Original Articles

Using propensity score matching models to assess the protection effectiveness in Pudacuo national Park, China

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A B S T R A C T

Scientific monitoring and assessment of ecosystem services (ESs) in national parks is an important path to strengthen the management and protection of national parks. In this study, we constructed a test scheme for the ESs protection effectiveness based on the InVEST model and the Propensity score matching model (PSM). Based on this scheme, we best-matched three groups of pairs inside and outside the national park, and analyzed the magnitude and significance of differences in ESs protection between the best-matched groups by *t*-test, and then assessed whether the establishment of Pudacuo National Park had a protective effect on ESs. The results show that: Except for soil conservation, all ESs within Pudacuo National Park and its external 0–10 km range were higher than those in the 10–20 km area outside the national park. Moreover, the ESs within the national park and its external 0–10 km showed the same increase and decrease, and the difference between the two was small. This indicates that the existence of Pudacuo National Park effectively protects ESs and also has a positive spillover effect on its outer 0–10 km range. In addition, this study found that the soil conservation protection effect of Pudacuo National Park was slightly deficient. It exhibits weaker soil conservation than areas outside the national park. It is recommended to further strengthen the investment in soil conservation services and develop relevant measures to curb soil erosion according to local conditions.

1. Introduction

A protected area (PA) is a clearly defined geographical space with unique natural and cultural resources that is recognized and managed through legal or other effective means (Chape et al., 2008; Dudley, 2008). The establishment of PAs is an important means of achieving long-term conservation of associated ecosystem services (ESs), cultural values, and biodiversity (Chen et al., 2022; Apda et al., 2022). As of 2021, global PAs cover 15.4 % of the Earth's land surface, and their coverage has been steadily expanding (Chen et al., 2022). Despite the world's tremendous efforts to increase the coverage of PAs, the rate of global biodiversity loss has not decreased. This may be due to the inadequate coverage of PAs, and the lack of judgement on the extent to which existing PAs are achieving the desired conservation objectives (Barber et al., 2012; Jenkins et al., 2013; Xu et al., 2020). Global PAs still need to be improved in terms of size, effectiveness, and connectivity (Secretariat of the Convention on Biological Diversity, 2014; Wei et al., 2016). Therefore, it is necessary to conduct regular effectiveness assessments of PAs, to understand their ability in achieving the desired conservation goals and identify threats or problems that arise in the conservation process in a timely manner.

PAs are generally established for specific conservation purposes. Researches related to the PAs protection effectiveness are also mostly focused on conservation objectives. Since the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD) in 2010, the conservation objectives of PAs have gradually expanded from a focus on biodiversity to the protection of biodiversity and ESs (Rands et al., 2010; Eastwood et al., 2016; Zeng et al., 2020). ESs are the natural environmental conditions and utilities that ecosystems create and maintain for human survival, and are an important link in the study of the relationship between humans and nature (Daily, 1997). A growing number of public administrations, environmental agencies and international organizations are increasingly interested in integrating ecosystem services into ecological conservation policy and decision-

making (Burkhard et al., 2013; Guerry et al., 2015; Schirpke et al., 2017). Meanwhile, several studies have shown that PAs provide important ESs to humans (Millennium Ecosystem Assessment, 2005; Anton et al., 2010; Jiricka-Purrer et al., 2019). Incorporating ESs into protection effectiveness studies in PAs can better support biodiversity conservation and ecosystem management decisions in PAs than in the PAs (Ingram et al., 2012). Thus, it is feasible to use the ESs status as a criterion to make quantitative judgments on the PAs protection effectiveness. Applying ESs to the study of PAs protection effectiveness can also help further integrate human needs and ecosystem development, promoting the development and improvement of ecological conservation theories, methods and applications.

Recently, studies on the PAs protection effectiveness with the object of ESs have gradually attracted the attention of scholars, but the related results are less accumulated. Those studies that have been conducted mostly assess the PAs protection effectiveness in terms of ES monetary values, lacking consideration of ecological processes and biomass (Schirpke et al., 2017; Wu et al., 2019; Zeng et al., 2020). The study scale focused on a specific ES and lacked an integrated consideration of ESs (Tang et al., 2011; Cao et al., 2021). The study methods focused on simple comparative analyses, such as comparisons between different types of PAs, before and after the establishment of the PAs, and between inside and outside the PAs (Yu et al., 2016; Zou et al., 2019; Zhang et al., 2022a). However, this simple comparative analysis ignores the influence of many environmental factors such as climate, soil, biology, and human activities, making it difficult to accurately determine the PAs protection effectiveness (Joppa & Pfaff, 2009; Zhao et al., 2013; Chen et al., 2017). Therefore, it is necessary to integrate each key ES, and then carry out a spatial comparative analysis of the PAs based on the weakening of the influence of environmental factors, in order to achieve a scientific and accurate assessment of their conservation effects.

National parks, as the most typical and highest level of PAs spatial design in China, are an important part of China's PA system (Zhang et al.,2022b). Scientific monitoring and evaluation of the ecological environment and natural resource status in national parks is important to strengthen the protection and management of national parks (Li et al., 2022). Pudacuo National Park is one of the earliest pilot national parks in China to start exploring the pathway of national park construction (Zheng et al., 2021). It is also a confluence area of the world's biodiversity hotspots, with high ecosystem integrity and biodiversity. Using Pudacuo National Park as the study area for ES protection effectiveness assessment, it not only provides a basis for decision-making on the future investment and management of conservation funds in Pudacuo National Park, but also provides a methodological reference for "medical examination" and optimization of global PAs.

In this study, we selected Pudacuo National Park as the study case. Using the InVEST model to achieve spatial quantification of the four key ESs: water conservation, soil conservation, carbon storage and habitat quality. Then, on the basis of using the propensity score matching model (PSM) to solve the problem of environmental factor bias in the spatial comparison analysis, we compared the status of ESs inside and outside Pudacuo National Park to determine the effectiveness of Pudacuo National Park establishment on the ESs protection. This study aims to address the following questions: (1) What are the dynamic change characteristics of ESs in Pudacuo National Park from 2005 to 2020? (2) Has the ES status within the national park improved compared to the external areas of the national park? These findings can provide a reference for realizing the refined management of PAs in future.

2. Materials and methods

2.1. Study area

Pudacuo National Park is located in Shangri-La City, Diqing Tibetan Autonomous Prefecture, Yunnan Province, China. It is located in the northern section of the alpine and canyon area of the Hengduan

Mountains, the transition zone between the Qinghai-Tibet Plateau and the Yunnan-Guizhou Plateau, with a geographical location of $99°59'16''$ $− 100°02'38''$ E, $27°43'52'' − 27°58'30''$ N (Zheng et al., 2021). Pudacuo National Park is mainly composed of Internationally Important Wetland Bitahai Nature Reserve, Shudu Lake Scenic Area in the Hongshan Area of the "Three Parallel Rivers" World Natural Heritage, and Militang Subalpine Ranch. The national park contains relatively complete forests and shrubs, alpine meadows, wetlands and lakes, geological relics, river and canyon ecosystems, etc., with rich landscapes, animal and plant types. In addition, being located in the intersection of three world biodiversity hotspots, the Eastern Himalayas, the India-Myanmar region, and the mountains of Southwest China, Pudacuo National Park is endowed with great significance in maintaining biodiversity and ecosystem authenticity (Fig. 1).

2.2. Delineating the comparison spaces

The existence of protected areas can have a spatial proximity effect on the unprotected areas around them (Clements et al., 2014; Zhao et al., 2019). This effect can affect the accuracy of conservation effectiveness assessment results for protected areas. To avoid the influence of spatial proximity effects on the conservation effect assessment results, this study needs to conduct conservation effect analysis on the basis of delineating the comparison space. Since the spatial proximity effect of protected areas occurs mainly within the 0–10 km range outside them (Bruner, 2001), we delineated the comparison space into three zones: Pudacuo National Park (A), the 0–10 km area outside the national park (B), and the 10–20 km area outside the national park (C). Among them, Pudacuo National Park region is a fully protected area; the 0–10 km area outside the national park is a spatial proximity area; the 10–20 km area outside the national park is an area that is neither protected nor affected by the spatial proximity effect of the national park (Fig. 2).

From 2005 to 2020, the land use structure of all three regions steadily shows that " forest mainly and grassland supplement", and these two land use types account for more than 95 % in the total area of their respective regions. Although the land use structure of the three regions have not changed in the last 15 years, their area share has changed slightly in an increasing or decreasing manner. In the Pudacuo National Park section, the land type area change showed mainly on forest and grassland, with a decrease of 0.0505 % in forest and an increase of 0.0432 % in grassland. In the 0–10 km area outside the national park, all land types decreased, except for a slight increase in the percentage of cropland and impervious. In the 10–20 km area outside the national park, the area of water and impervious increases while the rest of the land type decreases (Table 1).

2.3. Methods

2.3.1. Ecosystem services space quantification

As the intersection of three world biodiversity hotspots and an important section of the Jinsha River for water containment and soil conservation, Pudacuo National Park has an important role in water conservation, soil conservation, carbon storage, and habitat quality (Ma et al., 2022). The Integrated Valuation of Environmental Services and Tradeoffs (InVEST) is a model applicable to the assessment of ESs on a global scale or landscape scale (Sharp et al., 2015). The model enables visualization of ES dynamics quantification and is widely used for ESs assessment (Tang et al., 2015). Accordingly, this study used the fishing net tool of ArcGIS to divide the study area into a 30 m × 30 m grid. This was used as the unit to spatially quantify-four key ESs of Pudacuo National Park, namely water content, soil conservation, carbon sequestration and habitat quality services, by using the InVEST model. The model parameters and data sources are shown in Table 2.

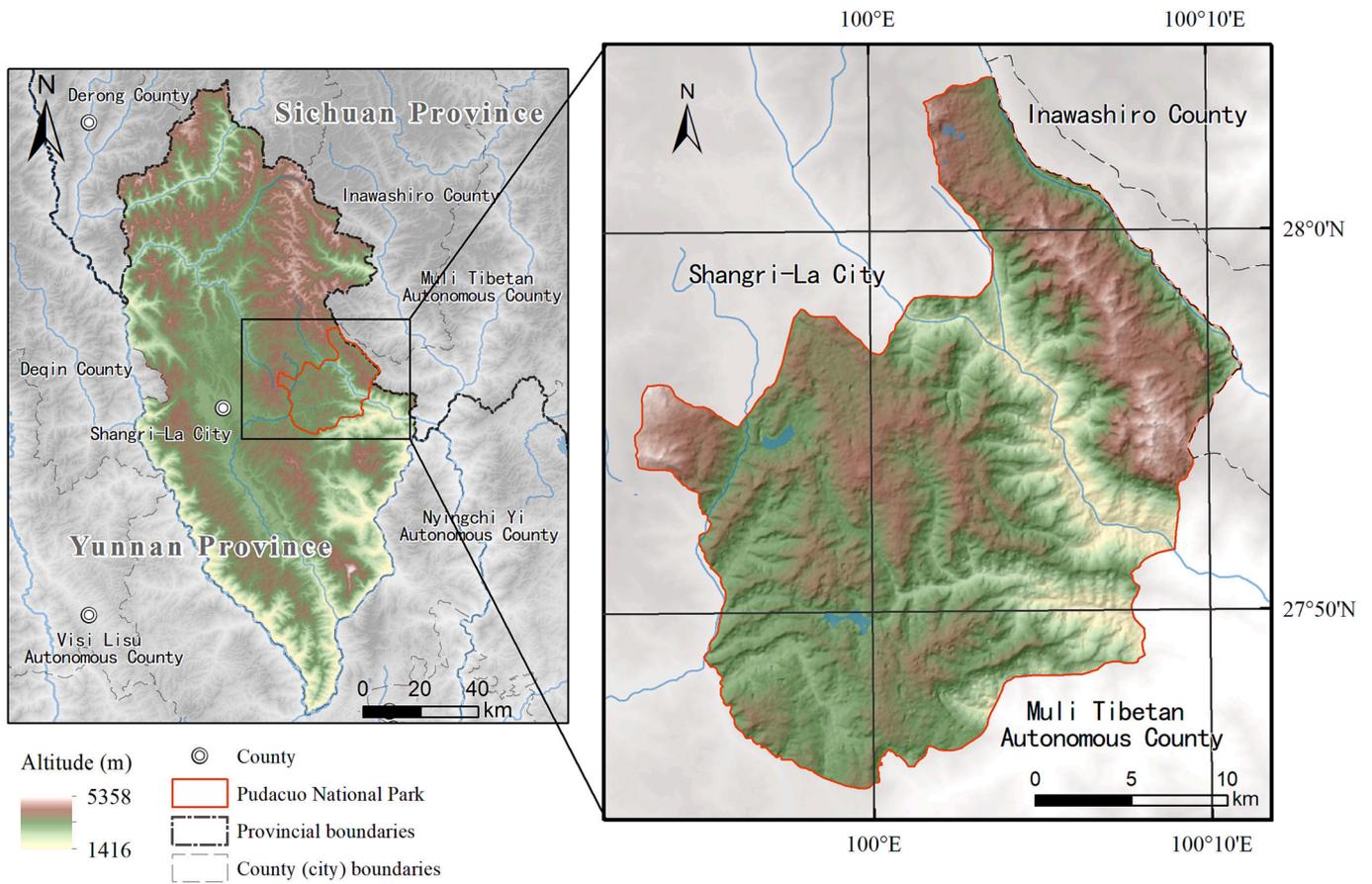*2.3.1.1. Water conservation.* The water yield module in the InVEST 3.11

Fig. 1. Geographic location of the Pudacuo National Park.

is essentially based on the Budyko coupled hydrothermal equilibrium assumption to calculate the average annual water conservation at the image element scale, i.e., the difference between the average annual rainfall and the average annual actual evapotranspiration for a given image element (Xiao & OuYang, 2019; Lan et al., 2021). The specific formula is as follows:

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

In the formula: Y_x is the annual water production of grid x (mm); P_x is the annual precipitation on grid x (mm); AET_x is the annual actual evapotranspiration of grid x (mm).

2.3.1.2. Soil conservation. The Sediment Delivery Ratio model module of the InVEST 3.11 considers the ability of the land mass itself to intercept upstream sediments based on the RUSLE equation. Therefore, the soil conservation service calculated by the model contains both soil erosion reduction and sediment holding capacity components (Li et al., 2021a). The specific formula is as follows:

$$SEDRET_x = R_x \times K_x \times LS_x \times (1 - C_x \times P_x) + SEDR_x \tag{2}$$

$$SEDR_x = SE_x \sum_{y=1}^{x-1} USLE_y \prod_{z=y+1}^{x-1} (1 - SE_z) \tag{3}$$

$$USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x \tag{4}$$

In the formula: $SEDRET_x$ is the soil retention amount (t); R_x is the rainfall erosivity factor (MJ mm hm-2 h-1 a-1) of grid cell x; K_x is the soil erodibility factor (t h/MJ mm-1); LS_x is the slope length factor; C_x is the vegetation management factor; P_x is the soil and water conservation

measure factor. $SEDR_x$ is the sediment flow (t); SE_x is the retention rate of grid cell x; SE_z is the sediment retention of upslope grid cells (t); $USLE_x$ is the actual soil erosion amount (t).

2.3.1.3. Carbon storage. Ecosystems often achieve climate regulation through greenhouse gas emissions, which store carbon in soils and plants over time and through land use change, thereby increasing carbon storage. The carbon storage and sequestration module in the InVEST 3.11 assesses carbon stocks based on four carbon pools: aboveground biomass, belowground biomass, soil and dead organic matter for different land use types or vegetation types (Li et al., 2021b; Jing et al., 2022). The specific formula is as follows:

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{5}$$

In the formula: C_{tot} is the total carbon storage (Mg); C_{above} is the above-ground biological carbon storage (Mg); C_{below} is the underground organism (Mg), C_{soil} is soil carbon storage (Mg); C_{dead} is dead organic matter carbon storage (Mg).

2.3.1.4. Habitat quality. Habitat quality determines the magnitude of the environment's ability to provide suitable living and production conditions for humans and other organisms. It is the key to biodiversity conservation (Sun et al., 2019). The Habitat Quality module of the InVEST 3.11 emphasizes the construction of connections between habitats and threat sources. The rationale is to estimate habitat quality indices based on land use data in terms of threat sources, sensitivity of habitat types to threat sources, and distance and weight of habitats relative to threat sources (Guo et al., 2022). Habitat quality indices characterize biodiversity levels, such that a higher habitat quality index indicates a higher level of biodiversity in a region (Sala et al., 2000). The specific formula is as follows:
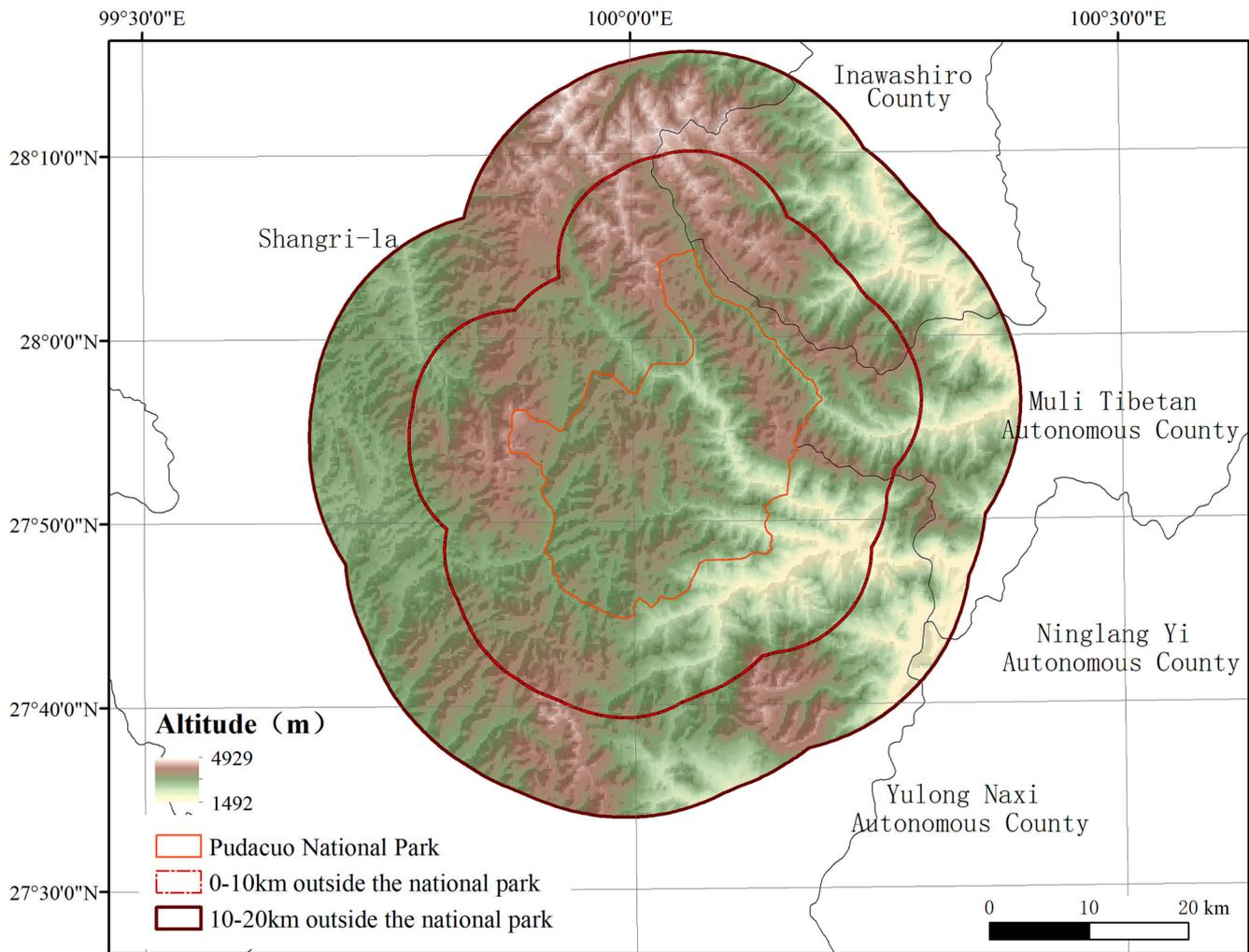
Fig. 2. Comparative Spatial Delineation.

Table 1
Area percentage of each land use type in 2005–2020 (%).

Land Cover	2005				2020			
	Overall study area	A	B	C	Overall study area	A	B	C
Cropland	2.7352	0.3511	2.0964	3.9127	2.6243	0.3494	2.0986	3.6849
Forest	67.1029	75.3363	65.1093	66.1023	67.0274	75.2858	65.0727	65.9874
Grassland	28.1793	21.7975	32.5504	26.8918	28.1195	21.8407	32.5412	26.769
Water	0.1489	0.5751	0.0253	0.112	0.1882	0.5771	0.0246	0.1916
Impervious	0.2965	0	0	0.6013	0.5048	0	0.0483	0.9882
Barren	1.5372	1.9399	0.2187	2.3799	1.5359	1.9471	0.2147	2.3789

A refers to the Pudacuo National Park; B refers to the 0–10 km area outside the national park; C refers to the 10–20 km area outside the national park.

$$Q_{xj} = H_j \left[1 - \frac{D_{xj}^z}{D_{xj}^z + K^z} \right] \tag{6}$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) \times r_y \times i_{rxy} \times \beta_x \times S_{jr} \tag{7}$$

In the formula: Q_{xj} is the habitat quality of grid cell x on land use type j; H_j is the suitability of land use type j; D_{xj} is the habitat degradation of grid unit x on land use type j; K is the half-saturation parameter; Z is the normalization constant; R is the stress factor of the threat source; y is the total number of grids of stress factors; Y_r is the grid number of the r th stress factor; w_r is the weight of the stress factor r; r_y is the stress factor value of grid cell y; i_{rxy} is the stress level of grid unit x by stress factor ry

of grid unit y; β_x is the accessibility of the stress factor to the grid cell x; S_{jr} is the sensitivity of land use type j to stress factor r.

2.3.2. Assessment of integrated ecosystem services

Considering that water conservation, soil conservation, carbon storage, and habitat quality are equally important in the ESs of Pudacuo National Park, they are given equal weights to construct a comprehensive ES function assessment model (Liu et al., 2021). The specific formula is as follows:

$$S_{CE} = \frac{S_{Ewy} + S_{Esc} + S_{Ecs} + S_{Ehq}}{4} \tag{8}$$

In the formula: S_{CE} is the comprehensive ES amount, which takes the value [0, 1]; S_{Ewy}、 S_{Esc}、 S_{Ecs}、 S_{Ehq} are the ESs of water conservation, soil

Table 2
Data sources for ecosystem services space quantification.

Ecosystem service	Type of data	Data Sources
Water yield	Digital elevation model	Geospatial Data Cloud
	Land use map	Geographical Information Monitoring Cloud Platform (2005, 2020)
	Annual rainfall	National Earth System Science Data Center (2005, 2020)
	Annual potential evapotranspiration	Calculated using data such as the difference in annual average temperature, annual maximum temperature and annual average minimum temperature
	Root restricting layer depth	Soil and Terrain Database (2017)
	Plant available water content	International Soil Reference and Information Centre (2017)
	Watersheds	Calculated using the digital elevation model to obtain
Soil coservation	Digital elevation model	Geospatial Data Cloud
	Land use map	Geographical Information Monitoring Cloud Platform (2005, 2020)
	Annual rainfall	National Earth System Science Data Center (2005, 2020)
	Rainfall Erosivity Index	Calculation of factor values using monthly average rainfall and annual average rainfall
	Soil property data	Harmonized World Soil Database version 1.2 (HWSD)
	Soil Erodibility	Soil property data such as sand (SAN), chalky (SIL), clay (CLA), and organic carbon (C) content (%) are used to calculate
Carbon storage	Carbon Density	The carbon densities in the same or similar areas as the study area were selected in preference to the relevant literature (Li et al., 2021; Jing et al., 2022).
Habitat quality	Digital elevation model	Geospatial Data Cloud
	Land use map	Geographical Information Monitoring Cloud Platform (2005, 2020)
	Interference source distribution	Obtained by conversion of land use data, road network data, population density data, etc.

conservation, carbon storage and habitat quality obtained after normalization, and the values of these indexes are all [0,1].

2.3.3. Ecosystem service protection effectiveness assessment

2.3.3.1. Propensity score matching model. The assessment method for the PAs protection effectiveness determines the accuracy of the assessment results. In recent years, the comparison of a PA with its surrounding area has been a popular method for assessing PAs protection effectiveness (Geldmann et al., 2013). With the in-depth research on conservation effects based on spatial comparative analysis, it has been found that PAs and their surrounding areas differ in environmental factors such as soil, biology, and topography. Such differences can interfere with the protection effectiveness assessment of PAs (Wang et al., 2013; Fuller et al., 2019). From this, some scholars have introduced Matching's analytical approach to protection effectiveness studies in PAs for improving the accuracy of their assessments (Gaveau et al., 2009; Ren et al., 2015).

Propensity score matching model (PSM), as one of the Matching analysis methods, is a method that allows causal judgments in non-randomized controlled studies involving more confounding factors (Imbens, 2004; Randolph et al., 2014). PSM is mainly used for

randomization-like equalization of covariate factors in the test group to weaken the effect of covariates (Huang et al., 2015; Chen et al., 2017). Overall, the PSM is divided into two main parts: propensity score and matching. The propensity score is the probability that the study sample will be classified into the test or control group given the covariates (Rosenbaum, 1989). Matching, on the other hand, selects subjects from the control group with the same or similar propensity scores as the test group for matching, so that the covariates are balanced between groups (Zhang et al., 2012).

2.3.3.2. Ecosystem services protection effectiveness assessment Program. Firstly, dividing the paired groups. In this study, two-by-two groupings were made based on the results of the comparative space division. In the matching of sample A with sample C, A will be the test group and C will be the control group. In the matching of sample B with sample C, B will be the test group and C will be the control group. In the matching of sample A with sample B, A will be the test group and B will be the control group (Chen et al., 2017).

Secondly, identifying environmental variables. According to the existing studies on the PAs protection effectiveness (Chen et al., 2017; Cao et al., 2021), combined with the actual situation of Pudacuo National Park, altitude, slope, slope direction, and soil type were selected as environmental variables in this study.

In this study, elevation, slope, slope direction, soil type, and distance from the road were used as covariates. The three paired groups were matched two-by-two by PSM separately, and the caliper value was set at 0.02. Thus, the sample pairs with the most similar environmental variables in each paired group were screened. Finally, t-tests were conducted on the screened sample pairs to determine the conservation effects of Pudacuo National Park through comparative analysis of means and significance of difference comparisons (Fig. 3).

3. Results

3.1. Changes in ecosystem services

3.1.1. Changes in water conservation

This study considered the Pudacuo National Park and its outer 20 km buffer zone as a whole study area. From the overall scope, in 2005 and 2020, the average water conservation of the whole region was 368.53 mm and 374.84 mm, respectively, and the water conservation capacity showed a slight upward trend. The change trend of the average water conservation of the three survey regions was consistent with that of the overall study area, showing a steady increase trend. Among them, the average water conservation of Pudacuo National Park increased the most, reaching 1.21 %, followed by the 0–10 km range outside the National Park, 1.10 %. The average water conservation within the 10–20 km range outside the national park had the smallest increased, which was lower than the average water conservation increased in the overall study area, only 0.40 % (Table 3).

The spatial distribution pattern of the average water conservation in the study area did not change significantly in 2005 and 2020. The overall spatial distribution was characteristics by "prominent north–south and insufficient east-west" (Fig. 4). The high-value area was characterized by the climatic conditions of high rainfall and low evapotranspiration. In addition, the distribution range of grassland in the northern high-value area was larger. In addition to the grassland in the southern high-value area, there were also a certain scale of swamps and bare rock land types. These land use types had weak interception ability to precipitation and high water conservation capacity. The low-value area was mainly dominated by forest land and cultivated land, which had a strong ability to intercept precipitation. Compared with the high-value area, the precipitation in this area was less, and the influence of evapotranspiration was high, which made the water conservation capacity weak.
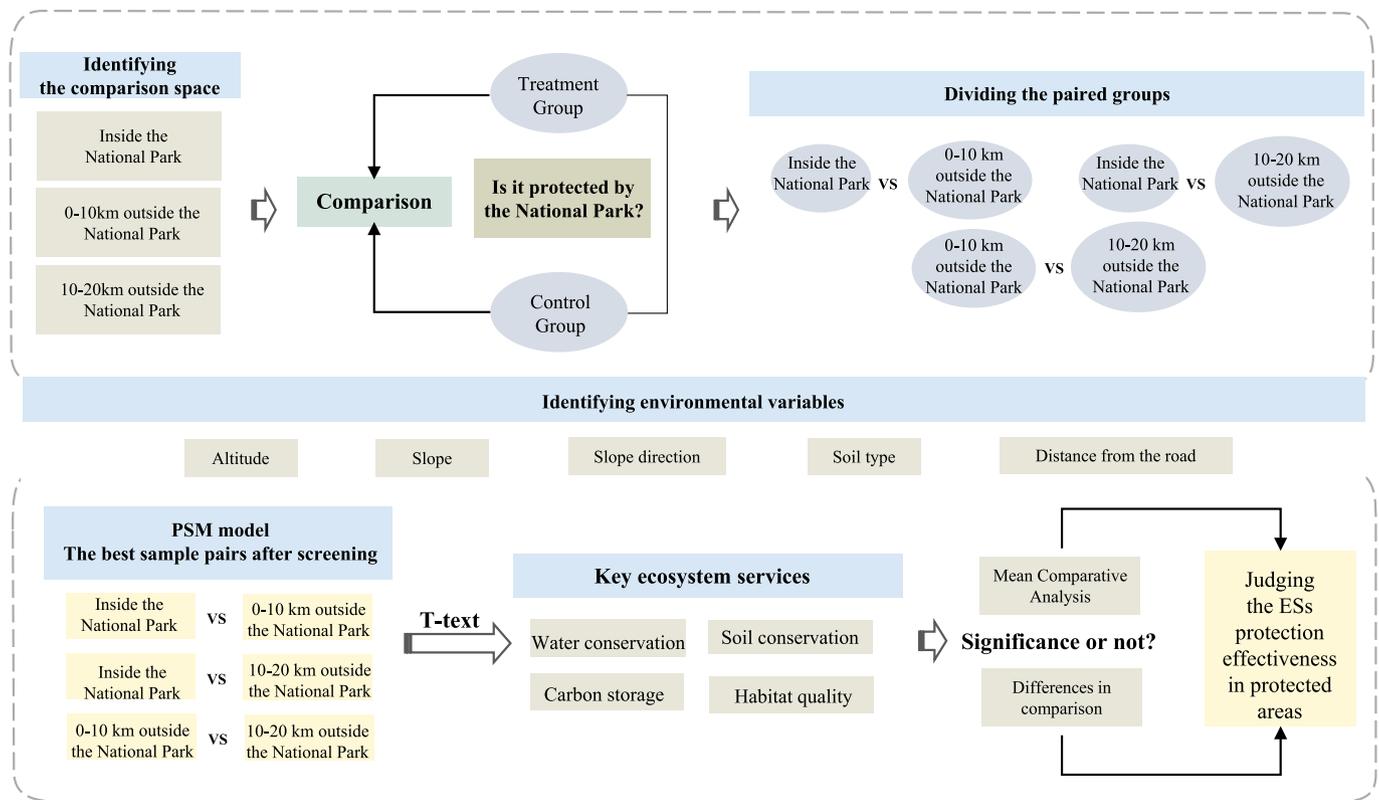
Fig. 3. Ecosystem Services Protection effectiveness Assessment Program.

Table 3
Overall ecosystem services inside and outside Pudacuo National Park during 2005–2020.

Ecosystem service	2005 Overall study area	A	B	C	2020 Overall study area	A	B	C	Change rate 2005–2020 (%) Overall study area	A	B	C
Water conservation (mm)	368.53	367.03	369.62	368.19	374.84	371.46	373.81	369.56	1.70	1.21	1.10	0.40
Soil conservation (t·km^2)	73.35	63.54	70.23	78.75	73.34	63.55	70.24	78.73	−0.01	0.02	0.01	−0.03
Carbon storage (t)	4.43	4.70	4.45	4.34	4.50	4.75	4.54	4.40	0.016	0.011	0.020	0.014
Habitat quality	0.9571	0.9741	0.9792	0.9358	0.9551	0.9736	0.9782	0.9326	−0.2090	−0.0513	−0.1021	−0.3420
Integrated ecosystem service	0.65	0.6655	0.655	0.6409	0.6367	0.6527	0.644	0.6261	−2.0462	−1.9234	−1.6794	−2.3093

A refers to the Pudacuo National Park; B refers to the 0–10 km area outside the national park; C refers to the 10–20 km area outside the national park.

3.1.2. Changes in soil conservation

In 2005 and 2020, the soil conservation per unit area of the study area was 73.35 t·km^2 and 73.34 t·km^2, respectively, and the soil conservation amount showed a slight decreasing trend during the study period. Combined with the land use status in this period, the grassland area in the study area has decreased from 2005 to 2020 due to the growth of productive and living land as well as water area. The conversion of grasslands with water and soil retention capacity to weak soil retention land types has weakened the soil retention capacity of the area to some extent. Comparing the changes of soil conservation capacity in the three survey regions, we found that the soil conservation capacity in the range of 10–20 km outside the national park decreased slightly by 0.0253 t·km^2 during 15 years, while the soil conservation capacity in the range of 0–10 km inside and outside the national park showed a slight increase by 0.0042 t·km^2 and 0.0062 t·km^2 respectively. Overall, soil conservation capacity was weakest within the national park, followed by 0–10 km outside the national park, and the soil conservation capacity in the 10–20 km range outside the national park was the highest among the three survey regions (Table 3).

According to the information given by the spatial distribution characteristics of soil conservation services in the study area from 2005 to 2020, the overall study area has a low soil conservation capacity and significant spatial heterogeneity (Fig. 4). The areas with high soil conservation capacity are mainly concentrated in the east central region where the distribution of forest land is larger and more contiguous. In the western region, due to the diversity of land use types, grassland, water and construction land with weak soil conservation capacity occupy a certain area, and the distribution of forest land is more fragmented, which makes the soil conservation capacity relatively weak.

3.1.3. Changes in carbon storage

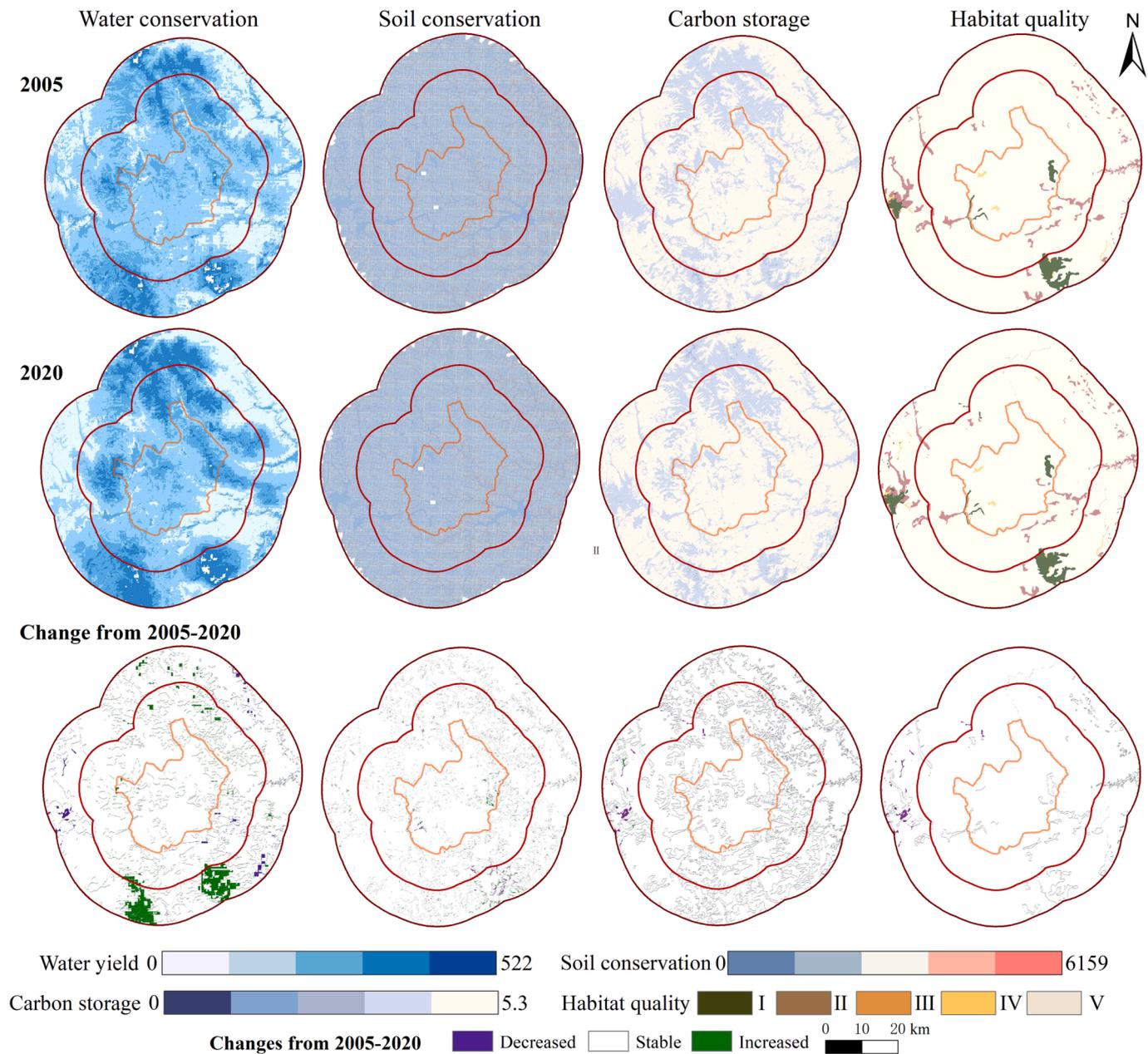From 2005 to 2020, the carbon storage per unit area in the study area

Fig. 4. Spatial distribution and change of ESs from 2005 to 2020.

showed a upward trend, the carbon storage per unit area has increased by 0.07 t, and the carbon sequestration ability has increased by 0.016 %. The main reason is the conversion of grassland to forest. Although both land types are high carbon density land types, the carbon density of forest land is slightly higher. The carbon storage in the three survey regions in the study area also differed, with Pudacuo National Park always being in the top position with 4.70–4.75 t. However, in terms of the growth rate, the carbon storage in the 0–10 km range outside the national park increased the most with 0.09 t, followed by 0.05 in the national park. For the 10–20 km range outside the national park, the change of carbon stock was always weaker than the other two survey regions, both in terms of the carbon storage situation and the growth rate (Table 3).

The spatial distribution of carbon storage in the study area showed a pattern of "high in the middle and low in the east and west", indicating that the carbon sequestration capacity gradually decreases from the middle to the east and west (Fig. 4). The distribution of high-value areas of carbon storage was large-scale, accounting for more than 80 % of the

study area, while the median and low-value areas of carbon storage were scattered and staggered on the east and west sides. This distribution pattern was associated with land use types and vegetation distribution in the study area. The high-value area of carbon storage was distributed with a certain scale of grassland and forest land, the middle-value area was dominated by cultivated land, and the low-value area corresponded to construction land, water and unused land types.

3.1.4. Changes in habitat quality

Combined with the actual situation of the study area, equal interval reclassify was used to divide the habitat quality into five grades: I [0,0.2), II[0.2,0.4), III[0.4,0.6), IV[0.6,0.8),V[0.8,1). The average habitat quality index of the study area in 2005 and 2020 was 0.9571 and 0.9551, respectively, indicating that the overall habitat quality of the study area was degraded. Comparing the habitat quality of the three survey regions in the study area, it was found that the habitat quality loss in the national park and its outer 0–10 km range was relatively slow, 0.0513 % and 0.1021 %, respectively. The habitat quality loss in the

range of 10–20 km outside the national park was larger than the other two sections, with a decrease of 0.3420 %. Although the habitat quality of the three survey regions was degraded to varying degrees, their levels remained in the high value range. From 2005 to 2020, except for the habitat quality zones I and IV, the area transformation of other grades showed a change characteristic of "transferring out more than transferring in", which mainly transformed to the habitat quality zone I grades. Although the area of each habitat quality grade area has changed, its structure is relatively stable. During the 15 years, the area of high-grade habitat quality areas has always dominated, accounting for more than 95 % (Table 3).

There were significant differences in the spatial distribution of different levels of habitat quality (Fig. 4). The V-level habitat quality areas were widely distributed, occupying most of the study area, and were characterized by agglomeration of grasslands and forests. The habitat quality areas of grades I and II presented a spatial distribution pattern of "cluster-belt-point". This area was dominated by cultivated areas and residential areas with relatively frequent human activities, which were greatly affected by human activities, and the habitat quality was slightly worse than other areas.

3.1.5. Changes in integrated ecosystem service

From 2005 to 2020, the integrated ecosystem services in the study area decreased from 0.6500 to 0.6367, taking a decrease of 2.0462 %. Comparing the integrated ecosystem service of the three survey regions, it was found that between the three regions, the level of integrated ecosystem services within the national park, and 0–10 km outside the national park were higher, 0.6527–0.6655, 0.6440–0.6550 respectively. In terms of changes in integrated ecosystem service, both Pudacuo National Park and its outer 20 km area showed an impairment of integrated ecosystem service. Among them, the decline in integrated ecosystem service in the 0–10 km range outside the national park was the weakest, with a decline of only 1.6794 %. Inside the national park was the next largest, at 1.9234 %; the 10–20 km range outside the national park showed the largest decline, at 2.3093 % (Table 3).

From 2005 to 2020, the spatial pattern of integrated ecosystem service in the study area was relatively stable, with the overall pattern of "high in the middle and north, and low in the south" (Fig. 5). The change in integrated ecosystem service showed a trend of gradually decreasing from north to south. The high-value areas of integrated ecosystem service occupied most of the area in sheets. Only the southeast and west showed low-value agglomeration. This phenomenon is related to the

fact that these areas were dominated by construction land, cultivated land and unused land, the disturbance intensity of human activities was strong, and the ecological function was relatively weak.

3.2. The protection effectiveness evaluation of ES

In this study, a PSM model was used to match three sets of paired samples from inside and outside the national park using elevation, slope, aspect, and soil type as covariates. Since this study examined the ESs protection effectiveness, a paired *t*-test was required for the dependent variable, ESs, between the three best-matched samples. The protection effectiveness of Pudacuo National Park was further explored through mean comparison and significance of differences analysis (Table 4, Fig. 6).

There were significant differences (P < 0.01) in the integrated ecosystem service protection effectiveness between the three surveyed regions inside and outside the national park. The integrated ecosystem service within the national park was higher than the 20 km range outside the national park. This suggests a correlation between the significant differences in integrated ecosystem services inside and outside national parks and their adoption of conservation measures. In addition, the magnitude of difference in integrated ecosystem services inside and outside the national park differed. The magnitude of difference between the areas within the national park and the 0–10 km range outside the national park was 0.145, while the magnitude of difference with the 10–20 km range outside the national park was 0.311. The difference between the two regions outside the national park was 0.22. This indicates that the integrated ecosystem services within the national park differ relatively little from the 0–10 km extent outside the national park (Table 4).

There are also differences in the individual ecosystem service protection effectiveness within and outside the national parks. The carbon storage services within the national park were more effective in protection. Its carbon sequestration capacity was more significantly different from the range of 0–10 km (P < 0.01) and 10–20 km (P < 0.01) outside the national park, with a difference of 0.113 and 0.266, respectively. Water conservation and habitat quality services within the national park were slightly lower than the 0–10 km range outside the national park, but the magnitude of the difference was small and the significance was weak. Compared to the 10–20 km range outside the national park, the water conservation and habitat quality protection within the national park and its external 0–10 km range was more
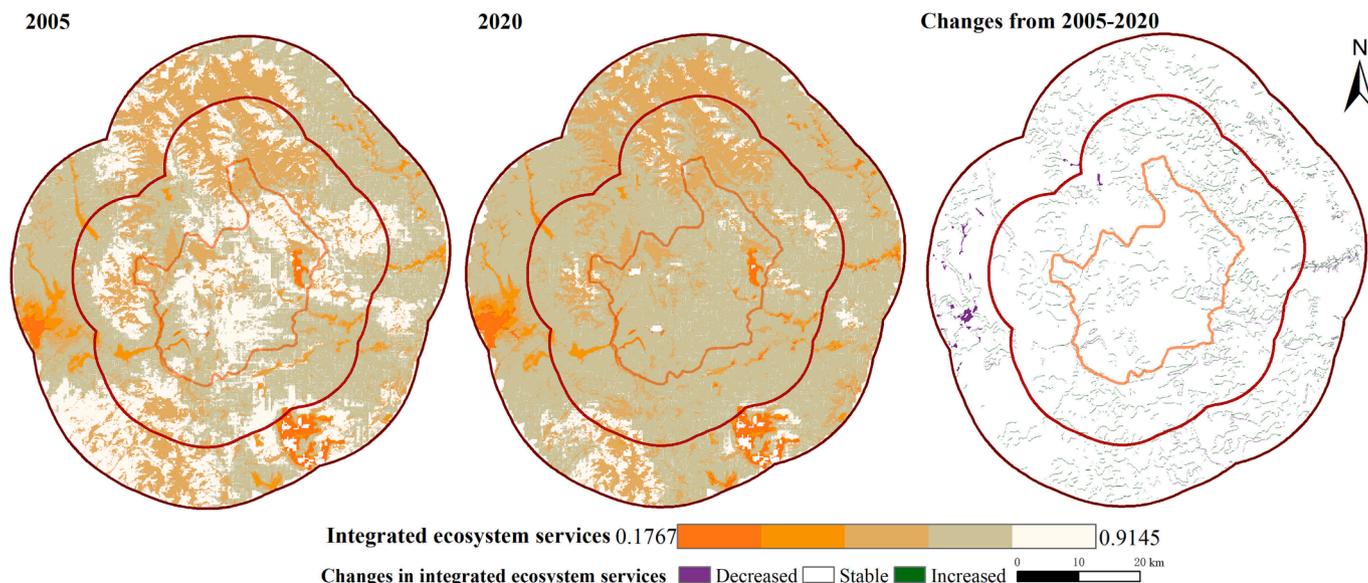

Fig. 5. Spatial distribution and change of integrated ecosystem service from 2005 to 2020.

Table 4
Paired *t*-test results of changes in ecosystem services for the three survey regions from 2005 to 2020.

	Integrated ecosystem services			Water conservation			Soil conservation			Carbon storage			Habitat quality		
	A_B	A_C	B_C	A_B	A_C	B_C	A_B	A_C	B_C	A_B	A_C	B_C	A_B	A_C	B_C
t	4.981	10.662	11.881	−1.941	4.808	2.406	−2.126	−1.507	1.384	3.909	9.16	6.886	−0.866	9.942	14.4
Cohen's d	0.145	0.311	0.22	0.056	0.14	0.045	0.062	0.044	0.026	0.113	0.266	0.128	0.063	0.289	0.267
P	0.000**	0.000**	0.000**	0.052	0.000**	0.000**	0.034*	0.082	0.166	0.000**	0.000**	0.000**	0.387	0.000**	0.000**

A refers to the Pudacuo National Park; B refers to the 0–10 km area outside the national park; C refers to the 10–20 km area outside the national park. * P < 0.05; ** P < 0.01; Cohen's d value indicates the magnitude of the difference, with larger values indicating larger differences.

effective and the level of service was significantly higher. In terms of soil conservation, the soil conservation capacity within the national park was slightly weaker than the 20 km range outside the national park, with a difference magnitude of 0.062 and 0.044 from the 0–10 km range and 10–20 km range outside the national park, respectively. But the variability inside and outside the national park was not significant (Table 4, Fig. 6).

In general, the establishment of Pudacuo National Park has achieved good protection effectiveness for both integrated ecosystem service and various ESs. ESs within and 0–10 km outside the national park are significantly better than in areas farther away from the national park. It also shows that conservation initiatives within national parks have a significant spillover effect on water conservation and habitat quality in surrounding regions (0–10 km). In addition, the soil conservation capacity within the national park is weaker than that of the external areas of the national park. This means that the establishment of Pudacuo National Park needs to improve the protection and management of soil conservation service.

4. Discussion

4.1. Pudacuo national park urgently needs to improve the protection effectiveness of soil conservation

The results of the study found that from 2005 to 2010, changes in ESs vary in national parks and their periphery. In terms of integrated ecosystem services, *water conservation,* carbon storage and habitat quality, the functional value of the national park and its outer 0–10 km range is always better than the 10–20 km range outside the national park. It can be seen that the establishment of Pudacuo National Park has alleviated the trend of ESs loss in the national park, confirming the existence of the national park and the effectiveness of related protection work.

Although the soil conservation function in Pudacuo National Park has also changed in the past 15 years, increasing by 0.0042 t, its soil conservation capacity is still weaker than that of the two surveyed areas outside the national park (Table 4). This further shows that the soil conservation capacity of Pudacuo National Park is relatively weak, and the establishment of the national park has not had a significant optimization effect on the soil conservation function in the park. Therefore, managers and decision makers in national parks should consider incorporating the optimization of soil conservation function into their priorities. By summarizing the advanced experience of similar national parks in soil conservation function maintenance, as well as scientific calculation and long-term planning, the anti-erosion ability of surface vegetation can be finally improved.

4.2. The establishment of PAs has spatial spillover effects on surrounding areas

The spatial proximity effect was first seen in the study of economic activities. It is often used to characterize an economic organization that reaps its effects while also having positive or negative effects on a certain range of people or society outside the organization (Liu et al., 2017). With the expansion of research on the spatial proximity effect, scholars found that this effect is also prominent in the fields of environmental policy formulation and biodiversity conservation (Chen, 2016; Amin, 2016).

According to existing studies, the spatial proximity effect of PAs can be mainly manifested as a positive spillover effect and a negative leakage effect (Ewers & Rodrigues, 2008; Zuo et al., 2019). For example, Russ et al. (2004) found in their study that Apo Island in the Philippines showed a threefold increase in fish stocks within its PA after an 18-year fishing closure, and also showed a more significant increase in fish stocks in the 200–250 m range outside its PA; Oliveira et al. (2007) found that the establishment of the Amazon Basin Nature Reserve
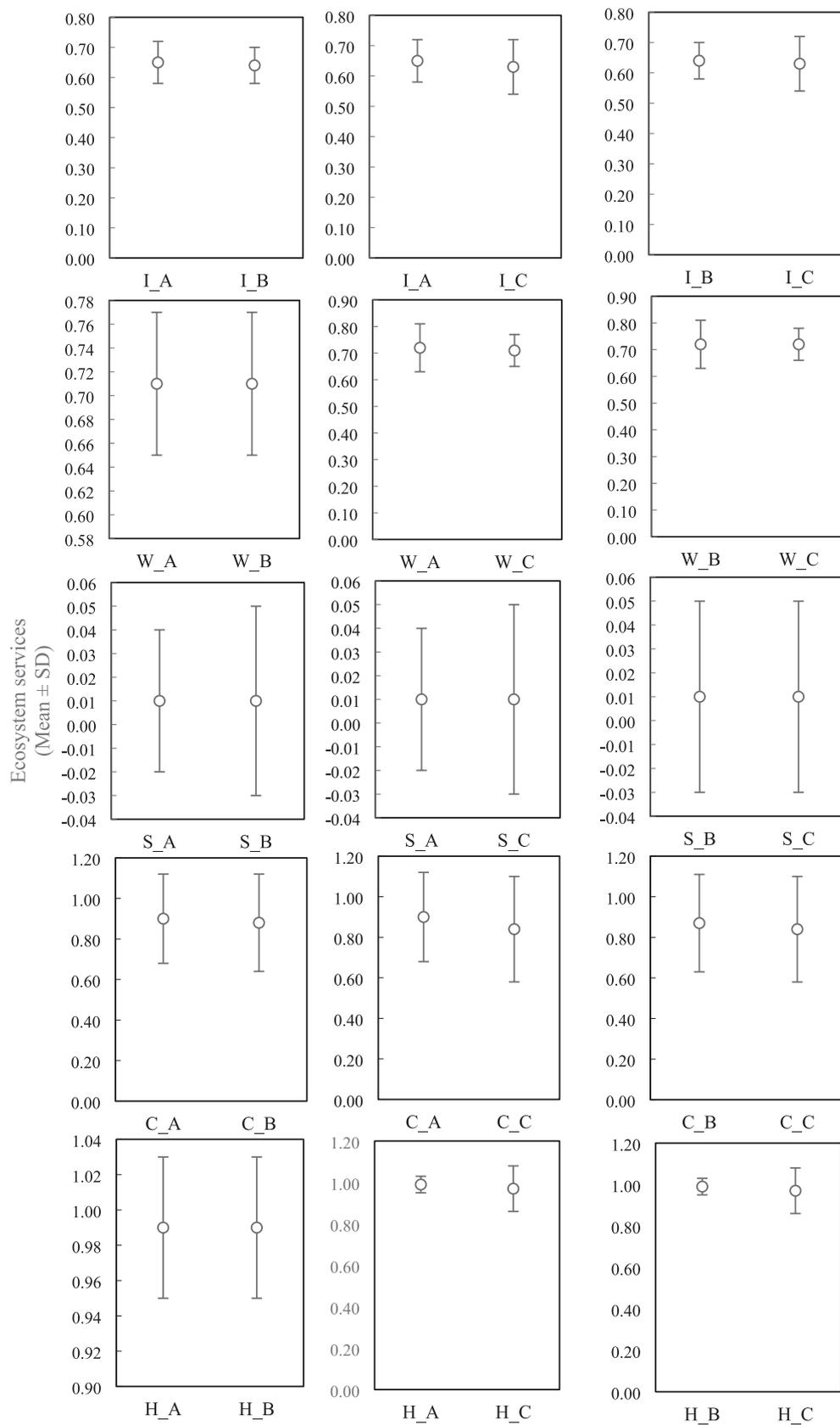
Fig. 6. Comparison of Mean Changes (Mean ± SD) in ESs for the three survey regions from 2005 to 2020.

effectively suppressed the rate of forest degradation within the reserve, while an increase in the rate of forest degradation occurred in the peripheral areas of the reserve. In this study, the protection effectiveness of ESs within Pudacuo National Park and its external 0–10 km range is better than that of ESs within 10–20 km range outside the national park. Moreover, both regions showed the same increasing and decreasing changes in all ESs with less variability. Pudacuo National Park has a positive spillover effect on the area within 0–10 km outside of it. The effect exists mainly from the establishment of the national park, which has brought about an improvement in relevant conservation policies and management levels, and to a certain extent mitigated the impacts caused by uncontrolled human activities. Since national parks are one of the important components of nature reserves, the spillover effect from Pudacuo National Park establishment is further evidence that spatial proximity effect exists in PAs.

4.3. The role of PSM in the PAs protection effectiveness evaluation

In recent years, most of the studies on the protection effectiveness of PAs are to compare the internal and external result variable of natural PAs (forest cover, species richness, etc.) (Western et al., 2009; Prowse et al., 2019), and to analyze the protection effectiveness based on their difference. Some scholars believed that there are differences in environmental factors such as climate, biology, and soil between inside and outside PAs. However, simply comparing the internal and external result variables will overestimate the protective effect of PAs, and it is difficult to accurately determine whether changes in relevant indicators are related to protection work.

As a quasi-experimental econometric method, the PSM model can minimize errors and imbalances caused by confounding environmental factors in non-randomized control studies (Schleicher et al., 2017; Schleicher et al., 2020). By comparing the rate of forest loss in Sumatra and its surrounding areas before and after matching, Gaveau et al. (2009) found that the deforestation rate was reduced by about 27 % before matching and to 7.4 % after matching. In the study of China's national forest protection plan and the effectiveness of PAs; Ren et al. (2015) pointed out that before the matching of samples inside and outside the PA, the establishment of the PA prevented the reduction of 4073 km^2 of forests, and the area after matching was reduced to 3148 km^2. Thus, the weakening effect of the PSM on the significant differences of samples was also confirmed. This study uses PSM to evaluate the protection effectiveness of national parks, verifies the applicability of this method in PAs protection effectiveness evaluation, which enriched the technical support for PAs environmental supervision and protection work optimization to a certain extent.

5. Conclusions

This study took Pudacuo National Park as the study case and constructed an ecosystem service conservation effectiveness assessment scheme based on the data from 2005 to 2020. The findings showed that the presence of Pudacuo National Park effectively mitigated the loss of four key ESs (water conservation, soil conservation, carbon storage and habitat quality). It also has a positive spillover effect on the 0–10 km area surrounding the national park. Although the loss of soil conservation in Pudacuo National Park was effectively mitigated, the difference was not significant compared with that outside the National Park. This suggests that the future course of action for Pudacuo National Park should focus on how to optimize and improve the soil conservation capacity of the area and reduce the intensity of soil erosion.

We constructed an ESs protection effectiveness assessment scheme based on the InVEST-PSM model, which realized dynamic tracking of ecosystem biomass changes, paid attention to the differences of environmental factors in comparative analysis, and improved scientific validity of protection effectiveness assessment. However, the complex interactions among ESs were neglected. In the following study, we will

enrich the evaluation metrics and explore the protection effectiveness assessment pathways that can integrate the changes in ESs and their trade-offs/coordination with each other.

CRediT authorship contribution statement

Zhang Xiaoyao: Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Zhong Linsheng:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Zhang Haizhou:** 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

The authors do not have permission to share data.

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