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RESEARCH ARTICLE

Spatial heterogeneity analysis of matching degree between endangered plant diversity and ecosystem services in Xishuangbanna

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Abstract

Biodiversity and ecosystem services (ESs) are closely linked. Human activities have caused critical damage to the habitat and ecosystem function of organisms, leading to decline in global biodiversity and ecosystem services. To ensure sustainable development of local ecological environments, it is critical to analyze the spatial matching degree of biodiversity and ESs and identify ecologically vulnerable areas. Taking Xishuangbanna, southern China, as an example, we constructed a pixel-scale matching degree index to analyze the spatial matching degree of endangered plant diversity (EPD) and four ESs and classified the matching degree into low-low, low-high, high-low, and high-high four types. The results revealed a mismatch relationship of EPD and ESs in more than 70% of areas. Under the influence of altitude and land use/land cover (LULC) type, the matching degree of EPD and ESs showed obvious spatial heterogeneity. In low-altitude areas in the south of Xishuangbanna, EPD and ESs mainly showed mismatch, while high-altitude areas in the west had a better match. Natural forest was the main land cover in which EPD and ESs showed high-high match and its areal proportion was much larger than that of rubber plantation, tea plantation, and cropland. Our findings also stress the need to concentrate conservation efforts on areas exhibiting a low-low match relationship, indicative of potential ecological vulnerability. The pixel-scale spatial matching degree analysis framework developed in this study for EPD and ESs provides high-resolution maps with 30 m × 30 m pixel size, which can support the implementation of ecological protection measures and policy formulation, and has a wide range of applicability. This study provides valuable insights for the sustainable management of biodiversity and ESs, contributing to the strengthening of local ecological environment protection.

Keywords Endangered plant diversity · Ecosystem services · Pixel-scale matching degree analysis · High-resolution maps · Xishuangbanna

Introduction

Ecosystem services (ESs) refer to the benefits of ecosystem functions that can be obtained by humans (de Groot et al. 2002; Faber and van Wensem 2012), as well as the

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direct or indirect contributions of ecosystems to humans (Kumar 2011). Biodiversity refers to the diversity of life forms, including intra-species, inter-species, ecosystem, and landscape diversity (Wilson 1993). Biodiversity is the basis of ecosystem services (Bai et al. 2011), and the two are closely related. The current sharp decline in global biodiversity is creating serious ecological problems (Bongaarts 2019). Land-use change caused by human activities is an important driving factor leading to biodiversity loss (Newbold et al. 2015). Most countries have signed international agreements aimed at reducing biodiversity loss, including the Convention on Biological Diversity (CBD) and the United Nations Sustainable Development Goals (SDGs) (Bongaarts 2019; Waldron et al. 2017). These aim to protect ESs and biodiversity through establishment of protected areas or formulation of protection plans and targeted policies (Karimi et al. 2020; Watson et al. 2020). However, this ignores ecosystem protection in most areas, as verified by the continuous decline in biodiversity worldwide (Narain et al. 2022). How to maintain the stability of ESs and avoid loss of biodiversity is a major challenge for humans (Xu et al. 2017; Bai et al. 2021).

Exploring the internal relationship between biodiversity and ESs is of great significance to further promote ecological restoration (Bullock et al. 2011). Earlier studies have assessed the relationship between biodiversity and ESs at the regional or watershed scale, but there are still gaps in the research on the relationship between biodiversity and ESs at pixel scale. At present, an important research method in the field of ecology is to judge the trade-offs and synergies of ESs through correlation analysis, which can be used to measure the interactions between different services (Plieninger et al. 2019). Pearson or Spearman coefficients are generally in correlation analysis of ESs (Hong et al. 2020), with positive values of these correlation coefficients representing synergies and negative values representing trade-offs. Bai et al. (2011) used correlation analysis to assess the correlation between biodiversity and ESs at the watershed scale; Liu et al. (2023) used correlation analysis to assess the trade-off synergies between biodiversity and ESs at the provincial scale. However, correlation analysis can only reflect the overall trade-off and synergistic relationship between biodiversity and ESs in the region and cannot reflect the spatial distribution at pixel scale. In addition, correlation analysis can only identify the degree of correlation between two ESs, such as one increasing and the other increasing at a fixed rate, or one increasing the other decreasing at a fixed rate. It cannot judge the quantity of the two ESs, which is not conducive to identification of ecologically fragile areas and fails to provide more targeted suggestions for policy makers. Therefore, there is an urgent need to propose a pixel-scale assessment framework to analyze the spatial distribution of the relationship between biodiversity and ESs and to identify ecologically vulnerable areas. The pixel-scale matching degree index proposed in this paper can make up the deficiency of correlation analysis. Construction of pixel-scale matching degree index can extend correlation analysis by analyzing the matching degree of biodiversity and ESs on each pixel in a study region. It can divide the matching degree into low-low, low-high, high-low, and high-high four types and can be displayed in a high-resolution map with 30 m × 30 m pixel size which can support decision-making in environmental policy.

Tropical regions are a recognized hotspot of biodiversity in the world, accounting for the vast majority of global biodiversity and making important contributions to important global ESs (Barlow et al. 2018). However, the tropics are currently experiencing unprecedented environmental degradation, mainly due to drastic changes in land use and deforestation, agricultural exploitation, and resource extraction (Curtis et al. 2018). Conversion of natural forests into artificial forests for commercial purposes destroys biodiversity and the integrity of natural systems. The expansion of artificial forests also contributes to habitat fragmentation in the tropics (Alroy 2017). Under the influence of climate and human activities, land use/land cover (LULC) varies at different altitudes (Becker et al. 2007; Fang et al. 2020). Differences in LULC are an important cause of changes in regional ESs supply levels and biodiversity levels (Carter Berry et al. 2020; Pelorosso et al. 2016). For the present analysis, we selected as our study area the region of Xishuangbanna in southern China, which is called the "tropical treasure house" of biodiversity. We focused on the spatial distribution of matching degree index between endangered plant diversity (EPD) and ESs on pixel scale and considered potential measures to protect local ecosystems based on local conditions. Specific objectives of the study were to (1) construct a matching degree index of EPD and ESs; (2) analyze the spatial distribution of matching degree index with 30 m × 30 m pixel size; and (3) put forward suitable policy suggestions.

Materials and methods

Study region

Xishuangbanna Dai Autonomous Prefecture is located in the south of Yunnan Province, China (21°10′–22°40′ N, 99°55′–101°50′ E). It has jurisdiction over three administrative regions, namely, Jinghong City, Menghai County, and Mengla County, covering an area of 19,125 km^2 (Fig. 1). The terrain in Xishuangbanna is mainly mountainous, with an elevation range of 369–2404 m above sea level (ASL). The region borders Laos to the

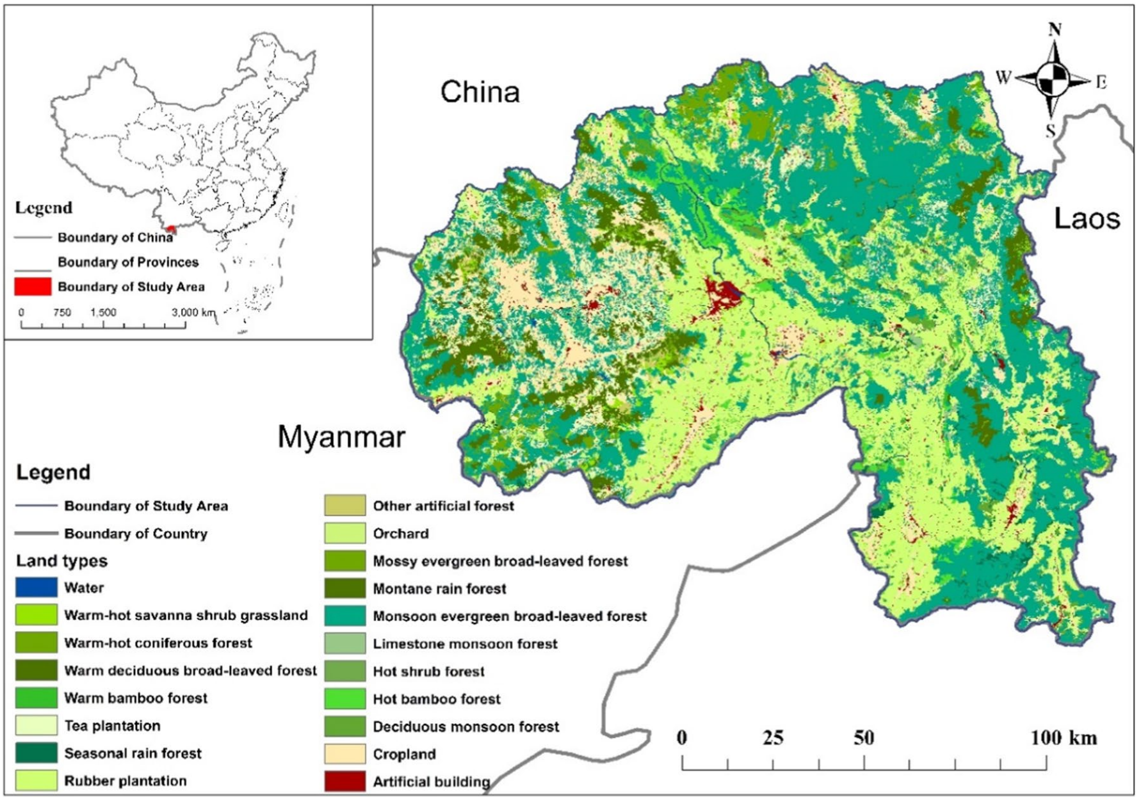

Fig. 1 Maps showing the location and land use/land cover (LULC) of the Xishuangbanna region in China

southeast and Myanmar to the southwest. Xishuangbanna has abundant rainfall and abundant sunshine, with mean annual precipitation of 1200–2800 mm and mean annual temperature of 20–22.5 °C.

Xishuangbanna is the most biodiversity-rich area in China. It contains the only tropical rain forest nature reserve in China and is part of the Indo-Myanmar tropical biodiversity hotspot (Myers et al. 2000). Xishuangbanna occupies only 0.2% of China's land area but contains more than 5000 species of its higher plants, accounting for 14.9% of the total number of higher plant species in China. Many plant species and genera grow in intersecting patterns, forming complex and diverse vegetation landscapes such as tropical rain forest, tropical monsoon rain forest, and subtropical evergreen broad-leaved forest (Li et al. 2018). Since rubber was first introduced to Xishuangbanna in the 1950s, the area of rubber plantations has increased dramatically, accounting for about 25% of total land area in 2016. The rapid expansion of rubber plantations in Xishuangbanna has led to a sharp decrease in the area covered by natural forest vegetation, which has had negative impacts on local ecological processes and the capacity for supply of ESs (Chazdon 2008; Qiu 2009). From 1976 to 2012, carbon storage and water yield services in Xishuangbanna decreased by 15.5% and 10.6%, respectively (Liu et al. 2017).

Analytical framework for matching degree of EPD and ESs

This study proposes a pixel-scale assessment framework to calculate the spatial matching degree of EPD and ESs and classify the matching degree to identify ecologically vulnerable areas. In this framework (Fig. 2), the MaxEnt model was used to predict the spatial distribution of EPD, and the InVEST model was used to quantify the spatial distribution of ESs. The spatial matching index is used to calculate the matching degree of EPD and ESs in each grid, and the entire calculation process needs to be completed in GIS software. The research framework mainly comprised four stages: (1) data preparation, using digital elevation model (DEM) data, LULC data, climate data, and other biophysical data; (2) model estimation and EPD and ESs assessment, including model selection, calculation, and result verification; (3) construction of matching degree index at pixel scale, displayed in high-resolution maps with 30 m × 30 m pixel size; and (4) analysis of results and proposal of effective protection measures.

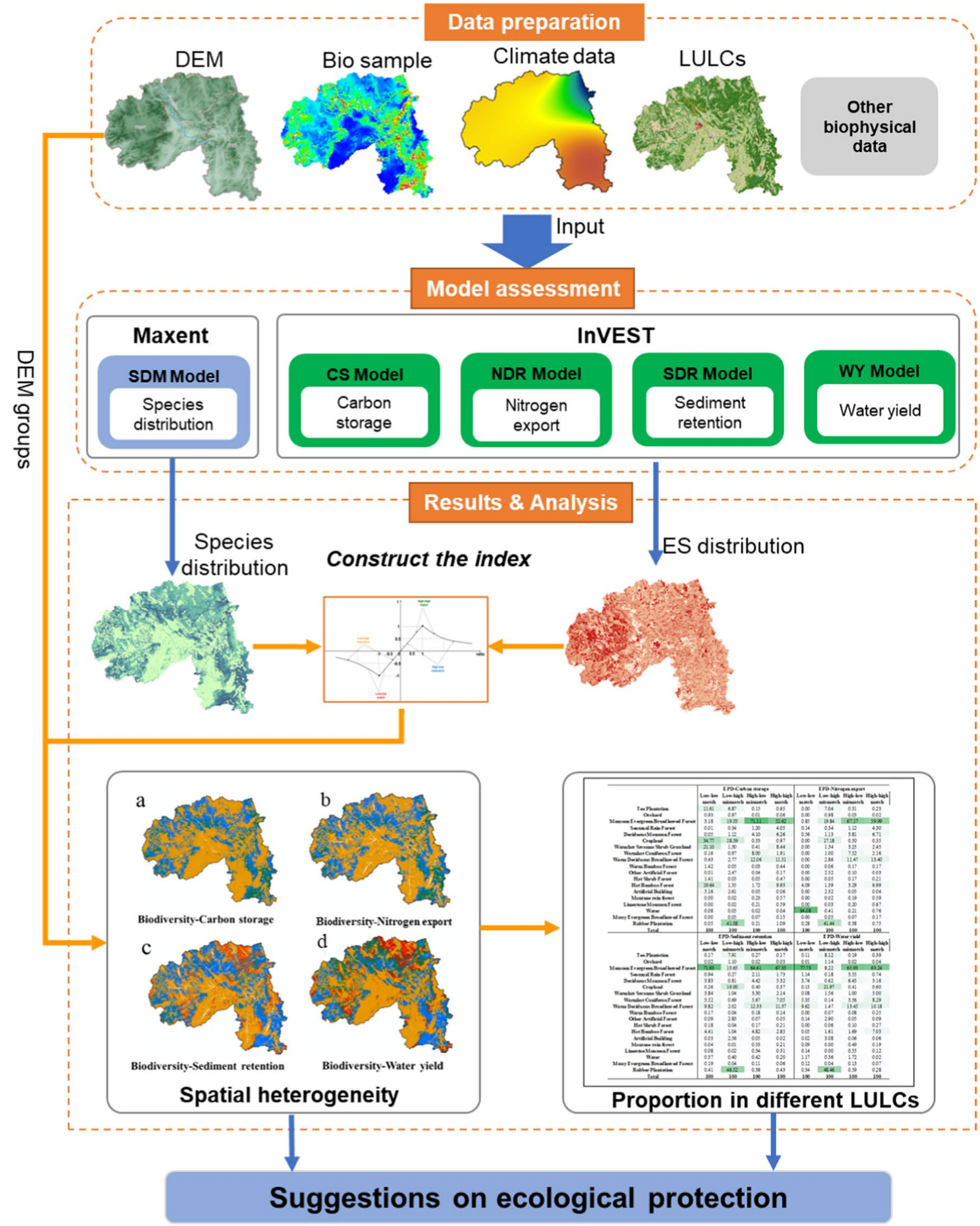

Fig. 2 Analytical framework for matching degree of endangered plant diversity and ecosystem services (DEM: digital elevation model, LULC: land use/land cover, CS: carbon storage, SDR: sediment delivery ratio, WY: water yield, NDR: nutrient delivery ratio, ES: ecosystem service)

MaxEnt prediction of EPD

We selected 39 species of endangered plants defined by the International Union for Conservation of Nature (IUCN) as species facing a high risk of extinction. Distribution data for endangered plants were obtained in field surveys conducted in April–June 2019. We used hand-held GPS (Garmin 64 s, with a positional accuracy of 3 m) to record the coordinates of the endangered species and to ensure accurate identification. These field surveys yielded 674 records of 35 species of endangered plants and another four species were not found in the field. In order to ensure better spatial correlation and geographical accuracy, if there were fewer than three records within 1 km, they were all retained, but if the same species were involved, one-third of these records was deleted. Through data collection and filtering, 410 records were selected for model analysis. The analysis focuses on the most diverse regions rather than focusing on each species during modeling.

We compiled and selected geographic information system (GIS) environmental variables for the whole of Xishuangbanna using a series of source data, which included different bioclimatic variables, or bioclimatic predictors, and a set of four geographical environmental factors. Details of the number of species and species distribution, and of selection and calibration of environment variables, can be found in SI (Part 1).

The maximum entropy (MaxEnt) model is a general-purpose machine learning method with a simple and precise mathematical formulation that has been shown to perform well in predicting habitat suitability and species distributions with presence-only data. We used MaxEnt version 3.4.1 to build an endangered plant species hotspot model for Xishuangbanna. We used all effective occurrence species data and set up MaxEnt as follows: (1) we randomly selected 25% of data as test data; (2) we set the regularization multiplier (RM) to 1.1; (3) we used the average of four replicates of cross-validation type from the model runs for further analysis; (4) we set the features linear, quadratic, product, and hinge; and (5) we used other default model settings.

In the present study, the biodiversity distribution was modeled for 35 target endangered species in the Xishuangbanna study area. We used the jackknife method to test the environmental variables and assessed the performance of the species model using area under the curve (AUC) of the receiver operating characteristic (ROC) (Phillips et al. 2006). We used the maximum specificity and sensitivity logistic threshold to convert all species data to a probability of 0 to 1 (Liu et al. 2013). The mean training and testing AUC obtained from four simulation iterations was 0.836 and 0.79, respectively, showing that the model provided acceptable predictions and highly accurate performance. Details of model validation can be found in SI (Part 1).

ESs assessment stage: selection, calculation, and validation

Selecting appropriate ESs index is crucial and challenging for regional ESs evaluation (Bai et al. 2018; Wong et al. 2015). A wide range of stakeholders are involved in the ecosystem and seek to use the same available resources for different purposes. Stakeholder analysis can systematically identify these stakeholders and evaluate and compare their specific interests, roles, and powers (Raum 2018). Therefore, we used stakeholder analysis to select ESs to be studied, taking into account human consumption of ESs, policy relevance, and data availability (Fang et al. 2020).

Based on these principles and considering the resource structure of Xishuangbanna and its major stakeholders (Table 1), we selected four ESs related to services: carbon storage service, water yield service, sediment retention service, and nitrogen export service. These four key ecosystem services are a priority for policy makers, and China invested heavily in the period 2000–2010 to protect and restore the value of these services (Ouyang et al. 2016).

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model has been widely used in many countries and regions (Bai et al. 2020; Goldstein et al. 2012). Unlike many other models, InVEST can spatially display the results of ESs quantification on a visual map. InVEST also has a number of (sub-)models with different levels of accuracy that users can choose from according to their needs and actual data accuracy, making it easier for users to use (Sharp et al. 2016).

The carbon storage (CS) and water yield (WY) models in InVEST were used here to assess the spatial distribution of carbon storage and water yield amount in Xishuangbanna. The sediment delivery ratio (SDR) model was used to calculate sediment retention amount, in order to quantify soil conservation services. The nutrient delivery ratio (NDR) model was used to calculate the amount of nitrogen

Table 1 Ecosystem services (ESs) selected for study in Xishuangbanna based on multi-stakeholder analysis

Stakeholders	Commercial plantation owners	Residents	Government
Goals	Develop commercial planting (especially rubber) to maximize economic benefits	Access to sufficient clean water	Good political achievements: ensure ecological health and balanced regional development
ESs concerned	Nutrient supply: higher nutrient supply gives better plant yield and more economic benefits for owner	Water yield: closely related to amount of surface water available for residents Water purification: a direct impact on the water quality of residents closely related to their health	Soil conservation: key assessment indicator of regional ecological protection Water purification: a direct impact on the quality of resident water supply, closely related to public health Carbon storage: reflects the contribution of carbon reduction in the region

exported, as a reflection of water purification and nutrient supply services (Fang et al. 2020). When commercial plantation owners use fertilizers or pesticides to advance their own economic interests, this results in soil erosion and water quality degradation. Excessive nutrient output due to excessive use of fertilizers creates obvious tradeoffs for other stakeholders (Kim et al. 2019). The results of all four models were validated with reference data for Xishuangbanna. Details of all sub-models and the calculation process for each ES can be found in SI (Part 2).

Data preparation stage

The two most important types of pixel data were prepared to run the models. These were biodiversity data, characterized by EPD data based on data availability which can be found in SI (Part 1), and four key pieces of data needed to calculate ESs, DEM, LULC, annual precipitation, and biophysical data (Table 2). The accuracy of the data was 30 m × 30 m, and 2016 was selected as the base year for the study. LULC data for 2016 were obtained from Yunnan Forestry Survey and Planning Institute. These were relatively new multi-classification land use data and contained the distribution of various types of vegetation, providing a data basis for analyzing the influence of different types of vegetation on the supply level of ESs and the level of biodiversity.

Spatial matching degree index construction

In order to fill in the shortcomings of existing research, realize the spatial heterogeneity analysis of the matching degree of EPD and ESs on a high-precision grid, build a spatial matching degree analysis model, and quantitatively evaluate the spatial matching degree between EPD and four ESs, the spatial matching degree index is constructed as follows.

First, the data on EPD and ESs were standardized by min-max and the original data were linearly transformed to map the result values to [0,1], to eliminate the influence of different dimensions on the calculation results. The conversion function for carbon storage service, water yield service, and sediment retention service, which have positive effects on ecosystem protection, is $x_i = \frac{x - \min}{\max - \min}$, where *max* is the maximum value of sample data and *min* is the minimum value. The conversion function of nitrogen export service, which has a negative effect on ecosystem protection, is $x_i = \frac{\max - x}{\max - \min}$.

$$\begin{cases} ratio_{i,j} = \frac{BIO_i}{ES_{i,j}}, \text{if } BIO_i \geq \overline{BIO} \\ ratio_{i,j} = -\frac{BIO_i}{ES_{i,j}}, \text{if } BIO_i < \overline{BIO} \end{cases}$$

$$\begin{cases} I = ratio_{i,j}, -1 \leq ratio_{i,j} \leq 1 \\ I = \frac{1}{ratio_{i,j}}, \qquad \text{else} \end{cases}$$

The matching degree index I is in the range [−1,1]. In the range $-1 \leq I < -0.5$, it indicates that there is a low-low match between the two variables, i.e., low EPD and ESs levels, with EPD lower than the mean value. In the range $-0.5 \leq I < 0$, it indicates that there is a low-high mismatch between the two, i.e., low EPD level (below the mean value) and high ESs level. In the range $0 \leq I < 0.5$, it indicates that there is a high-low mismatch between the two, i.e., EPD higher than the mean value and ESs level lower. Finally, in the range $0.5 \leq I \leq 1$, it indicates that there is a high-high match between the two, i.e., high EPD and ESs levels, with EPD higher than the mean value. The function curve and range distribution of matching degree index are shown in Fig. 3.

Statistical analysis

Spatial statistical tools in ArcGIS were used as a complement to the InVEST model to quantify the altitude-associated matching degree between EPD and different ESs. Based on elevation in 25% of the area, the whole study area was divided into four elevation gradients (400–800, 800–1000, 1000–1300, and 1300–2400 m (ASL)), and the distribution of each area was analyzed using statistical tools.

Table 2 Key data for the InVEST model in this study

Data	Data source	Type	Related model
Digital elevation model (DEM)	Geospatial Data Cloud, http://www.gscloud.cn	Raster	SDR, NDR
Land use/land cover	Yunnan Institute of Forest Inventory and Planning	Raster	CS, SDR, WY, NDR
Annual average precipitation	China Meteorological Data Centre, http://data.cma.cn/	Raster	SDR, WY, NDR
Biophysical data	Literature, InVEST user's guide	.CSV file	SDR, WY, SDR

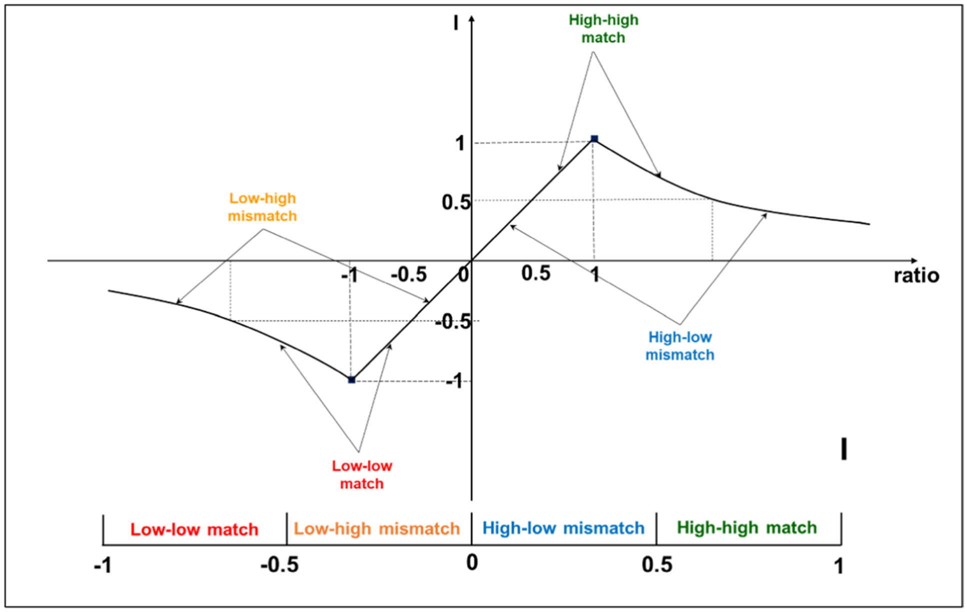

Fig. 3 Function curve and range distribution of matching degree index

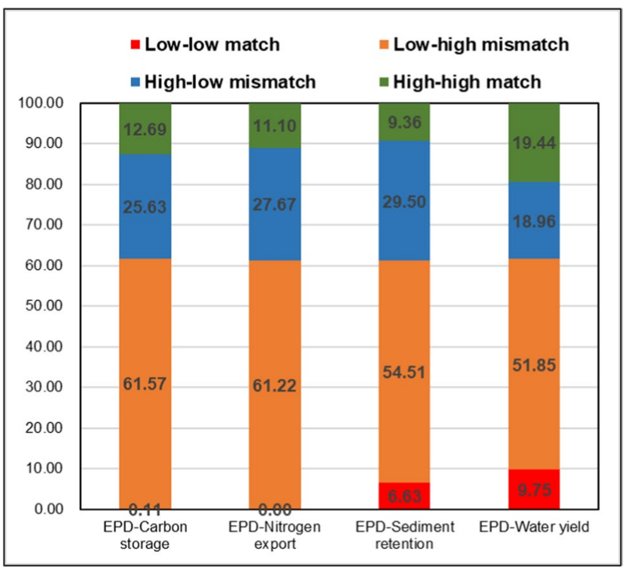

Fig. 4 Ratio of matching degree between endangered plant diversity (EPD) and four ecosystem services (ESs) in Xishuangbanna

Results

Trend analysis of matching degree between EPD and ESs

Endangered plant diversity and the four ESs studied mainly showed mismatch relationships, accounting for more than 70% of the total, with low-high mismatch relationships accounting for more than 50% of these (Fig. 4). Regions with ESs above the average level had a low level of EPD and habitat conditions needed to be improved. Among the four ESs, the mismatch relationship between EPD and nitrogen export service was highest (88.89%) and the high-high match relationship between EPD and water yield service was relatively high (19.44%).

With increasing elevation, the proportion of low-high mismatch between EPD and ESs showed a sharp decline and then a gentle decline (Fig. 5a–d). The proportion of high-low mismatch between EPD and carbon storage, nitrogen export, and sediment retention services showed a trend of rapid increase and then gentle increase in all cases (Fig. 5a–c). However, the proportion of high-low mismatch with water yield service showed a trend of first increasing, then decreasing, and then increasing again (Fig. 5d). This indicates that the level of EPD increased significantly with increasing elevation. The proportion of high-high match between EPD and carbon storage and nitrogen export services also showed a trend of first increasing, then decreasing, and then increasing again (Fig. 5a–b). With increasing altitude, the proportion of areas with high-high match with water yield service gradually increased (Fig. 5d).

Spatial heterogeneity analysis of matching degree between EPD and ESs

The spatial distribution of matching degree between EPD and ESs at pixel scale is shown in Fig. 6. Low-high mismatch relationships between EPD and the four ESs were mainly distributed in low-altitude (400–800 m) areas in the south of Xishuangbanna and in medium- and high-altitude (1000–1300 m) areas in the north. High-low mismatch relationships were mainly distributed in medium-altitude (800–1300 m) areas in the middle of Xishuangbanna and

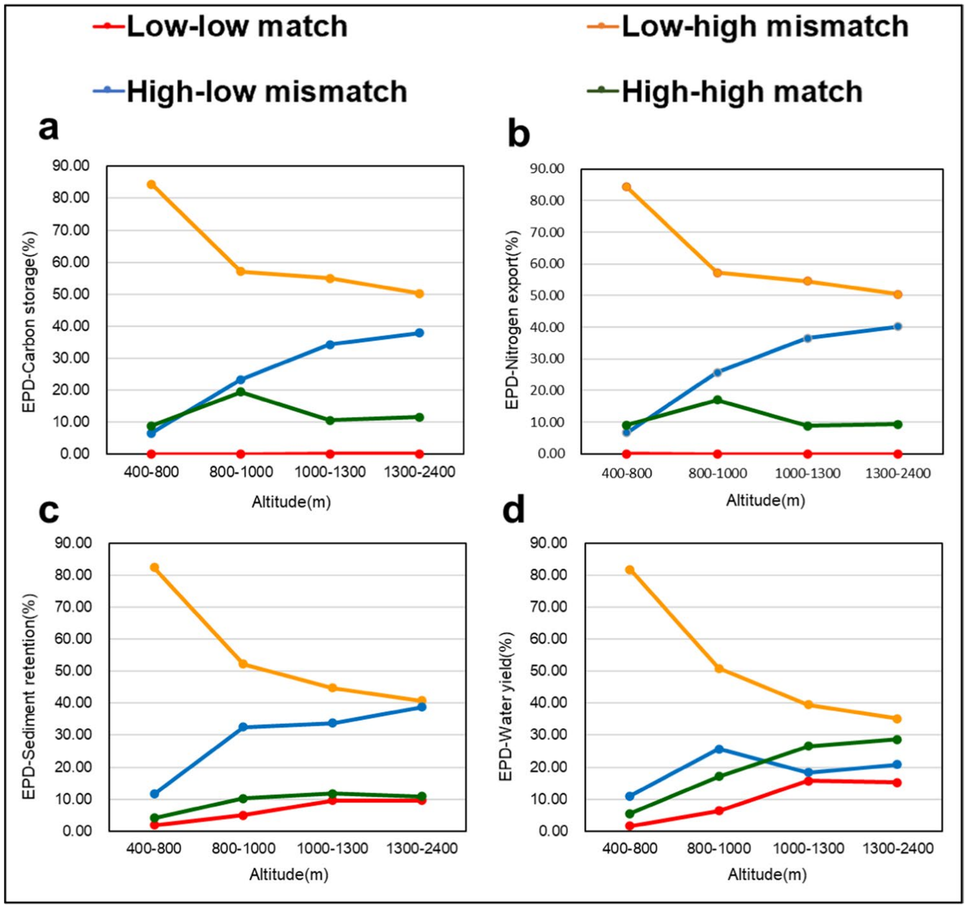

Fig. 5 Four types of matching degree between endangered plant diversity (EPD) and ecosystem services (ESs) in Xishuangbanna with elevation change

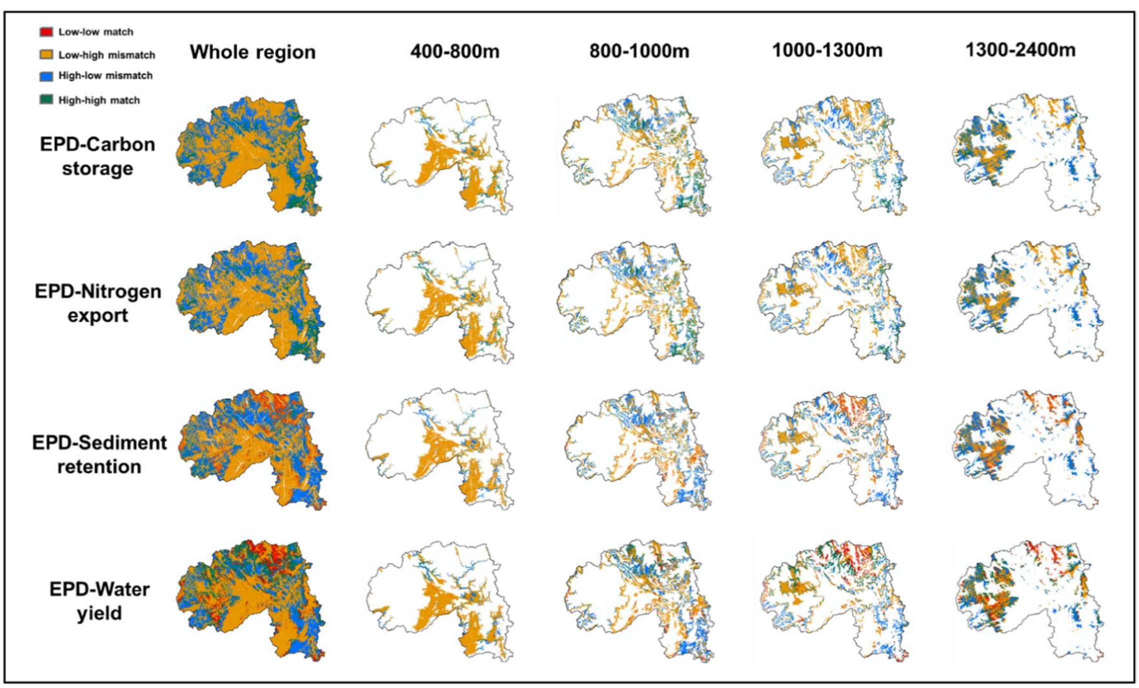

Fig. 6 Spatial distribution of matching degree between endangered plant diversity (EPD) and ecosystem services (ESs) within different altitude classes in Xishuangbanna

in high-altitude (1300–2400 m) areas in the west. Low-low match of EPD with sediment retention service and water yield service were mainly distributed in medium- and high-altitude (1000–2400 m) areas in the north of Xishuangbanna and in high-altitude (1300–2400 m) areas in the southwest. High-high match relationships were mainly distributed in central and southeastern areas of Xishuangbanna (800–1000 m). High-high match of EPD with sediment retention service and water yield service were mainly distributed in medium-altitude (1000–1300 m) areas in the middle of Xishuangbanna and in high-altitude (1300–2400 m) areas in the west (Fig. 6).

The ratio of matching degree between EPD and ESs at different altitudes is shown in Fig. 7. Low-low match relationships between EPD and nitrogen export service were almost all distributed in the low-altitude (400–800 m) region, while low-low match relationships between EPD and carbon storage, sediment retention, and water yield services were mainly distributed in medium- and high-altitude areas (above 1000 m), accounting for more than 70%. Low-high mismatch relationships between EPD and the four ESs were mostly distributed in the 400–800 m altitude area, accounting for 30~40%. High-low mismatch relationships between EPD and the four ESs were less frequent in the 400–800 m area and more frequent at altitudes above 1000 m. High-high match relationships between EPD and carbon storage and nitrogen export services were distributed more in the 800–1000 m altitude region. High-high match relationships between EPD and sediment retention service were mainly distributed in medium- and high-altitude areas (above 800 m) and the maximum distribution (31.8%) was found between 1000 and 1300 m. High-high match relationships between EPD and water yield service were mainly distributed in the 1300–2400 m altitude area (36.8%).

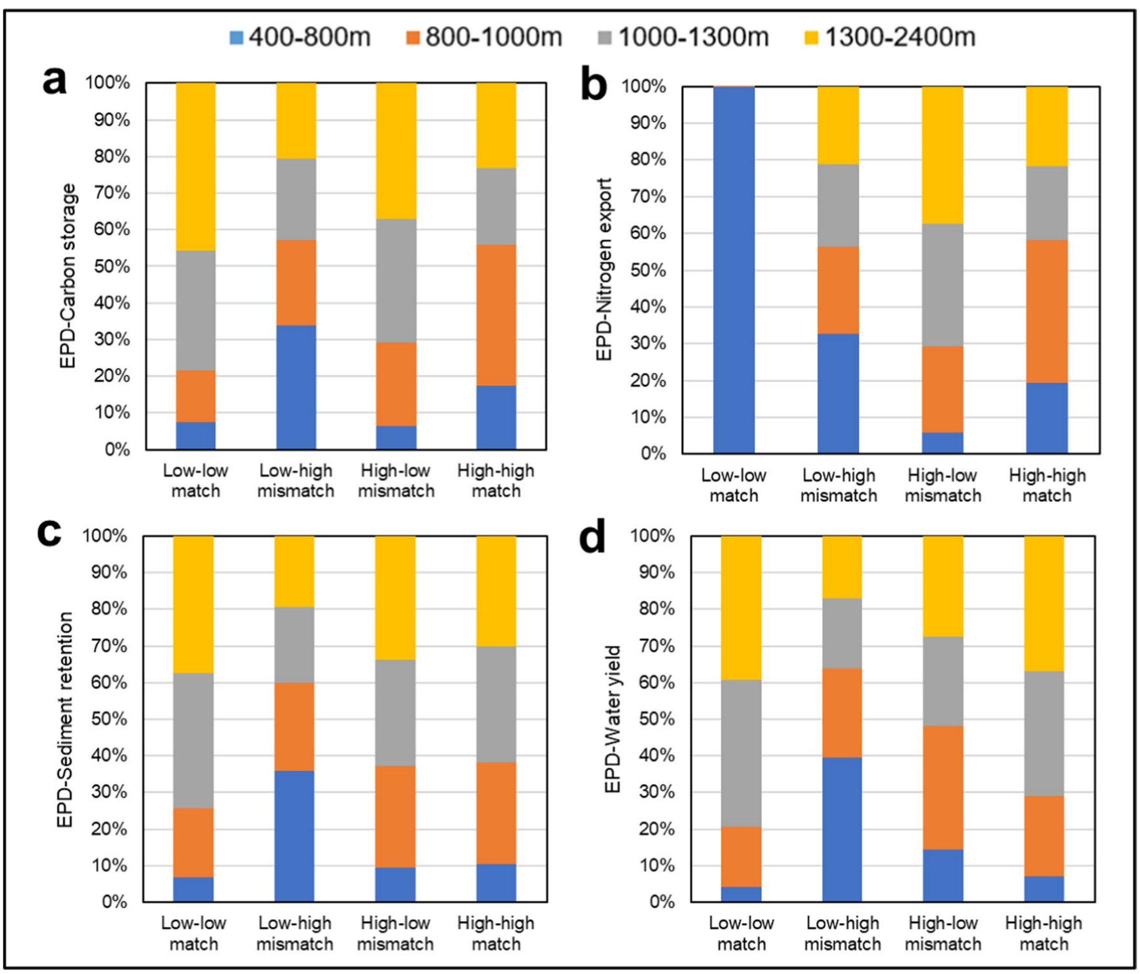

Fig. 7 Ratio of matching degree between endangered plant diversity (EPD) and ecosystem services (ESs) at different altitudes in Xishuangbanna

Analysis of matching degree between EPD and ESs with different LULC

The distribution of matching degree between EPD and ESs was affected by LULC. The proportions of matching degree between different LULCs in each matching relationship are shown in Fig. 8. In areas with low-low match relationships between EPD and carbon storage service, cropland, warm hot savannah shrub grassland, hot bamboo forest, and tea plantations accounted for a relatively high proportion, indicating that these regions had low EPD and low carbon storage service. In areas with low-high mismatch relationships, the proportions of rubber plantation, monsoon evergreen broadleaved forest, and cropland were relatively high, indicating low EPD and relatively high carbon storage service in these regions. In areas with low-low match relationships between EPD and nitrogen export service, open water accounted for the largest proportion (94%). In areas with low-high mismatch relationships, rubber plantation, monsoon evergreen broadleaved forest, and cropland accounted for the highest proportion. The distribution of matching degree between EPD and sediment retention service and water yield service were similar for different LULCs. Monsoon evergreen broadleaved forests and rubber plantations respectively occupy the highest proportions in low-low match and low-high mismatch areas. More than half of the areas with high-low mismatch and high-high match relationships were monsoon evergreen broadleaved forests, indicating that the EPD under this vegetation is relatively high. In areas where EPD and ESs exhibit a high-low mismatch and a high-high match relationships, monsoon evergreen broadleaved forests account for more than half of the proportion

	EPD-Carbon storage				EPD-Nitrogen export			
	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Low-low match	Low-high mismatch	High-low mismatch	High-high match
Tea Plantation	11.61	6.87	0.15	0.65	0.00	7.04	0.31	0.23
Orchard	0.93	0.97	0.01	0.06	0.00	0.98	0.03	0.02
Monsoon Evergreen Broadleaved Forest	3.18	19.33	71.11	52.62	0.85	19.84	67.17	59.99
Seasonal Rain Forest	0.01	0.34	1.20	4.05	0.14	0.34	1.12	4.30
Deciduous Monsoon Forest	0.05	1.12	4.10	6.26	0.56	1.13	3.81	6.71
Cropland	34.77	18.59	0.33	0.97	0.00	17.18	0.50	0.35
Warmhot Savanna Shrub Grassland	21.10	1.30	0.41	8.44	0.00	1.34	3.25	2.45
Warmhot Coniferou Forest	0.16	0.97	8.00	1.91	0.00	1.00	7.52	2.16
Warm Deciduous Broadleaved Forest	0.43	2.77	12.06	11.51	0.00	2.86	11.47	13.40
Warm Bamboo Forest	1.42	0.05	0.03	0.44	0.00	0.06	0.17	0.17
Other Artificial Forest	0.01	2.47	0.04	0.17	0.00	2.52	0.10	0.03
Hot Shrub Forest	1.41	0.05	0.05	0.47	0.00	0.05	0.17	0.21
Hot Bamboo Forest	19.64	1.35	1.72	9.93	4.09	1.39	3.29	6.99
Artificial Building	5.16	2.61	0.05	0.06	0.00	2.32	0.05	0.04
Montane rain forest	0.00	0.02	0.23	0.57	0.00	0.02	0.19	0.59
Limestone Monsoon Forest	0.00	0.02	0.21	0.59	0.00	0.03	0.20	0.67
Water	0.08	0.05	0.02	0.04	94.08	0.41	0.21	0.76
Mossy Evergreen Broadleaved Forest	0.00	0.05	0.07	0.15	0.00	0.05	0.07	0.17
Rubber Plantation	0.05	41.08	0.21	1.09	0.28	41.44	0.38	0.75
Total	100	100	100	100	100	100	100	100

	EPD-Sediment retention				EPD-Water yield			
	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Low-low match	Low-high mismatch	High-low mismatch	High-high match
Tea Plantation	0.17	7.91	0.27	0.17	0.11	8.12	0.19	0.39
Orchard	0.02	1.10	0.02	0.03	0.01	1.14	0.02	0.04
Monsoon Evergreen Broadleaved Forest	71.63	13.65	64.61	67.33	77.73	8.22	65.93	63.24
Seasonal Rain Forest	0.94	0.27	2.11	1.73	1.14	0.18	3.55	0.74
Deciduous Monsoon Forest	3.83	0.81	4.42	5.32	3.74	0.62	6.45	3.16
Cropland	0.26	19.00	0.40	0.37	0.15	21.97	0.41	0.60
Warmhot Savanna Shrub Grassland	3.84	1.04	3.30	2.14	0.08	1.56	1.00	5.00
Warmhot Coniferou Forest	3.52	0.69	5.67	7.05	5.35	0.14	3.56	8.29
Warm Deciduous Broadleaved Forest	9.82	2.02	12.33	11.37	9.62	1.47	13.45	10.18
Warm Bamboo Forest	0.17	0.04	0.18	0.14	0.00	0.07	0.08	0.25
Other Artificial Forest	0.09	2.83	0.07	0.05	0.14	2.90	0.05	0.09
Hot Shrub Forest	0.18	0.04	0.17	0.21	0.00	0.06	0.10	0.27
Hot Bamboo Forest	4.41	1.04	4.82	2.85	0.05	1.61	1.69	7.03
Artificial Building	0.03	2.56	0.05	0.02	0.02	3.08	0.06	0.06
Montane rain forest	0.04	0.01	0.33	0.21	0.09	0.00	0.49	0.19
Limestoe Monsoon Forest	0.08	0.02	0.34	0.31	0.14	0.00	0.55	0.12
Water	0.37	0.40	0.42	0.20	1.17	0.36	1.72	0.02
Mossy Evergreen Broadleaved Forest	0.19	0.04	0.11	0.06	0.12	0.04	0.13	0.07
Rubber Plantation	0.41	46.52	0.38	0.43	0.34	48.46	0.59	0.28
Total	100	100	100	100	100	100	100	100

Fig. 8 Proportions of different land use/land covers in each matching relationship between endangered plant diversity (EPD) and ecosystem services (ESs) in Xishuangbanna

in both cases, indicating that the EPD under this vegetation type is relatively high.

The proportions of different matching relationships in each LULC type are shown in Fig. 9. In LULC types such as tea plantation, orchard, cropland, other artificial forest, artificial building, and rubber plantation, an overwhelming majority of over 95% of the area exhibits a low-high mismatch relationship. In contrast, LULC types like monsoon evergreen broadleaved forests, deciduous monsoon forest, and warm deciduous broadleaved forest show a comparatively high prevalence of the high-low mismatch relationship. For areas covered by mossy evergreen broadleaved forest and open water, the mismatch relationship accounts for more than half of the total area. In other LULC types, high-low mismatch or high-high match relationships are dominant, suggesting a relatively elevated level of EPD within these areas.

Discussion

Advanced compared to existing methods

A large number of literatures were keen on ESs hotspot mapping and provide ESs hotspot maps of different scales in different regions of the world (Bagstad et al. 2017; Blumstein and Thompson 2015; Schröter and Remme 2016), which was helpful for spatial identification of ecological hotspot. A growing number of literatures combined correlation analysis and hotspot overlap analysis to assess the spatial consistency of biodiversity and ESs (Bai et al. 2011). Recent work that integrates biodiversity with ESs was often based on co-occurrence mapping of high values for both objectives (Hermoso et al. 2018; Hou et al. 2018). However, most studies can only analyze the correlation between biodiversity and ESs at the regional scale, or analyze the spatial distribution

	EPD-Carbon storage					EPD-Nitrogen export				
	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Total	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Total
Tea Plantation	0.20	97.01	0.92	1.88	100	0.00	97.51	1.91	0.57	100
Orchard	0.11	97.95	0.60	1.34	100	0.00	98.30	1.41	0.29	100
Monsoon Evergreen Broadleaved Forest	0.01	32.26	49.69	18.05	100	0.00	32.48	49.70	17.81	100
Seasonal Rain Forest	0.00	20.06	30.06	49.88	100	0.00	21.02	31.04	47.94	100
Deciduous Monsoon Forest	0.00	27.13	41.66	31.21	100	0.00	27.83	42.25	29.92	100
Cropland	0.22	98.01	0.72	1.05	100	0.00	98.34	1.30	0.37	100
Warmhot Savanna Shrub Grassland	0.79	40.27	5.37	53.58	100	0.00	41.13	45.22	13.65	100
Warmhot Coniferou Forest	0.00	20.51	71.14	8.35	100	0.00	20.88	70.95	8.17	100
Warm Deciduous Broadleaved Forest	0.01	27.22	49.55	23.22	100	0.00	27.31	49.48	23.21	100
Warm Bamboo Forest	1.08	33.95	7.59	57.38	100	0.00	34.96	45.97	19.08	100
Other Artificial Forest	0.00	97.93	0.71	1.36	100	0.00	98.07	1.68	0.25	100
Hot Shrub Forest	1.01	29.48	12.27	57.23	100	0.00	31.19	45.93	22.88	100
Hot Bamboo Forest	0.58	32.61	17.41	49.40	100	0.01	33.57	35.87	30.56	100
Artificial Building	0.24	98.51	0.76	0.49	100	0.00	98.69	1.00	0.32	100
Montane rain forest	0.00	7.34	41.62	51.04	100	0.00	7.86	41.55	50.59	100
Limestone Monsoon Forest	0.00	10.57	37.16	52.27	100	0.00	10.87	37.85	51.28	100
Water	0.15	74.24	12.37	13.24	100	0.82	63.28	14.66	21.25	100
Mossy Evergreen Broadleaved Forest	0.00	46.86	26.04	27.10	100	0.00	46.72	26.03	27.25	100
Rubber Plantation	0.00	99.25	0.21	0.54	100	0.00	99.26	0.41	0.33	100

	EPD-Sediment retention					EPD-Water yield				
	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Total	Low-low match	Low-high mismatch	High-low mismatch	High-high match	Total
Tea Plantation	0.25	97.58	1.81	0.36	100	0.25	97.18	0.83	1.74	100
Orchard	0.24	98.33	1.01	0.43	100	0.14	98.09	0.55	1.22	100
Monsoon Evergreen Broadleaved Forest	12.55	19.89	50.90	16.66	100	20.58	11.64	34.14	33.63	100
Seasonal Rain Forest	6.21	14.83	62.83	16.13	100	10.85	9.19	65.91	14.05	100
Deciduous Monsoon Forest	10.08	17.72	52.40	19.80	100	14.37	12.67	48.53	24.43	100
Cropland	0.16	98.40	1.11	0.33	100	0.12	98.20	0.67	1.01	100
Warmhot Savanna Shrub Grassland	12.64	28.47	48.93	9.96	100	0.39	40.81	9.56	49.24	100
Warmhot Coniferou Forest	7.87	12.79	57.06	22.28	100	18.01	2.50	23.43	56.06	100
Warm Deciduous Broadleaved Forest	10.01	17.11	56.50	16.37	100	14.98	12.21	40.97	31.84	100
Warm Bamboo Forest	11.40	23.90	51.82	12.88	100	0.31	35.13	15.16	49.40	100
Other Artificial Forest	0.36	98.05	1.29	0.30	100	0.86	97.46	0.59	1.09	100
Hot Shrub Forest	11.76	19.60	49.59	19.06	100	0.37	30.33	17.83	51.47	100
Hot Bamboo Forest	11.37	22.30	55.94	10.38	100	0.20	33.01	12.65	54.13	100
Artificial Building	0.13	98.74	0.98	0.15	100	0.10	98.58	0.66	0.67	100
Montane rain forest	2.31	5.64	76.91	15.14	100	6.33	0.99	66.55	26.13	100
Limestoe Monsoon Forest	3.49	7.33	69.59	19.59	100	9.35	1.26	73.34	16.05	100
Water	6.33	56.96	31.88	4.83	100	18.01	29.54	51.95	0.51	100
Mossy Evergreen Broadleaved Forest	17.16	29.60	44.92	8.32	100	17.48	29.13	34.44	18.95	100
Rubber Plantation	0.10	99.30	0.44	0.16	100	0.13	99.21	0.44	0.21	100

Fig. 9 Proportions of different matching relationships in each land use/land cover type between endangered plant diversity (EPD) and ecosystem services (ESs) in Xishuangbanna

of hotspot overlapping areas, and cannot obtain the spatial relationship map at the pixel scale. Therefore, it was easy to ignore the ecological protection in non-hotspot areas and even aggravated the environmental deterioration in ecologically fragile areas.

MaxEnt model was good at simulating the distribution of potential species under the influence of natural climate, and InVEST model has been widely used in the measurement of ESs. On this basis, we created a spatial matching degree index of high-resolution with 30 m × 30 m pixel size. Taking Xishuangbanna as an example, we modeled and depicted the spatial matching degree index of EPD and ESs using this framework. The framework can provide high-resolution maps of spatial matching degree between EPD and ESs in Xishuangbanna and also helps to identify ecologically fragile areas with low EPD and poor ESs. It can accurately locate the priority areas of EPD and ESs and provide an effective reference for decision-making on relevant planning and management. In Xishuangbanna, where tropical vegetation was abundant and has been greatly affected by human activities in recent years, the method was able to identify ecologically fragile areas with low-low match that deserve more attention and protection.

Effects of altitude and LULC on the matching degree between EPD and ESs

Although Xishuangbanna is known as a tropical treasure house, this analysis showed that the ecological environment in low-altitude areas and some high-altitude areas has been damaged. The prevailing mismatch relationship between EPD and the four studied ESs, particularly the prominence of low-high mismatching, raises significant concerns. These trends suggest that areas providing high levels of ESs may not necessarily harbor high biodiversity, particularly in terms of EPD (Bai et al. 2011; Liu et al. 2023). This could be attributed to the pressures from human activities such as intensive agriculture or urban development, which can drive ESs but often at the cost of biodiversity (Sannigrahi et al. 2020). Our findings highlight a potential conflict between biodiversity conservation and ESs provision, which should be carefully addressed when planning land use and conservation strategies.

The observed trend of increasing EPD with altitude underlines the importance of high-altitude areas for biodiversity conservation. As these areas often experience less human pressure, they may provide refuges for endangered plants (Fang et al. 2020). However, the different trends between EPD and ESs across altitudes indicate that there are complex interactions between these factors, potentially influenced by differences in habitat types and climate conditions across altitudes (Sun et al. 2021). These interactions need to be better understood to effectively manage biodiversity and ESs in mountainous regions. The strong influence of land use on the relationship between EPD and ESs reflects how human activities shape biodiversity and ESs patterns (Fang et al. 2022). The dominance of monsoon evergreen broadleaved forests in areas with high matching degree suggests that these forests are crucial for both biodiversity conservation and ESs provision. This emphasizes the need for maintaining and restoring these forests in the face of potential pressures such as deforestation and land conversion for agriculture (Knoke et al. 2021; Milheiras and Mace 2019).

The low-low matching areas between EPD and ESs represent ecologically fragile areas of requiring particular concern. These regions exhibit low EPD and ESs levels, indicating a strong degradation of both biodiversity and ecosystem functionality. This could be due to intensive human activities such as agriculture, urban development, or overexploitation of resources, which can result in habitat loss and degradation, and ultimately, loss of biodiversity and ESs (Huang et al. 2022). It is essential to explore the specific drivers behind the low-low matching patterns in these areas. For example, in regions where agriculture is dominant, intensive farming practices may lead to a loss of both EPD and ESs (Simoncini et al. 2019), whereas in urban areas, habitat loss due to infrastructure development may be the main cause (González-García et al. 2022). Understanding these underlying causes will be crucial for designing effective intervention strategies.

The presence of ecologically fragile areas with low-low matching highlights an urgent need for targeted conservation and restoration efforts. These could include measures aimed at habitat restoration (Bustamante et al. 2019), such as reforestation or creation of green spaces in urban areas, and measures to protect endangered plant species (Yang et al. 2021), such as the establishment of protected areas or implementation of species recovery programs. The habitats of endangered plants are narrow and scattered, and the current protected areas cannot fully cover the hotspots of endangered plants (Yang et al. 2021). Therefore, establishment of county-level protected areas may be the best way to protect endangered plants. Furthermore, preventive strategies should be implemented to halt and reverse the downward trend of EPD and ESs in these regions. This could involve promoting sustainable land use practices, strengthening regulations against habitat destruction, and raising awareness among local communities about the importance of EPD and ESs (Karimi et al. 2020). Lastly, regular monitoring of these areas is required to evaluate the effectiveness of implemented strategies and adjust them as needed. Tools such as remote sensing and biodiversity surveys can be used to track changes in EPD and ESs over time. The low-low matching areas pose a significant challenge for biodiversity conservation and sustainable development. Addressing this challenge will require a holistic approach that integrates biodiversity conservation with ESs provision, considers the specific conditions and drivers in each area, and involves various stakeholders, including local communities, policymakers, and conservation organizations. Future research should focus on developing and testing effective strategies for improving EPD and ESs in these low-low matching areas.

Main limitations and future research

The new framework developed for evaluating pixel-scale matching degree still has some obvious limitations. Due to limited availability of data, this study only considered matching degree between EPD and ESs for plant species and not for animal diversity. Data availability was another disadvantage. LULC data used in this study were from 2016, while EPD data were from 2019, which cannot accurately reflect the current status of ecosystems in Xishuangbanna.

However, the evaluation framework constructed has good data adaptability, and the results of the study can be enriched and updated as more data become available. In future research, we suggest applying the framework in different regions to analyze the spatial heterogeneity of multi-regional, multi-year matching degree between biodiversity and ESs.

Conclusions

This study pioneers a pixel-scale matching degree analysis framework, utilizing the MaxEnt and InVEST models to quantify EPD and ESs in Xishuangbanna. Our findings highlight a significant mismatch relationship between EPD and ESs, particularly evident in the low-high mismatching relationship, and underscore the substantial influence of altitude and land use changes in determining this relationship. We note with urgency the necessity to prioritize areas showing a low-low match between EPD and ESs, indicative of potential ecological vulnerability. Identifying and addressing the reasons behind their reduced EPD and ESs are fundamental steps for effective conservation efforts and the achievement of sustainable development in these regions. Recognizing and addressing the causes for their low EPD and ESs are essential for conservation efforts and the realization of sustainable development in these regions.

In light of our findings, we recommend that future research and policy-making should consider both biodiversity and ESs, along with the complex interactions between them. A better understanding of the spatial congruence between biodiversity and ESs can guide the spatial planning of conservation efforts, aid in identifying areas of potential conflict or synergy between biodiversity and ESs, and inform the design of management strategies that balance the needs of both. There is a pressing need for additional research to explore the drivers behind the observed patterns, including the impacts of different types of land use and land management practices. Understanding these drivers will be crucial for developing effective measures to improve the spatial matching between biodiversity and ESs.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate I am free to contact any of the people involved in the research to seek further clarification and information.

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Competing interests The authors declare no competing interests.

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