeast Group, regulate uncontrolled land cultivation strictly. (ii) Limit cropland expansion in the Northwest Group and stabilize the cropland area within NPAs. (iii) Minimizing the use of pesticides and fertilizers in the Southwest Group, while also preserving appropriate space for agricultural development helps to alleviate human-nature conflicts in NPAs and maintain the ecological and social stability in border regions. (iv) Modestly integrate the natural landscape patches of the Eastern Group to reduce human impacts on NPAs.

The driving factor for the increase in per capita cropland in NPAs in the Northeast Group (including Heilongjiang Province, Jilin Province and Liaoning Province) is the rural Gini coefficient (standardized coefficient of −0.716), with $R^2 = 0.51$ (Fig. 7d). This implies that farmers in this region have a single income source, with agriculture playing a dominant role in income structure. This region is well endowed with natural resources suitable for food production and since the 1950s large-scale agricultural reclamation activities have been carried out with the encouragement of the Chinese government (Marx et al., 2016). At present, the total area, density (Fig. 2a-b), and per capita area of cropland (Fig. 7a) are still at elevated levels in NPAs of this region. The carrying capacity of the land is under extreme stress, resulting in soil erosion, nutrient depletion, and thinning of the humus layer, among other adverse effects (Gong et al., 2013). Therefore, it is vital to conduct inspections for unauthorized expansion of cropland in NPAs and facilitate their gradual retreat. Specifically, cropland in NPAs experiencing significant soil erosion, pollution, and organic matter depletion, as well as those within the core zones of ecological function protection, should be prioritized for withdrawal.

The driving factors in the Northwestern Group are per capita water resource possession (0.894) and terrain (−0.183), with an R^2 value of 0.92. Water availability and terrain are limiting factors for agricultural cultivation in this area. Moreover, being located in arid and semi-arid zones, this region exhibits relatively low biodiversity (Fig. 6). Cropland expansion (Fig. 7c) might pose risks and uncertainties to the ecological environment in the NPAs of the Northwestern Group (Qian et al., 2019). Hence, the establishment of legal regulations to strictly limit unauthorized and covert cultivation in NPAs is imperative for this region. Additionally, improving agricultural infrastructure and increasing yield per unit area (Li et al., 2016; Zhang et al., 2019) could serve to conserve cropland and curtail its uninhibited expansion, thus minimizing damage to natural habitats.

The driving factor for the Southwestern Group is per capita rural electricity consumption (−0.601), with an R^2 value of 0.36. In regions where the ecological environment is fragile and rural infrastructure is inadequate, survival and sustenance often take precedence over ecological preservation. Over the past decade, cropland in NPAs in the Southwestern part of Yunnan Province and the Sichuan-Tibet region (Fig. 7a-c) has expanded rapidly (Sun et al., 2021). Qi et al. (2019) have suggested that cropland within the core areas of NPAs should gradually and systematically be phased out. However, this study argues that for border regions such as Nyalam County in Tibet Autonomous Region, retaining a certain amount of space for agricultural development can play an important role in alleviating conflicts between farmers' livelihoods and ecology, stabilizing the border population, and strengthening local governance (Xu and Melick, 2007). Conversely, the drawbacks of compulsory cropland reversion may outweigh the benefits, such as illicit cultivation in NPAs, thereby exacerbating soil organic matter loss and nitrogen and phosphorus pollution. Appropriate ecological compensation and proactive environmental protection controls can also be effective conservation strategies (He et al., 2018; Zhang et al., 2017; Gao et al., 2023a; Wang et al., 2023).

The driving factors for the Eastern Group are per capita GDP (0.638) and income of farmers (−0.427), with an R^2 value of 0.22. The impact of the level of economic development on the expansion of agriculture in eastern NPAs is twofold. On the one hand, cities with high GDP per capita are more economically developed, and rural-urban migration leads to an increase in the per capita area of cropland in NPAs. On the other hand, the lower the income of farmers, the more inclined they are to cultivate cropland in NPAs to improve living conditions. Despite the eastern NPAs having undergone long-term human modification (Zhang et al., 2017), they have a smaller per capita cropland area (Fig. 7a), and it is showing a general downward trend (Fig. 7b). In the densely populated NPAs of the East and South, human activities should be reduced. Plans for ecological restoration and recovery should be established, and natural landscape patches should be moderately integrated. This viewpoint is consistent with those of Wu et al. (2011) and Volis (2018).

4.3. *Challenges of achieving effective control of future protected areas*

To balance the needs of the inhabitants in the protected areas and the objectives of ecological protection, we propose potential challenges in the future from the perspectives of scientific research and practical management. Data insufficiency stands out as a significant obstacle for conducting follow-up research. Firstly, the geographic databases for biological resources are still incomplete, and there is an urgent need for biodiversity data with high-temporal-spatial resolution. Only through comprehensive species surveys and the refinement of geographical boundary data for protected areas at all levels can we establish a robust database for informing future conservation decisions (Volis, 2018). Furthermore, the symbiotic relationship between cropland utilization and biodiversity in the NPAs is conducted at a macro level. However, we still lack a full understanding of the driving mechanisms of agricultural chemical inputs and regional climate changes on biodiversity in NPAs. For instance, the impact of agrochemicals on cropland species has been widely discussed internationally (Baker et al., 2013; Geiger et al., 2010). Yet, the absence of sub-provincial-scale fertilizer and pesticide data has hindered such research. In addition, future needs include long time-series and high spatial-resolution remote sensing data, scientific observation stations and land-use change models to enhance technical support (Gao et al., 2023b, 2023c; Ye et al., 2014, 2018). These serve as an essential foundation for assessing and monitoring long-term land-use type changes in the protected areas. Finally, more agricultural information should be gathered, such as the proportion of cash crop cultivation, to discern whether cropland expansion in NPAs is driven by food demand or economic returns. Based on a comprehensive consideration of cropland, population, and socio-economic conditions in the NPAs and their combined ecological impact, appropriate cropland control schemes should be designed (Xu et al., 2016).

Management practices of NPAs can be improved in the following four aspects. Firstly, a high density of cropland in NPAs such as deserts, wetlands, and coastal areas has been found. Establishing clear penalties can provide strong legal support for the management of these types of NPAs (Xie et al., 2014). In 2021, China issued the *Wetlands Conservation Law* (National People's Congress, PRC, 2021), and coastal cities are actively promoting the establishment of coastal protection regulations. The stringent implementation of China's Ecological Redline policy can serve as a blueprint for global biodiversity conservation (Meng et al., 2023). Secondly, many NPAs in the East are scattered among densely populated agricultural areas (Volis, 2018), and the conflicts between the protected areas and residents urgently need to be resolved (Zhang et al., 2017). Encouraging residents to participate in the planning and management of protected areas can enhance their sustainability and legitimacy (Xie et al., 2014). Moreover, previous studies advocated for the strict withdrawal from cultivation in core areas (Batisse, 1982; Qi et al., 2019; Xie et al., 2014). Conversely, our research advocates for diverse management strategies. Additionally, by implementing cropland occupation and replacement balance (Liu et al., 2023), or promoting environmentally friendly farming, as well as guiding low fertilizer and zero pesticide farming pattern can also reduce conflicts between humans and the protected areas. Kim et al. (2023) confirmed that the institution of payments for ecosystem services (PES) can incentivize farmers in South

Korean protected areas to engage in eco-friendly agriculture. Last, we found that joint management by multiple departments is one of the reasons for the chaotic expansion of cropland in the NPAs. Xu et al. (2014) pointed out that >100 NPAs overlap to varying degrees with scenic spots or national geological parks. This leads to low administrative efficiency (He et al., 2018; Liao et al., 2019; Volis, 2018; Zhang et al., 2017), hence the need to clarify the management responsibilities of government departments.

5. Conclusions

The rapid expansion of cropland within protected areas is a globally entrenched issue that poses a significant threat to biodiversity. Due to the high intensity of human activities, the natural landscapes in these protected areas are often subject to considerable pressures arising from socioeconomic goals. Therefore, striking a balance between ecological conservation and the ever-growing demand for food in National Protected Areas (NPAs) is a complex challenge. In order to mitigate conflicts between conservation and agriculture, gaining an in-depth understanding of cropland in protected areas is of paramount importance. This study evaluates the spatial and temporal changes, and driving factors of cropland in NPAs on the mainland of China. Given the regional heterogeneity of cropland distribution, the spatial and temporal distribution pattern of cropland in NPAs were categorized according to geographical divisions, latitude and longitude, biomes, and types of protected areas. Subsequently, the spatial difference in cropland density inside and outside NPAs were quantified by the Pearson correlation coefficient. From the perspective of balancing ecological protection and cropland utilization, the covariance between cropland density and species richness were measured. Using multiple linear regression analysis, the comprehensive driving factors of cropland density in NPAs were explored. Ultimately, the drivers of cropland expansion in NPAs in different regions were identified, and sustainable cropland stewardship measures were determined accordingly. The key findings of this study are as follows. From 2000 to 2020, cropland in NPAs continued to expand, increasing from 1.93 million to 2.34 million hectares. The average cropland density is approximately 0.4, displaying a trend of first decreasing then increasing. The distribution of cropland density in NPAs exhibits latitudinal zonation, with a higher cropland density in NPAs located in the north of China, including flooded grasslands & savannas and deserts & xeric shrublands, among other biomes. Improved management measures can restrict the expansion of cropland. In NPAs with established protection regulations, such as forests, grasslands, and wildlife, the internal cropland density is <0.5. However, in desert, wetland, and marine types of NPAs, where there is a legal vacuum, the expansion of cropland is severe and urgently needs legislative regulation. The cropland density inside NPAs is generally less than outside nationwide. However, the difference in cropland density inside and outside NPAs in the northern region (32°-54°N) and eastern region (90°-135°E) is relatively small. The cropland density in NPAs far exceeds that outside usually lie at national borders or tri-province junctions. Fragmented management authority and intense human-nature relations are probably the main reasons for the inefficient implementation of cropland control measures. The Tibet region, in particular, is facing a particularly serious problem of cropland expansion. There is a trade-off between food production and biodiversity protection in NPAs. High cropland density and high species richness can hardly coexist. In contrast to the South, the expansion of cropland in NPAs in the North, particularly in the Northeast, where natural resources are well endowed, and in the Northwest, where marginal returns from agriculture are high, has encroached on species habitats and exacerbated biodiversity loss. For the southwestern border areas, a moderate amount of space for agricultural development and urban construction should be retained to ensure the economic and social stability of the border defense areas. In contrast, for other regions with high-density cropland in NPAs, we should actively advocate for ecological crop reduction, promote sustainable intensification, and guide a low-fertilizer, zero-pesticide cultivation pattern. Cropland development density in NPAs is a result of comprehensive coordination among ecosystems, species, the economy, population, and land use. In order to control the problem of cropland reclamation, there is a need to strengthen legal regulation, adjust financial incentives and foster eco-friendly agriculture. This research is highly pertinent to the urgent issue of preserving sustainable human-nature interactions amidst land reclamation concerns in NPAs. It lays the groundwork for the harmonious coexistence of human society and natural habitat, thereby enhancing the sustainable development of various ecological systems more effectively.

CRediT authorship contribution statement

Bin Du: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. **Sijing Ye:** Conceptualization, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Peichao Gao:** Methodology, Resources. **Shuyi Ren:** Data curation, Investigation, Writing – review & editing. **Chenyu Liu:** Data curation, Investigation. **Changqing Song:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169102.

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