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The impact of policies on land cover and ecosystem services dynamics in the Poyang Lake Ecological Economic Zone, China

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ABSTRACT

Understanding how land cover and ecosystem services respond to diverse policies is essential for economic development and ecological conservation. However, few efforts have been made to analyze the policies in conjunction with land cover and ecosystem services in the Poyang Lake Ecological Economic Zone (PYLEEZ), limiting the sustainable improvement of the region. Therefore, this study quantified changes in land cover and four ecosystem services, evaluated the relationships between them, and analyzed how various policies affected land cover and ecosystem services in the PYLEEZ from 2000 to 2020. The results showed that artificial surfaces expanded at the expense of cultivated land. Agricultural encroachment resulted in the loss of most woodland and wetland. Under ecological policies, 2062.19 km^2 of cultivated land have been returned to natural land, leading to a net wetland area increase of 760.8 km^2. In terms of ecosystem services, crop production increased significantly (+151 %) and carbon storage reduced slightly (-2.7 %) under the influence of agricultural policies and rapid urbanization. Furthermore, habitat quality and water yield increased by 252.75 km^2 and 61.3 × 10^8 m^3, respectively. Carbon storage presented a clear trade-off relationship with crop production, while habitat quality was synergistic with water yield and crop production. Given the current policies in the PYLEEZ, it is worthwhile to focus on water ecological safety and minimize the loss of natural land and ecosystem services driven by economic policies. This study is expected to help achieve the balanced development of the social economy and ecological conservation in the PYLEEZ.

1. Introduction

Ecosystem services (ES), linking social and ecological systems (Costanza et al., 1997), are essential for human well-being (Deeksha and Shukla, 2022). Over the past half century, rapid industrialization and urbanization have altered the structure and function of ES in a noticeable manner, which greatly disrupted the ES balance (Sannigrahi et al., 2020). Moreover, climate change under the global warming trend brought many ecological problems, such as frequent extreme weather and resource shortages (Haerani et al., 2023; Dai and Nie, 2022; Pang et al., 2022). ES evolve dynamically, and trade-offs and synergies are two kinds of relationships that exist among ES. Synergies happen when changes among ES show positive correlations, while trade-offs occur when changes among ES show negative correlations. Considering multiple factors such as climate, biology, and the complexity within ecosystems, scholars have noticed that spatial and temporal heterogeneity in the relationships between ES tends to exist (Zheng et al., 2016).

It has been shown that land cover is one of the main drivers of ES dynamics (Lawler et al., 2014; De Groot et al., 2010). Human activities largely influence the distribution and coverage of land cover (Zhang et al., 2018; Ma et al., 2021b), specifically under the scenario when various land cover-regulated policies are implemented (Hansen et al., 2013). On the one hand, the development of urbanization and industrialization unavoidably led to habitat degradation (Chao, 2009; Xie and Ng, 2013), loss of biodiversity (Li et al., 2010), and changes in water yield (Song and Deng, 2017). The cultivated land expansion increased crop production but also caused a decline in carbon storage. On the other hand, frequent natural disasters caused by human-induced ecological degradation highlight the importance of environmental protection. Since 2000, China has implemented a collection of environmental protection policies, such as 'Natural Forest Conservation Program' and 'Returning Farmland to Lake Program'. The implementation of these policies has improved the ES (Benayas et al., 2009; Zhou et al., 2020) and the ecological environment to some extent.

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Numerous efforts have suggested that a comprehensive assessment of policies' impact on land cover and ES is beneficial for sustainable development in the region (Mao et al., 2019; Li et al., 2022b).

The Poyang Lake Ecological Economic Zone (PYLEEZ) is a new region for China to explore the mutual development of its environmental protection and social economy. With ES as the object, previous studies in the Poyang Lake region just focused on the spatial and temporal changes in ES (Li et al., 2022a; Sun et al., 2017; Hu et al., 2021; Liu et al., 2020). In the analysis of driving factors, most studies simply considered the effect of land cover on ES (Wang et al., 2023; Yuan et al., 2021; Fu et al., 2021). However, few efforts have been made to analyze the policies in conjunction with land cover and ES in a comprehensive manner. In fact, it has been revealed that urbanization was the main driver of changes in ES under economic policies in some areas (Sun et al., 2018; Ye et al., 2018; Song and Deng, 2015). In other regions of China, some studies have discussed the relationship between policies and ES, such as in Northeast China (Mao et al., 2019), Liaoning Province (Li et al., 2022b), the Loess Plateau (Lv et al., 2012; Jiang et al., 2018), and the Three-River Headwaters Region (Jiang et al., 2016). Regional variability makes the results different. In the PYLEEZ, how land cover and ES are affected by various policies remains unclear, posing a challenge to supporting future policy formulation and adjustment. Thus, a comprehensive study about how diverse policies affect land cover and ES is much needed in the PYLEEZ.

Therefore, the main objectives of our study are: (1) to investigate land cover dynamics, especially changes in natural land, cultivated land, and artificial surfaces; (2) to quantify the dynamics of multiple ES and evaluate their relationships; and (3) to analyze the impacts of economic and ecological policies on land cover and multiple ES. The findings of the study are helpful for sustainable improvement and decision making in the PYLEEZ.

2. Data and methods

2.1. Study area

The PYLEEZ, covering 38 counties, is situated in the north of Jiangxi Province (Fig. 1). Plains are dominant in the PYLEEZ, with a total area of 51,200 km^2. The PYLEEZ owns a typical subtropical monsoon climate. Located in the center of the region, Poyang Lake is the largest fresh waterlake in China, bearing various ecological functions. In 1992, Poyang Lake became the Wetlands of International Importance based on the Ramsar Convention. Its unique natural conditions, rich in farmland resources, water resources, and biological resources, allow Poyang Lake Plain to be an important grain production base in China. In 2009, the PYLEEZ was officially incorporated into the national development strategy, and since then, it has seen accelerated urbanization progress.

2.2. Data sets

This study acquired land cover data from GlobeLand30, a 30-meter resolution product. We reclassified the ten primary types of GlobeLand30 by combining wetland and water bodies as wetland, forest and shrubland as woodland, and tundra and bareland as unused land, while keeping the other categories unchanged (i.e., cultivated land, grassland, and artificial surfaces). The precipitation data was derived from the Meteorological Administration of China. We processed daily rainfall values to obtain annual precipitation data for 46 meteorological stations in the area near the PYLEEZ and obtained raster maps with 30 m resolution using Inverse Distance Weighted (IDW). The study calculated reference evapotranspiration data using the EtoCalculator tool, which combines the temperature, humidity, sunshine duration, and wind speed data of the meteorological stations. We interpolated the evapotranspiration data via IDW. The soil database (Fischer et al., 2008) was from the

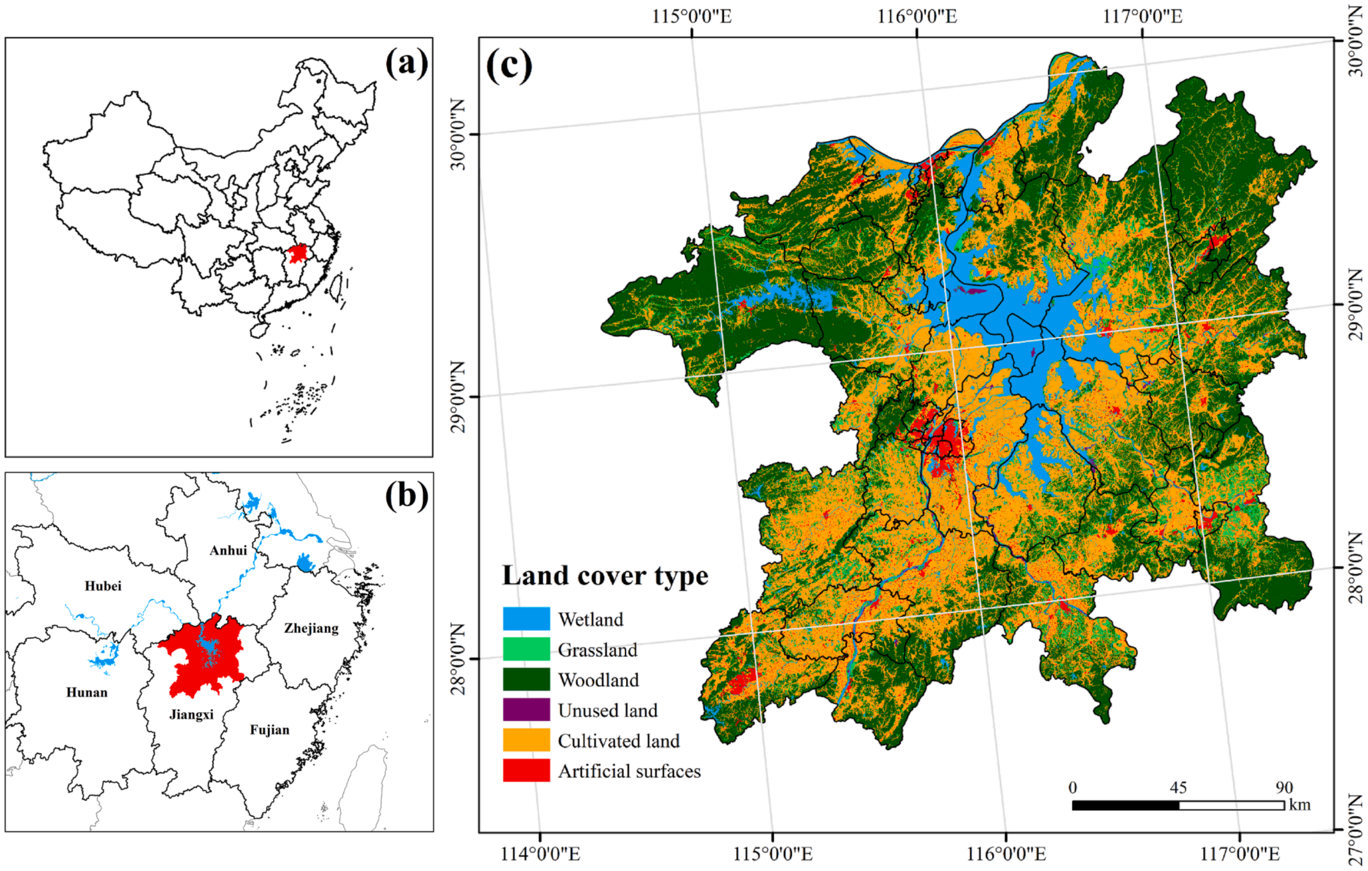

Fig. 1. The location and land cover of the region: (a) in China; (b) in the east of China; (c) land cover of the area.

National Tibetan Plateau Data Center. We obtained the basins in our study by calculating the flow direction and rate using the hydrological analysis tool in ArcGIS software. In addition, the crop production for each county was provided by the CElnet Statistics Database and government statistical yearbooks. Nighttime light remote sensing imagery was obtained from NPP-VIIRS-Like Nighttime Light Data (Chen et al., 2021). Table 1 provides the details on data sources, categories, and resolutions.

2.3. Methods to quantify ecosystem services

Following Fang et al. (2021), Mao et al. (2019), Ma et al., (2021a), and considering the data availability in our study area, we identified four ES: water yield, habitat quality, carbon storage, and crop production. Due to topographic and climatic factors, cultivated land occupies a large portion of the PYLEEZ, so we considered crop production. Given the abundant forests and lake wetlands in the region, we believe it's important to assess carbon storage and habitat quality, as they are high-quality biological habitats with strong carbon sequestration capacity. It is well known that water is vital to life (Nayak and Shukla, 2023). As an important region in the middle reaches of the Yangtze River basin, the PYLEEZ has a well-developed water system with rich precipitation. Since 2000, rapid urbanization has notably transformed the natural ground into impervious surfaces, which largely impacted water yield, habitat quality, and carbon storage.

This study utilized the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model to quantify multiple ES. Originally designed for effective natural resource management (Yang et al., 2012), the InVEST model is a software tool developed by the Natural Capital Program. It can quantify various ES and express them in the form of a graph, which is widely applied in the evaluation and research of ES (Fang et al., 2021; Shukla et al., 2018; Pathak et al., 2019).

2.3.1. Water yield

According to the water balance principle, the water yield module in InVEST represents the difference between the precipitation and actual evapotranspiration of a raster. In practice, many elements, e.g., meteorology, soil, and land cover, also affect the water yield. These elements were taken into account in the model. The calculation for the water yield is as follows:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \tag{1}$$

where Y_x and AET_x are the water yield and actual evapotranspiration of the raster x, respectively, and P_x represents the precipitation of the raster x.

For the vegetation cover type, this study calculated $\frac{AET_x}{P_x}$ according to Zhang et al. (2004) and the Budyko curve proposed by Fu (1981):

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - \left(1 + \left(\frac{PET_x}{P_x}\right)^{\omega_x}\right)^{\frac{1}{\omega_x}} \tag{2}$$

Here, PET_x is the potential evapotranspiration, which is expressed as:

$$PET_x = K_c \times ET_0 \tag{3}$$

where K_c represents the vegetation evapotranspiration coefficient, which is related to land cover type. The value of K_c was determined based on the relevant research (Allen et al., 1998; Li et al., 2022d). And ET_0 is the reference evapotranspiration. This study calculated ET_0 using the Eto Calculator, which was a tool developed by the Food and Agriculture Organization of the United Nations (FAO).

In Eq. (3), ω_x characterizes the non-physical parameter of natural climatic soil properties, whose calculation follows Donohue et al. (2012):

$$\omega_x = Z \times \frac{AWC_x}{P_x} + 1.25 \tag{4}$$

where AWC is the amount of water available for vegetation, and its calculation follows:

$$AWC = Min(Rest.layer.depth, root.depth) \times PAWC \tag{5}$$

where $Rest.layer.depth$ stands for root restricting layer depth, specifically the depth at which root penetration is inhibited due to physical and chemical effects. The data was obtained from the China soil map based harmonized world soil database. And $root.depth$ represents vegetation rooting depth, usually the depth at which 95 % of the root biomass of the vegetation type is typically found. The study determined it according to Li et al., (2022d), Fu et al. (2013), and Bao et al. (2016). $PAWC$ is the proportion of water in the soil horizon that is available for plant growth, and its value is a dimensionless decimal between 0 and 1. Based on the soil data, we calculated $PAWC$ using the algorithm proposed by Zhou et al. (2003). In Eq. (4), the parameter Z is a constant used to characterize precipitation in a region. In order to get the optimal value, different Z were utilized for calculation, and the results were compared with the data in the Water Resources Bulletin.

In Eq. (1), for other land cover types, the actual evapotranspiration can be calculated as:

$$AET_x = Min(PET_x, P_x) \tag{6}$$

Table 1
Description of the data used in the study.

Data	Resolution	Type	Source
Land cover	30 m	Raster	GlobeLand30
Precipitation, Reference evapotranspiration	30 m	Raster	China daily values of surface climate information database (V3.0)
Soil data	1 km	Raster	China soil map based harmonized world soil database (HWSD) (v1.1) (2009)
DEM	30 m	Raster	the Yangtze River economic belt DEM database (ASTER GDEM V2)
Crop production	–	Text	the statistical yearbooks and CElnet Statistics Database
Nighttime light data	500 m	Raster	NPP-VIIRS-Like Nighttime Light Data

2.3.2. Carbon storage

This study applied InVEST to get the total carbon storage of the region. The model calculated results based on a land cover type map and four carbon densities corresponding to different land cover types. Among them, carbon densities include above-ground and below-ground carbon, soil carbon, and dead organic carbon. Thus, the calculation of the total carbon storage follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{7}$$

The carbon density parameters suitable for the region were determined by Ke and Tang (2019) (Table S1).

2.3.3. Habitat quality

Biodiversity is an important indicator to characterize ES. The habitat quality module was used to reflect biodiversity, given the existence of a positive relationship between them. The value of habitat quality in the InVEST is between 0 and 1, with higher values representing richer biodiversity. Before running the model, we need to classify land cover into threat sources or habitat types. Considering the frequent human activities on built-up land and cultivated land, which pose challenges to biodiversity, they were considered threat sources in this study. In addition, unused land was also classified as a threat source because of its low vegetation coverage and poor ecological conditions. According to the sensitivity of land cover and the intensity of threat sources (Dai et al., 2020; Sharp et al., 2015; Liu et al., 2021; Fu et al., 2021), we can determine habitat quality in the region considering the maximum distance affecting habitat quality, threat weights, and the type of attenuation of each threat:

$$Q_{xj} = H_j \times \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right) \tag{8}$$

where Q_{xj} is the habitat quality of raster x in land cover j; H_j is the habitat suitability of land cover j. Q_{xj} ranges from $0 - 1$, representing the lowest and highest levels of suitability, respectively; D_{xj} represents the habitat stress level of raster x in land cover j; k is the half-saturation constant. And z is the normalized index, usually taken to be 2.5. Referring to Dai et al. (2020) and Liu et al. (2021) and considering the uniqueness of our study area, we classified habitat quality values into four classes, i.e., excellent (0.9–1), good (0.7–0.9), medium (0.5–0.7), and poor (0–0.5). We used the area with the value of habitat quality greater than 0.7 to characterize the habitat quality, with larger areas representing better habitat quality.

2.3.4. Crop production

The Poyang Lake Plain inside the PYLEEZ is a crucial food base in China, and the main crops are rice and oil plants. In this paper, we quantified food supply services in terms of grain (mainly rice) and oil production. In total, crop production for 2000, 2010, and 2020 was obtained for 30 counties.

2.4. Ecosystem service trade-offs and synergies degree index

To better understand ES, we applied ESTD to describe the relationship between them (Li et al., 2016). ESTD can characterize the direction and degree of interactions among various ES. Thus, it has been widely applied to analyze the relationship between multiple ES (Xiang et al., 2020; Gong et al., 2019). The ESTD index is calculated as:

$$ESTD_{ij} = \frac{ESC_{ib} - ESC_{ia}}{ESC_{jb} - ESC_{ja}} \tag{9}$$

where $ESTD_{ij}$ represents the trade-off or synergy degree between i and j. If ESTD is greater than 0, it denotes synergistic, otherwise trade-off; ESC_{ia} and ESC_{ib} denote the values of the i ES at time a and b, respectively. ESC_{ja} and ESC_{jb} denote the values of the j ES at time a and b, respectively. To mitigate the magnitude disparity, we normalized the ESC values to 0 to 1, representing the lowest and highest levels of ES, respectively.

3. Results

3.1. Land cover dynamics in the PYLEEZ

From Fig. 2, we found that cultivated land and woodland make up the majority of the PYLEEZ, followed by lake wetland. Cultivated land was mostly distributed near Poyang Lake and the southwestern part of the region, while woodland was located at the periphery. From 2000 to 2020, artificial surfaces expanded significantly due to the urbanization process, and they were mostly concentrated inside or at the edges of cultivated land. The cultivated land experienced a notable reduction in coverage as it was mainly transformed into artificial surfaces and woodland, followed by wetland and grassland (Fig. S1). Transitions are also notable between grassland and woodland and between cultivated land and woodland.

We used the transfer matrix (Table 2) to quantify land cover changes and transformations. Table 2 shows that wetland and artificial surfaces increased by 761.74 km^2 and 1635.28 km^2, respectively, from 2000 to 2020, with significant growth during 2010–2020. Meanwhile, cultivated land, grassland, and woodland were reduced by 1332.48 km^2, 445.17 km^2, and 508.76 km^2, respectively, of which cultivated land presented the most obvious reduction. As shown in Table 2, natural land has been restored to some extent. For example, 1041.71 km^2 of woodland, 598.09 km^2 of wetland, and 422.39 km^2 of grassland were converted from cultivated land. The expansion of artificial surfaces mainly came from cultivated land (1275.51 km^2). In addition, agricultural encroachment on natural land still existed, with the increase in cultivated land being mainly converted from woodland (1155.39 km^2), grassland (406.18 km^2), and wetland (287.44 km^2).

3.2. Changes in multiple ecosystem services

3.2.1. Water yield

The spatial patterns of water yield during 2000–2020 were obtained from the InVEST (Fig. 3). In the investigated area, the total water yield in 2000, 2010, and 2020 was 582.4 × 10^8 m^3, 755.2 × 10^8 m^3 and 643.7 × 10^8 m^3 respectively. Specifically, the mean values of water yield were 1137.48 mm, 1475.08 mm, and 1257.32 mm in 2000, 2010, and 2020, respectively. From a spatial perspective, areas with low water yield mostly occur in Poyang Lake, while areas with high water yield are distributed in the east, southwest of the region, and north of Poyang Lake. From spatial patterns of water yield (Fig. 3), precipitation (Fig. S2), and potential evapotranspiration (Fig. S3), we noticed a close

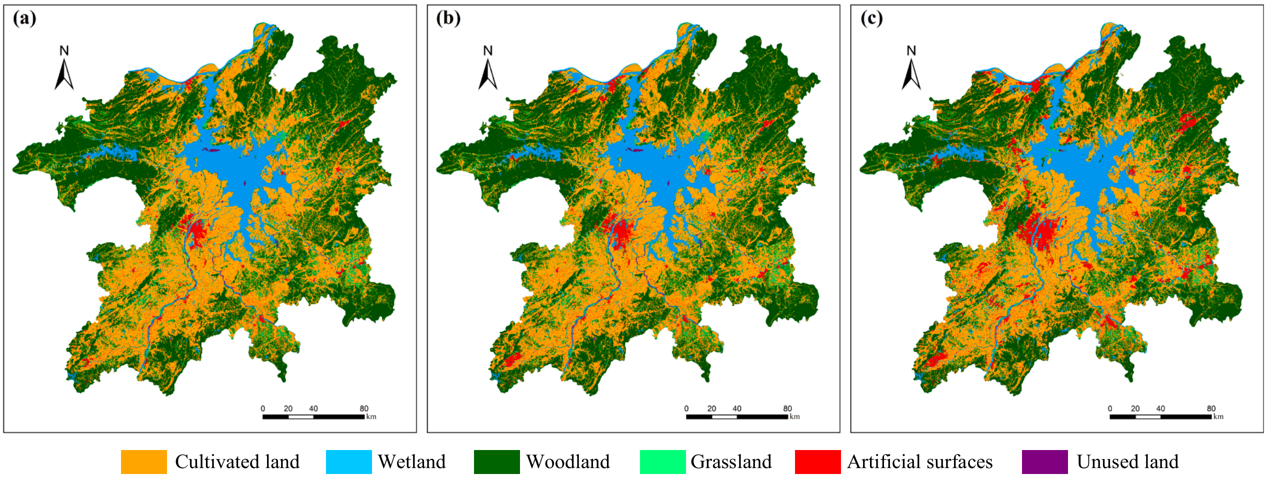

Fig. 2. Land cover maps of the PYLEEZ in 2000 (a), 2010 (b), and 2020 (c).

Table 2

The conversion matrix of land cover in the PYLEEZ during 2000–2020.

Area (km^2)	Cultivated land	Wetland	Grassland	Woodland	Artificial surfaces	Unused land	total_2020
Cultivated land	17938.89	287.44	406.18	1155.39	142.75	17.35	19948.00
Wetland	598.09	4942.24	209.92	297.87	15.88	96.34	6160.33
Grassland	422.39	39.66	1591.25	738.28	8.70	13.10	2813.38
Woodland	1041.71	57.07	820.23	17325.39	14.63	0.66	19259.68
Artificial surfaces	1275.51	58.93	228.26	250.55	1117.03	4.15	2934.43
Unused land	3.89	13.26	2.72	0.96	0.16	48.14	69.13
total_2000	21280.48	5398.59	3258.55	19768.44	1299.15	179.75	51184.95
changes	−1332.48	761.74	−445.17	−508.76	1635.28	−110.62	/

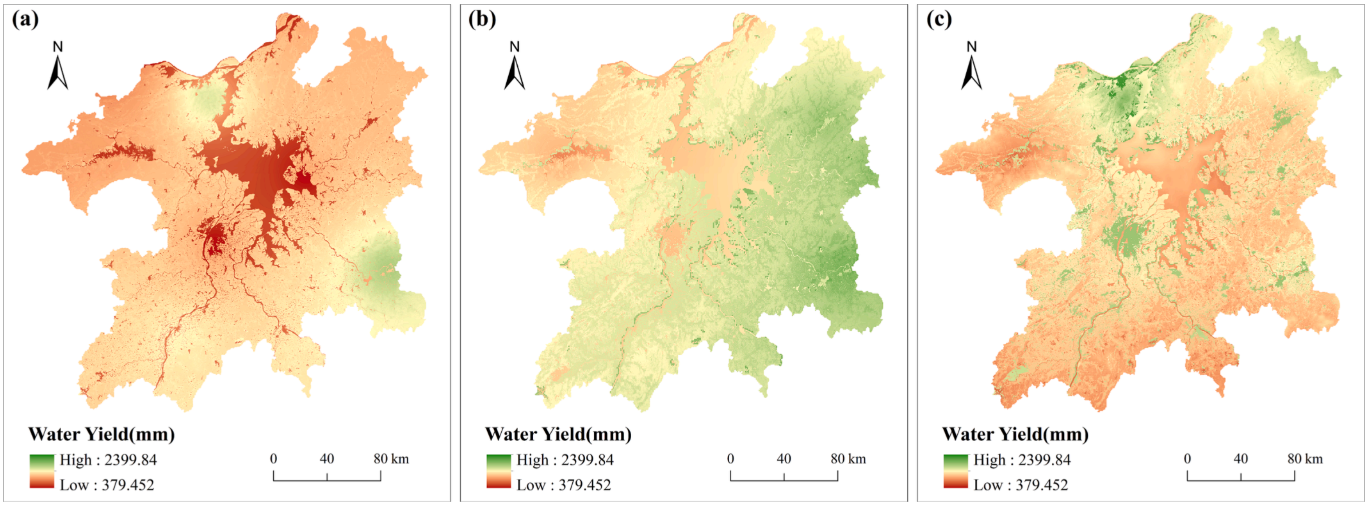

Fig. 3. Spatial patterns of water yield in 2000 (a), 2010 (b), and 2020 (c).

correlation between them, i.e., areas with high precipitation and low potential evapotranspiration tended to present a higher water yield.

3.2.2. Carbon storage

Using the InVEST, we acquired the spatial distribution of carbon storage in the PYLEEZ during 2000–2020 (Fig. 4.) The areas with high carbon storage density were located in the middle and edges of the region, as those areas were dominated by wetland and woodland, which usually own high soil carbon density. In contrast, the carbon sequestration capacity of cultivated land and grassland was slightly weaker, while urban areas, as expected, did not have carbon storage. The carbon storage of the region in 2000, 2010, and 2020 was 616.2 Tg C, 612.9 Tg C, and 600.2 Tg C, respectively, indicating a persistent decrease in the total amount. Rapid urbanization has resulted in an accelerated conversion from natural land to artificial surfaces, leading to the fact that carbon storage has been reduced by 12.7 Tg C (2010–2020), which was three times as much as that of 2000–2010 (3.3 Tg C).

3.2.3. Habitat quality

In general, there was a certain correlation between habitat quality suitability and land cover type. From Fig. 2 and Fig. S4, we found that high habitat quality areas were mainly located in natural land, such as

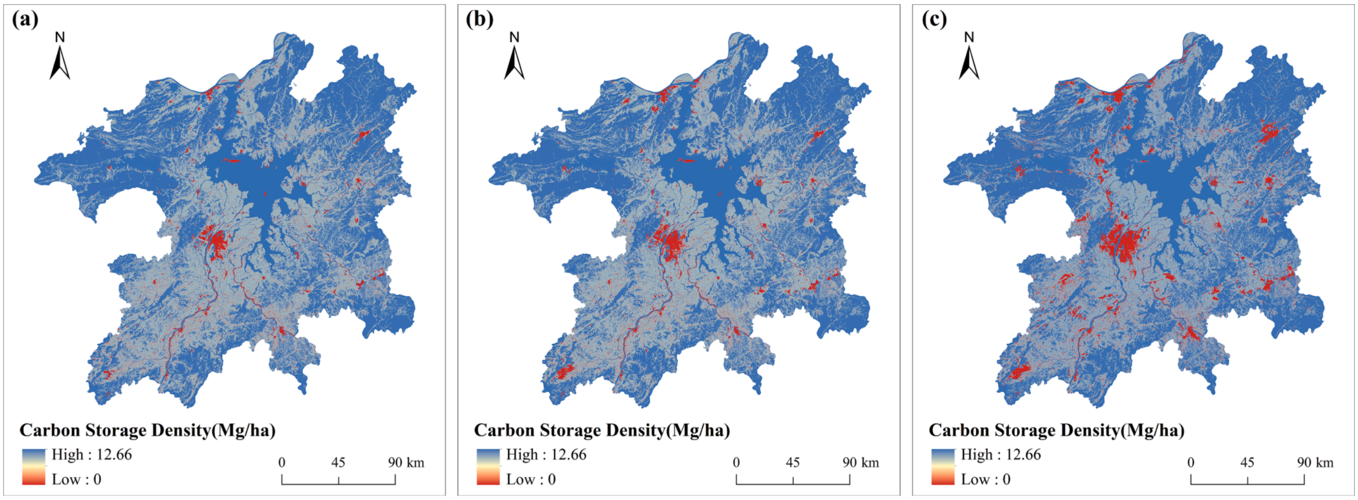

Fig. 4. Spatial patterns of carbon storage in 2000 (a), 2010 (b), and 2020 (c).

woodland and wetland, while the habitat quality was generally poor in areas with frequent human activities, e.g., urban and cultivated land. In this study, habitat quality suitability was classified into four classes, namely excellent, good, medium, and poor (Table 3). During 2000–2020, the area of excellent and medium suitability grades decreased by 508.11 km^2 and 445.19 km^2 respectively, while the area of good and poor suitability grades increased by 760.86 km^2 and 192.54 km^2, respectively. In 2000, areas with excellent and good suitability grades occupied 49.18 % of the total area in the PYLEEZ, and this value increased slightly by 2020 (49.67 %).

3.2.4. *Crop production*

A significant improvement in crop production was observed in the PYLEEZ during 2000–2020 (Fig. 5). The total crop production grew nearly 2.5 times (from 73.6 × 10^5 t to 184.8 × 10^5 t) in just 20 years. Grain production in 2000, 2010, and 2020 was 68.7 × 10^5 t, 97.7 × 10^5 t and 177.6 × 10^5 t, respectively, while oil plant production was 4.9 × 10^5 t, 6.4 × 10^5 t, and 7.1 × 10^5 t, respectively.

3.3. *Synergies and trade-offs between ecosystem services*

Based on Eq. (9), Fig. 6 demonstrated the relationships between four ES. During 2000–2010, the degree of trade-off between water yield and habitat quality was 162.66, indicating a significant inverse change between them. Besides, the trade-off between crop production and habitat quality was 117.32. The same occurred between crop production, water yield, and carbon storage, respectively (Fig. 6a). Between 2010 and 2020, the trade-off between water yield and habitat quality, crop production and carbon storage weakened. A synergistic relationship was identified between crop production and habitat quality, water yield and carbon storage, with 38.49 and 7.16, respectively (Fig. 6b). Among them, the former has a higher degree of synergy. In general, crop production and habitat quality had the same trend of change, with a degree of synergy of 60.54. And there was a continued trade-off relationship between crop production and carbon storage (Fig. 6c). Fig. 6(d) shows the variation of ESTD values between 12 groups of ES from 2000 to 2020.

4. Discussion

4.1. *Changes in land cover resulted from diverse policies*

Between 2000 and 2020, the land cover of the PYLEEZ has undergone notable changes (Table 2). We listed the main national macro policies and local land policies implemented in the region over the last 40 years to analyze their relationship with land cover (Fig. 7).

4.1.1. *Effects of economic development policies on land cover*

Since the 1980 s, a collection of policies have been implemented in the PYLEEZ to regulate agricultural and economic development. Focusing on contracting production to households, the Household Contract Responsibility System (the 1980 s) directly linked farmers' labor to their income and greatly boosted crop production. The implementation of agricultural policies resulted in increased reclamation activities. Besides, since China joined he WTO in 2001, food markets have expanded with increased agricultural profits. There has been extensive conversion of natural land into cultivated land. For example, 1155.39 km^2 of woodland, 406.18 km^2 of grassland, and 287.44 km^2 of wetland were transformed into cultivated land during 2000–2020 (Table 2). Despite the net loss of cultivated land area during 2000–2020, its proportion still ranked first compared to other land cover types (Table 2), which is consistent with the conclusions of Wen et al. (2022).

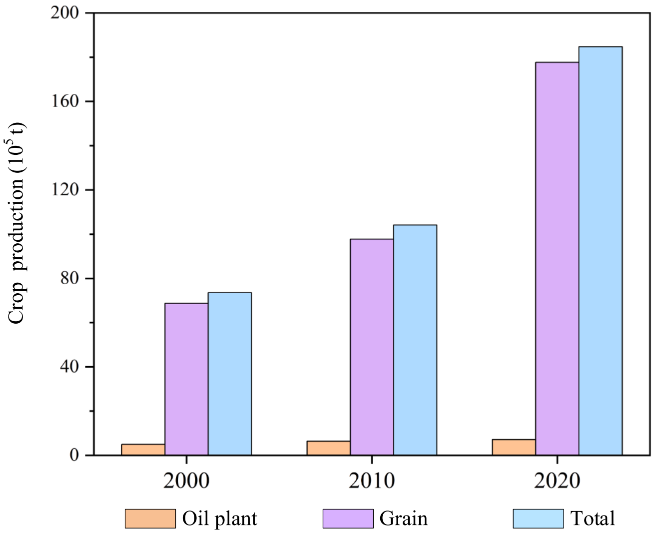

Fig. 5. Changes in crop production in the PYLEEZ during 2000–2020.

Rapid urbanization affects land cover a lot because of economic development and population expansion (Huang et al., 2018; Cai et al., 2022). Since 2000, with the accelerated pace of economic construction, a large number of surplus rural laborers have continued to transfer to cities, and the artificial surface has become the category that experienced the largest and fastest increase in the PYLEEZ (Table 2). Nighttime light data reflects the intensity of light on the Earth's surface at night and can be applied to characterize urbanization (Levin et al., 2020). We calculated the sum of nighttime light values in the region (Fig. S5). The results showed that the economy presented a generally rising trend during 2000–2020 with a rapid increase from 2010 to 2020 in the PYLEEZ. The artificial surface area increased by 1635.28 km^2 (125.86 %), and the increase in the latter decade (i.e., 2010–2020) reached 1333.52 km^2. As reported by Wen et al.(2022), construction land expanded by 1707 km^2 from 1999-2018 in the peripheral area of Poyang Lake.

4.1.2. *Effects of ecological conservation policies on land cover*

The implementation of economic policies has promoted development but also brought about many ecological problems. The catastrophic flood of the Yangtze River basin in 1998 caused huge human and economic losses. Many pieces of evidence have suggested that excessive deforestation and the reclaiming of lakes for farmlands were responsible for the flood (Ren and Hu, 2001; Wu, 1999). Since 2000,

Table 3
Changes in the area (km^2) and proportion (%) of diverse habitat quality suitability grades.

Year/period	Excellent		Good		Medium		Poor	
	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
2000	19776.62	38.63	5400.47	10.55	3259.31	6.37	22760.99	44.46
2010	19739.64	38.56	5401.67	10.55	3221.63	6.29	22833.99	44.60
2020	19268.51	37.64	6161.33	12.03	2814.11	5.50	22953.53	44.83
2000–2010	−36.97	−0.07	1.20	0.00	−37.67	−0.07	73.00	0.14
2010–2020	−471.14	−0.92	759.66	1.48	−407.52	−0.80	119.54	0.23
2000–2020	−508.11	−0.99	760.86	1.49	−445.19	−0.87	192.54	0.38

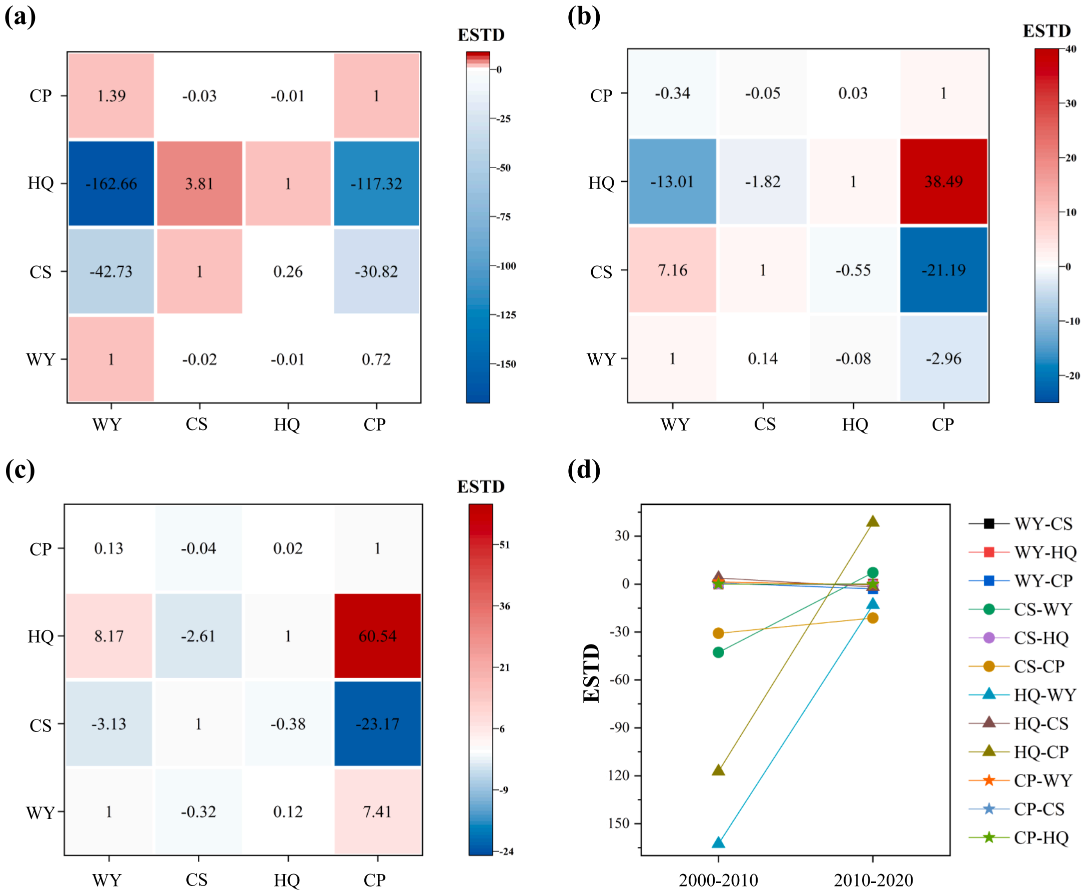

Fig. 6. The ESTD between four ecosystem services during different periods: (a) 2000–2010; (b) 2010–2020; (c) 2000–2020; (d) Changes in ESTD between 2000 and 2020.

many ecological protection policies have been announced (Fig. 7), including 'Natural Forest Conservation Program', 'Returning Farmland to Lake Program', and 'the Grain to Green Program'(GTGP) (Zheng et al., 2023; Luo et al., 2019; Wu et al., 2019a). As reported by Liu et al. (2022), 1548 km^2 of sandy land were converted to grassland in the Hunshandak Region of northern China between 2000 and 2020 due to ecological policies. To take advantage of the ecological functions of Poyang Lake Wetland in the region, local wetland protection and lake conservation regulations have been gradually proposed (Fig. 7). Table 2 showed that the environmental protection policies achieved some success, as 1041.71 km^2, 598.09 km^2, and 422.39 km^2 of cultivated land have been converted into woodland, wetland, and grassland, with continued increased coverage of wetlands. The areas of grassland and woodland presented a small decreasing trend, indicating that natural lands failed to recover to the previous level.

Driven by policies, the establishment of ecological reserves and wetland parks can also change the distribution of land cover. Xiang et al. (2020) found that the wetland loss rate decreased significantly after the implementation of the National Wetland Conservation Program in the Sanjiang Plain. Lv et al. (2012) documented that grassland and farmland were the main land cover types before the GTGP on the Loess Plateau, while between 2000 and 2008, woodland and grassland increased by 4.9 % and 6.6 %, respectively, and farmland decreased by 10.8 %.

4.2. *Analysis of ecosystem services dynamics caused by land cover*

Human interventions, including the implementation of diverse policies, have largely influenced land cover dynamics, resulting in ES dynamics in terms of constitution, structure, and patterns (Jiang et al., 2023; Locher-Krause et al., 2017). Many studies have explored the relationship between land cover and ES at varying scales, e.g., urban and watershed scales (Wang et al., 2015; Li et al., 2022c; Song and Deng, 2017). In fact, the results and conclusions varied from place to place because of the regional variability in heterogeneous ES and various policies (Mao et al., 2019; Li et al., 2022b; Liu et al., 2022; Ren et al., 2023; Ye et al., 2018).

Many scholars have explored the impact of land cover on water yield in terms of runoff changes, urbanization, and runoff formation (Piao et al., 2010; Kang et al., 1998). Spatially, Fig. 3 shows that the water yield in Poyang Lake was low given the high evapotranspiration of the lake wetland. In general, the impervious surface in urban areas blocks the infiltration of precipitation, thus increasing the water yield (Fletcher et al., 2013; Burns et al., 2012; Hanson et al., 2010). The conversion of natural land to cultivated land leads to reduced evapotranspiration, thus improving water yield (Yosef et al., 2018). Compared to land cover, water yield is more sensitive to precipitation (Hu et al., 2021). The climatic zone may be one of the influencing factors, and many pieces of evidence suggest that the effect of land cover dynamics on water yield was greater in arid and semi-arid regions (Li et al., 2022c).

In terms of carbon storage, we found that it had a strong correlation with land cover changes. As Fig. 4 demonstrates, areas with high carbon storage density were distributed in wetlands and woodland, while cultivated land and grassland presented a weaker carbon sequestration capacity, with urban areas having no carbon storage. The decline in carbon storage is closely related to the degradation of natural ecosystems due to anthropogenic factors (Ouyang et al., 2016; Guo and Gifford, 2002). In other regions, such as the Pearl River Delta urban agglomeration, it has been revealed that carbon storage was slightly reduced by 1.94 % from 2000 to 2018 under urbanization (Wang et al., 2022b). Overall, in the PYLEEZ, the increase in wetland (+761.74 km^2)

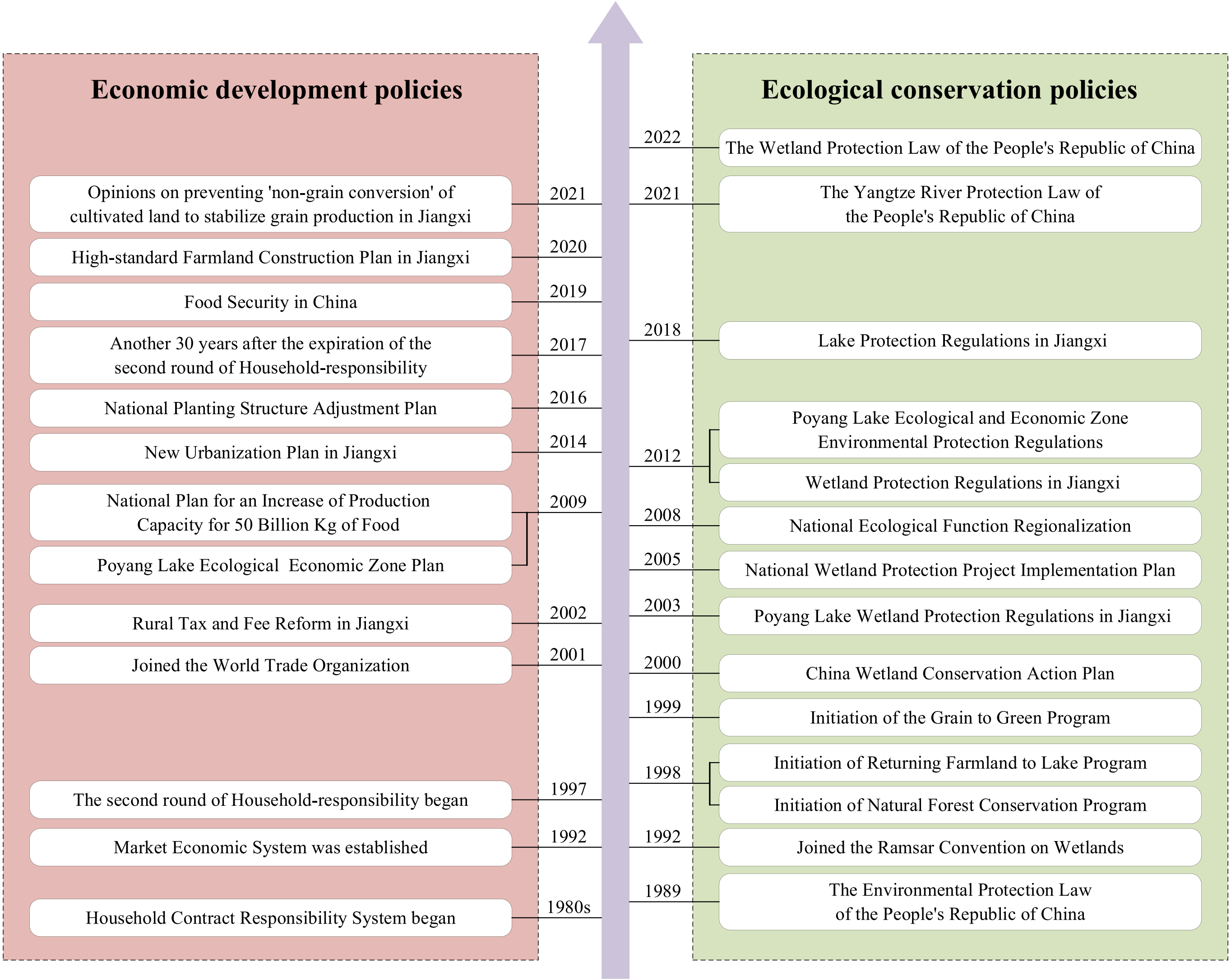

Fig. 7. The main economic and conservation policies implemented in the PYLEEZ since the 1980s.

failed to offset the impact of the decrease in woodland (-508 km^2) and the expansion of artificial surfaces (+1635.28 km^2), leading to the reduction of carbon storage from 616.2 Tg C in 2000 to 600.2 Tg C in 2020. Moreover, the rapid expansion of urbanization after 2010 accelerated carbon storage losses.

In general, compared to places with frequent human activities, the habitat quality on natural land is better. Shang et al. (2021) documented that habitat quality weakened between 1995 and 2015 in the Poyang Lake region. Unlike that, this study revealed that habitat quality improved slightly in the PYLEEZ. Specifically, areas with excellent and good suitability grades increased by 252.75 km^2. Differences in the selection of parameters in the InVEST model and the setting of habitat quality classes could result in various results. In this study, we also found that the area of the excellent suitability grade region decreased by 508.11 km^2 and the proportion declined from 38.63 % to 37.64 % because of the dynamics of land cover (Table 2; Table 3). Both urban expansion and the decline of wetlands and woodlands are responsible for the accelerated habitat degradation of ecological land (Wang et al., 2015; Wu et al., 2019b).

From 2000 to 2020, the crop production of the PYLEEZ grew from 73.6 × 10^5 t to 184.8 × 10^5 t (Fig. 5). Conversion between cultivated land and other types existed during 2000–2020. A considerable amount of cultivated land was converted to natural land and artificial surfaces, leading to a notable decline in cultivated land (from 21282 km^2 in 2000 to 19,950 km^2 in 2020). In contrast to the results of Wang et al. (2015) and Morton and Defries (2006), the growth of crop production in this study was not attributed to farmland expansion but to other reasons, such as cropping patterns, cultivation methods, the level of agricultural technology, and climate elements (Piao et al., 2010; Fang et al., 2018).

ES are complex and diverse, with intercorrelation between one another. Investigating the relationship between ES is beneficial for promoting coordinated development (Jiang et al., 2018). From the perspective of overall changes, habitat quality was significantly synergistic with carbon storage (Fig. 6c), as the higher carbon density of woodland was more suitable for the survival of living beings (Xu et al., 2019). Changes in water yield and crop production presented high consistency (Fig. 6c), presumably due to the common driving effect of precipitation and temperature, which agreed with the discussion from Wei et al. (2018). Crop production increased when natural land was converted to cultivated land. However, since the carbon density of cultivated land was significantly smaller than that of natural land, a trade-off existed between carbon storage and crop production.

4.3. Climate factors that lead to the variation of land cover and ecosystem services

In fact, in addition to human activities and related policies, some climatic factors, such as precipitation and temperature, also have an important effect on land cover and ES (Wang et al., 2022a; Li and Xu, 2023). Some studies have revealed the impact of climate change on ES (Wei et al., 2017; Lobell and Field, 2007). Between 2000 and 2020, the annual mean precipitation showed a rising trend, and the temperature increased steadily at a rate of 0.0247 °C/year over 20 years (Fig. 8), consistent with the overall change in global warming (Dang et al., 2022). We found that the highest mean annual temperature (18.192 °C) and the lowest annual precipitation (1170.474 mm) occurred in 2007, while the lowest temperature (16.888 °C) and the highest precipitation (2290.754 mm) both occurred in 2012 (Fig. 8). The ongoing global warming has resulted in changed climate patterns, leading to more frequent abnormal weather (Cai et al., 2014; Cohen et al., 2014).

Spatially, water yield presented a strong sensitivity to precipitation (Fig. 3; Fig. S2). The abundant precipitation (2265.646 mm) in 2010 led to a high water yield of 755.2 × 10^8 m^3. In the Qinghai Lake watershed, Qi et al. (2020) also found that natural factors had a greater impact on water yield than human activities. The warm climate and plentiful rainfall in the PYLEEZ are beneficial to the growth of vegetation. The temperature also affects crop production. For example, Tang et al. (2021) showed a significant positive effect of increasing temperature on crop production in Jiangxi Province. Costanza et al. (1997) found that corn and rice production in Heilongjiang Province increased by about 541.6 kg/ha and 336.8 kg/ha, respectively, along with a 1 °C rise in temperature.

4.4. *Developing balanced policy-driven approaches to sustainable economic and ecological development in the PYLEEZ*

As a national strategic development area, the PYLEEZ matters for the water ecological security of the Yangtze River. To achieve sustainable development in the region, policies should be adapted to the economic development pattern and the carrying capacity of the natural environment (Fang et al., 2021).

First, we need to focus on water ecological safety. The climatic conditions of rich precipitation and the geographical location result in frequent floods in the Poyang Lake Region. The water quality and quantity of Poyang Lake are also directly relevant to the water security of its surroundings and even the Yangtze River. Different from the vast and flat fields in Northeast China, the cultivated land of the PYLEEZ is sensitive to water quality and quantity, as are the economic and ecological functions of Poyang Lake. Therefore, the safety of the water ecosystem in the PYLEEZ is a priority for sustainable development. The government has released many wetland and lake protection regulations during the past decade (Fig. 7). Second, we argue that urbanization should not be at the sacrifice of ecological quality. At present, challenges exist during the development of the PYLEEZ. To promote the urbanization process more scientifically, continuous exploration of urban–rural integration is needed to further improve the quality of urbanization and sustainable development capacity.

4.5. *Limitations and potential improvements of this study*

This study focused on how various policies affected land cover and ES in the PYLEEZ between 2000 and 2020. The findings were helpful in formulating and adjusting policies to balance economic development and ecological conservation in the region. However, it is essential to recognize several limitations. Firstly, in terms of the spatial scale, we only analyzed ES from a regional perspective without considering the grid, county, or watershed scales. The PYLEEZ is rich in water resources and can be divided into different watersheds according to the water systems. Some studies have found that the watershed scale could reflect ES effectively (Wang et al., 2022b; Zhao et al., 2018). Secondly, the data availability and parameters were not satisfactory, which increased the uncertainty of the results. For example, meteorological stations in the PYLEEZ are unevenly distributed and not intensive, so the precipitation and evapotranspiration data obtained using the IDW method may have some errors. Finally, only four types of ES (i.e., water yield, carbon storage, habitat quality, and crop production) were selected in this paper, which is not comprehensive enough for the study in the PYLEEZ. Some other important indicators, such as soil retention and Net Primary Productivity (NPP), were not taken into account.

In the future, research can be improved in the following aspects: (1) Conduct research on ES at more spatial scales, such as the watershed scale, the city scale, and the county scale. (2) Obtain higher-quality data and build regional spatial datasets to ensure model accuracy through field inspection and verification. (3) Select diverse ES for more comprehensive research in the region.

5. Conclusions

This study analyzed policy-driven dynamics in land cover and ES in the PYLEEZ from 2000 to 2020. Notable land cover conversions existed

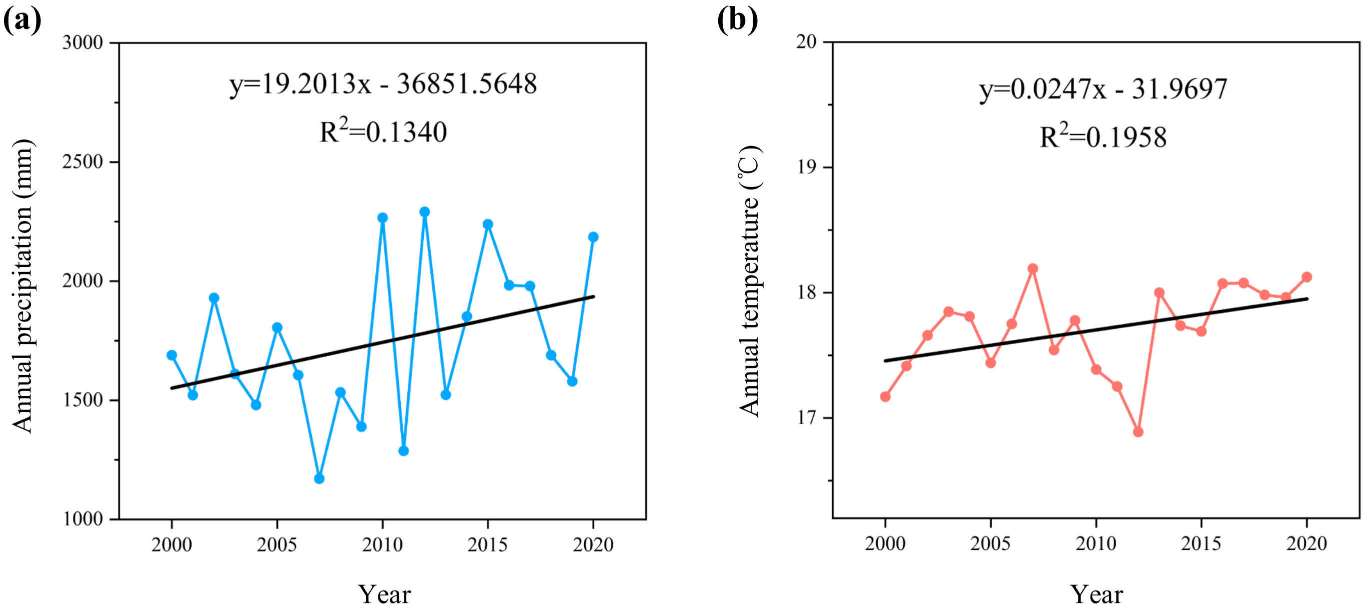

Fig. 8. Changes in annual precipitation and temperature in the PYLEEZ between 2000 and 2020.

in the region. Driven by economic policies, artificial surfaces expanded significantly at the expense of cultivated land. The agricultural development resulted in the degradation of most natural land, with about 1155.39 km^2 of woodland and 287.44 km^2 of wetland being converted to cultivated land. Under ecological policies, the natural land has been recovered to a certain extent, including a net wetland area increase of 760.8 km^2. In terms of ES, areas with excellent and good suitability grades occupied 49.18 % of the total area in 2000, and this value increased slightly by 2020 (49.67 %), indicating habitat quality in the PYLEEZ improved. Furthermore, crop production increased significantly (+151 %) and carbon storage reduced slightly (−2.7 %) under the influence of agricultural policies and rapid urbanization. Through the ESTD, we found that carbon storage presented a clear trade-off with crop production. Habitat quality, water yield, and crop production increased in synergy. Given the natural conditions of the PYLEEZ, focusing on water ecological safety matters a lot. Besides, challenges of unbalanced development between social economy and ecological conservation still exist, and it is worthwhile to minimize the loss of natural land and ES driven by economic policies. Overall, our findings are expected to better understand the relationship between policies and ES within the PYLEEZ and provide important scientific guidance for sustainable development.

Credit authorship contribution statement

Ying Deng: Data curation, Investigation, Methodology, Software, Formal analysis, Writing – original draft. **Zhenfeng Shao:** Methodology, Supervision, Funding acquisition, Writing – review & editing. **Chaoya Dang:** Methodology, Data resources, Writing – review & editing. **Xiao Huang:** Writing – review & editing. **Qingwei Zhuang:** Conceptualization, Writing – review & editing.

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.ecolind.2023.111169.

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