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IMPACT OF VEGETATION CHANGE ON ECOSYSTEM SERVICES IN LAOS FROM 2000 TO 2020

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Changes in vegetation have a significant effect on the functions of ecosystem services. The evaluation of the ecosystem service functions provided by vegetation is crucial for promoting sustainable development in the region. This research focuses on Laos as the area of study. Initially, the spatiotemporal changes in vegetation over the last 20 years are analyzed, and the influencing factors are determined using the geographic detector model. Subsequently, the InVEST model is utilized to quantitatively evaluate four essential ecosystem services: carbon storage, habitat quality, soil conservation, and water yield. The balance of these services is analyzed by studying transitions between various vegetation types and non-vegetated land categories. The results show that: (1) In Laos, the extent of forest and shrubland is declining, with the most noticeable reduction occurring in forested areas. Vegetation degradation is mainly concentrated in cities and their surrounding areas. (2) The primary driving factors behind vegetation changes in Laos include average annual temperature, average annual precipitation, and the human footprint. (3) Forest restoration has positively impacted the carbon storage, habitat quality, and soil conservation functions of Laos' vegetation. The expansion of vegetation cover has strengthened nearly all ecosystem services within the area under study. This research offers valuable insights for promoting sustainable ecological development in Laos, as well as for the effective management and use of vegetation resources.

***Key words:** vegetation change, ecosystem services, driving factors, InVEST, Geodetector, Laos*

1. Introduction

The cornerstone for the long-term existence and advancement of human society is the provision of goods and a living environment by natural ecosystems. Ecosystem services are crucial for the sustainable development of human civilization, the economy, and the environment, as they form an essential connection between natural ecosystems and human well-being (Seppelt et al., 2011). The swift expansion of the global population and economy has resulted in a notable increase in the demand for resources and environmental services. Prolonged, intensive exploitation of ecosystems by humans has caused resource depletion, land degradation, vegetation loss, and a decline in ecosystem service functions, threatening the harmonious and sustainable development of the economy, environment, and human well-being (Costanza et al., 2014; Kremen, 2005). Climate change and human activities have intensified these effects, altered vegetation and diminished its capacity to deliver vital ecosystem services (Bateman et al., 2014). The importance of vegetation's carbon sequestration capacity has been continuously emphasized, and vegetation protection and the assessment of ecosystem services provided by vegetation have become research hotspots. The United Nations launched the Millennium

Ecosystem Assessment at the beginning of the 21st century, marking the first comprehensive evaluation of global ecosystem changes over time. At the heart of this strategy was the evaluation of ecosystem services, focusing significantly on the importance of vegetation restoration and protection in mitigating climate change and improving ecosystem services.

Currently, there is a lack of quantitative research evaluating the effects of vegetation restoration on ecosystem services. International research on ecosystem services primarily focuses on the following theoretical aspects: (1) knowledge of the idea of ecosystem services (Wilson, Matthevs, 1970; Daily, 1997). It mostly consists of two parts. First, natural ecosystems serve the purpose of delivering "services" (Daily, 2012; Costanza et al., 1997), and second, people can gain from the advantages of these services (de Groot et al., 2000; de Groot et al., 2002). (2) Ecosystem services' makeup and classification (Odum, Odum, 2000; Wu et al., 2021; Zhao et al., 2000). This premise serves as the foundation for evaluating how well ecosystem services perform (Chee, 2004). Ecosystem services have been categorized differently by various specialists (Pagiola, 2008; Lin et al., 2018). Among them, the supply, regulation, culture, and support classification system suggested by the United Nations Millennium Ecosystem Assessment Panel has received widespread international acclaim (Bateman et al., 2014; Farber et al., 2002). (3) Ecosystem service assessment technique (Nemec, Raudsepp-Hearne, 2013). At the moment, the primary methodologies used to assess ecosystem services are energy analysis (Odum, Odum, 2000), material quality assessment (Zhao et al., 2000), and value assessment (Pagiola, 2008). In summary, the research scope of ecosystem services is very broad. Recent studies mainly focus on the impact of land use changes on ecosystem services, frequently neglecting the dynamics of supply and demand related to vegetation for these services. Utilizing detailed vegetation classification datasets to assess changes in ecosystem service functions is crucial for addressing this gap.

Laos has undergone significant transformations in its land use, as well as in the pattern, structure, and intensity of its vegetation, due to the expansion and intensification of human activities. These changes have also had a substantial impact on the area's biological environment. This region has become one of the regions with relatively fragile ecological environments in Asia and even the world. As a result of climate change, Laos is encountering ecological and environmental challenges, including water scarcity, vegetation degradation, increased frequency of natural disasters, and species extinction. Using ecosystem services sustainably is subject to demands and difficulties never before (Wang et al., 2020). At present, there is limited research on how changes in vegetation area affect ecosystem services in Laos. The examination of how various vegetation types affect ecosystem services is still inadequate, and the services offered by vegetation in Laos have not been thoroughly comprehended. These ambiguities present challenges for upcoming research and management efforts. This study seeks to identify changes in vegetation types, examine the primary drivers of these shifts, and assess their impacts on different ecosystem services. The insights gained from these changes will be crucial for regional management and decision-making.

2. Materials and methods

2.1. Study area

The Lao People's Democratic Republic (Laos) is a landlocked nation located in Southeast Asia (14°10′ - 22°30′N, 100°05′ - 107°40′E). Laos shares its borders with Vietnam to the east, China to the north, Myanmar and Thailand to the west, and Cambodia to the south (Figure 1). Laos has 18 provinces (including 1 municipality, namely the capital Vientiane), with a total area of approximately 236,800 km^2. Laos experiences a tropical monsoon climate, characterized by three distinct seasons: the climate consists of a rainy season from May to October, a cool season from November to February, and a hot season from March to April. The average annual precipitation is about 1,500 to 2,500 mm, but it varies in mountainous areas and river valleys. Vegetation types mainly include tropical rainforests, monsoon forests, mountain forests, and bamboo forests, and the vegetation types vary in different regions. Laos has a variety of soil types, mainly red soil, yellow soil, alluvial soil, and limestone, depending on the geographical location and climatic conditions. Vegetation destruction and the ecological environment in Laos are affected by many factors, including agricultural expansion, illegal logging, infrastructure construction, and climate change. To address these issues, the Lao government and international organizations are working to implement a series of protection measures, including forest protection, sustainable agricultural practices, and environmental education, to reduce vegetation destruction and improve the ecological environment.

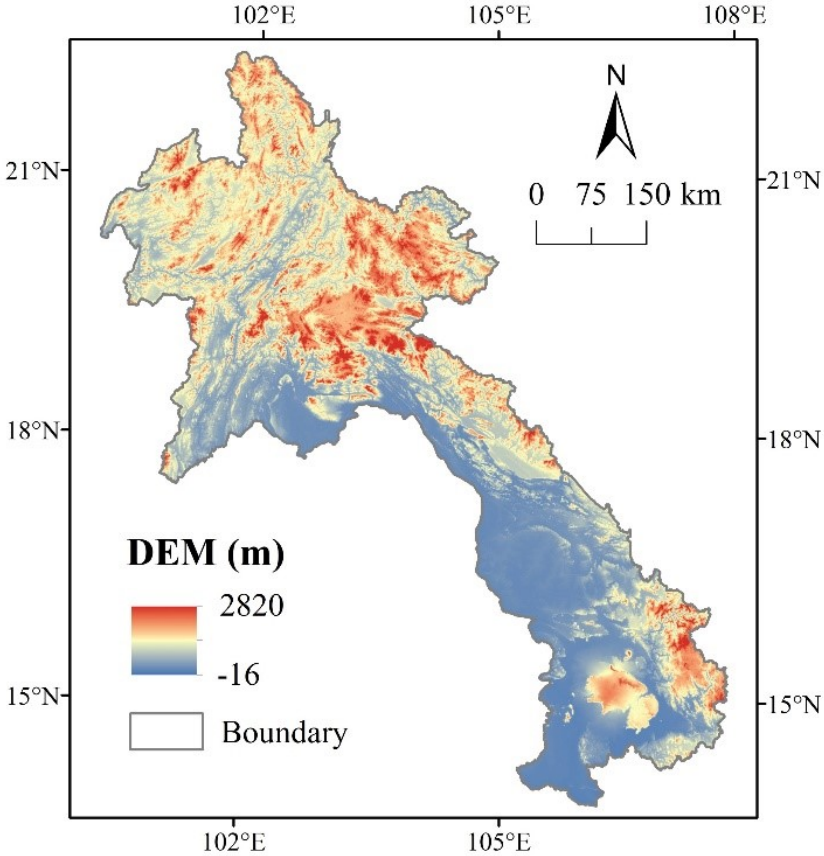

Figure 1. Study area map

2.2 Data Source and Data Preprocessing

This study primarily utilizes data from the normalized difference vegetation index (NDVI), digital elevation model (DEM), land use, meteorological sources, soil information, and socio-economic factors. These data are utilized to analyze vegetation changes, investigate driving mechanisms, quantitatively assess ecosystem service functions, and examine the impacts of vegetation changes on ecosystem services. Necessary preprocessing steps, including clipping, projection, and reclassification, have been performed on all data using ArcGIS 10.2 software.

Table 1 presents detailed information about the data.

Table 1. **Data information used in the study**

Data	**Unit**	**Source**
Digital Elevation Model	m	USGS EarthExplorer
Slope	°	Using DEM data extraction
Average annual temperature	°C	Level-1 and Atmosphere Archive & Distribution System (LAADS DAAC)
Annual precipitation	mm	Google Earth Engine (GEE)
Potential evapotranspiration	mm	Google Earth Engine (GEE)
Soil type	-	Food and Agriculture Organization (FAO)
Land use type	-	Climate Data Store
Population density	Per/km^2	WorldPop
Night light	-	Google Earth Engine (GEE)
Human Footprint	-	Figshare
Maximum root burial depth	mm	Level-1 and Atmosphere Archive & Distribution System (LAADS DAAC)
Plant available water content	%	International Soil Reference and Information Centre (ISRIC)
River basin	-	Using DEM data extraction
Seasonal factor constant	-	InVEST Guidebook
Table of Biophysical Coefficients	-	Food and Agriculture Organization (FAO)
Precipitation erosion factor	mm	Google Earth Engine (GEE)
Soil erodibility factor		International Soil Reference and Information Centre (ISRIC)
Calibration parameters K_b and IC_0		Using DEM data extraction
Maximum sediment transport rate		InVEST Guidebook
Habitat Threat Factor Scale		Refer to relevant research (Song et al., 2020; Sun et al., 2019)
Habitat Sensitivity Scale to Threat Factors		InVEST Guidebook

2.3. Research methods

2.3.1. Detection of driving forces of vegetation change

Vegetation change is affected by a range of factors, encompassing both natural and socio-economic elements. We initially identified the spatiotemporal patterns of vegetation change in Laos and subsequently employed the Factor Detector and Interaction Detector modules of the Geographic Detector model to analyze the driving forces behind these changes (Wang et al., 2021a). To accomplish this, we identified 11 essential factors that play a crucial role in this process. These factors include the digital elevation model (DEM), slope, soil type, average annual precipitation, average annual temperature, average annual evaporation, land use type, GDP, population density, night lights, and human footprint GeoDetector is a quantitative method used to determine the extent to which the spatial distribution of dependent variables aligns with that of independent variables. It is a brand-new spatial statistical technique that does not rely on any linear presumptions and finds driving elements by spotting geographical variability. The GeoDetector model can quantify the relative contribution of each driving force in spatiotemporal changes and address the combined effects of these forces on the spatiotemporal changes of dependent variables (Wang et al., 2021b). The factor detection and interaction detection processes of the GeoDetector function as follows:

(1) Factor Detector

Factor detectors can quantitatively describe the relative importance of influencing factors and measure the explanatory power of independent variable X to dependent variable Y by constructing q statistics. The value of q is between 0 and 1. A larger value indicates a stronger explanatory power of the independent variable X on the dependent variable Y, and conversely, a smaller value suggests weaker explanatory power. A q value of 0 indicates no coupling relationship between Y and X, while a q value of 1 signifies that Y is entirely determined by X. The formula for calculating the q statistic is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \delta_h^2}{N\delta^2} \quad (1)$$

In the formula, factor X is composed of L layers, and h represents the level or category of factor X (h = 1, 2, ..., L); N_h represents the number of elements in layer h, while N denotes the total number of elements in the entire region; δ_h^2 and δ^2 represent the variance of Y in layer h layer and the variance of Y across the entire region, respectively.

(2) Interaction detector

The interaction detector quantitatively assesses the relationship between two factors to determine whether they operate independently or if their combined effect on the dependent variable Y is amplified or diminished (as shown in Table 2). This is done by calculating the q values (q (x_1) and q (x_2)) for the independent variables x_1 and x_2 with respect to the dependent variable Y, as well as the q value ($q(x_1 \cap x_2)$) for the combined interaction of these variables. The nature of their interaction is evaluated by comparing the sizes of the q values.

Table 2. **Types of interaction relationship between two factors**

Interaction	**Description**
Weaken, nonlinear	$q\ (x_1 \cap x_2) < \mathrm{Min}\ (q\ (x_1), q\ (x_2))$
Weaken, uni-	$\mathrm{Min}\ (q\ (x_1), q\ (x_2)) < q\ (x_1 \cap x_2) < \mathrm{Max}\ (q\ (x_1), q\ (x_2))$
Enhance, bi-	$\mathrm{Max}\ (q\ (x_1), q\ (x_2)) < q\ (x_1 \cap x_2) < q\ (x_1) + q\ (x_2)$
Independent	$q\ (x_1 \cap x_2) = q\ (x_1) + q\ (x_2)$
Enhance, nonlinear	$q\ (x_1 \cap x_2) > q\ (x_1) + q\ (x_2)$

2.3.2. Quantitative Assessment of Ecosystem Services

(1) Water yield

In this study, the water yield services in Laos were calculated and assessed using the water production module of the InVEST model. This model is founded on the Budyko curve and the principles of water balance, allowing for the calculation of water production for each grid based on climate, land use, and other relevant data (Fu, 1981; Zhang et al., 2004). The model necessitates several data inputs, including annual mean precipitation, reference evapotranspiration (ET_0), crop evapotranspiration coefficient (Kc), vegetation root depth, soil depth, plant available water content (AWC), and water consumption associated with different land use/land cover (LULC) categories.

(2) Soil conservation

In this study, inland soil erosion of Laos was calculated using the InVEST sand transport model. The three index parameters of soil erosion, sand transport, and sand storage were then obtained, and the regional and spatial scale soils of Laos were assessed. The grid is used as the calculation unit in the InVEST sediment transport model. First, each unit's soil erosion and sediment amount are calculated. Next, each unit's SDR is calculated. Finally, the sediment transported through each unit is determined based on these calculations (Lal, 2014).

(3) Carbon storage

This study calculated the carbon storage in Laos from 2000 to 2020 using the carbon model from InVEST. The amount of carbon stored in ecosystems is fundamentally determined by four primary carbon pools: above-ground biomass, below-ground biomass, soil organic matter, and dead organic matter. Additionally, a fifth carbon pool encompasses the carbon storage in wood and other products (Ghosh et al., 2020). The carbon of specific products it represents will not enter the atmosphere. Therefore, it is not easy to get pertinent data. The fifth form of carbon pool is thus not considered in our analysis.

(4) Habitat quality

The habitat service capacity and geographic distribution of habitat quality in Laos are estimated and assessed using the habitat quality module of the InVEST model. This module effectively integrates habitat suitability and human threats to biodiversity, allowing for a comprehensive assessment of habitat quality and providing valuable insights into the status of biodiversity (Sallustio et al., 2017). Unlike other methods in the field of biodiversity research, the model does not require information about species distribution or existence but uses data available almost anywhere in the world. This advantage makes it particularly suitable for habitat quality studies that lack species distribution data and are applied to mixed habitat types (Terrado et al., 2016; Tang et al., 2020).

2.3.3. Impacts of vegetation change on ecosystem services

The vegetation and non-vegetation transfer matrix is a method employed to depict the changes in both the direction and magnitude of vegetation type transitions by examining the transformations between vegetation and non-vegetation at the start and end of the study period. Its calculation formula is:

$$X = |X_{ij}| = \begin{bmatrix} X_{11} & X_{12} & X_{13} & \cdots & X_{1n} \\ X_{21} & X_{22} & X_{23} & \cdots & X_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ X_{n1} & X_{n2} & X_{n3} & \cdots & X_{nn} \end{bmatrix} \quad (2)$$

Where: X denotes the absolute value of X_{ij}, with X_{ij} representing the land area (km²) of vegetation type i at the beginning of the study that has been converted to vegetation type j by the end of the study. In this context, i refers to the vegetation type at the beginning of the study, while j represents the vegetation type at the end of the study. i and j range from 1 to n, where n denotes the total number of vegetation types.

3. Results Analysis

3.1 Analysis of vegetation changes in Laos from 2000 to 2020

3.1.1 Temporal and spatial variation characteristics of vegetation

Figure 2 shows the area changes of various vegetation types in Laos from 2000 to 2020. In 2020, the areas of cultivated land and non-vegetated land in Laos increased significantly compared with 2000, with net change areas of 3,687.86 km^2 and 482.48 km^2 respectively. The area of grassland increased slightly. The areas of forest and Shrubland experienced a decrease, with net change areas of 2,821.06 km^2 and 1,375.06 km^2 respectively. These phenomena indicate that the ecological space of vegetation is gradually shrinking, and the area of vegetation is decreasing.

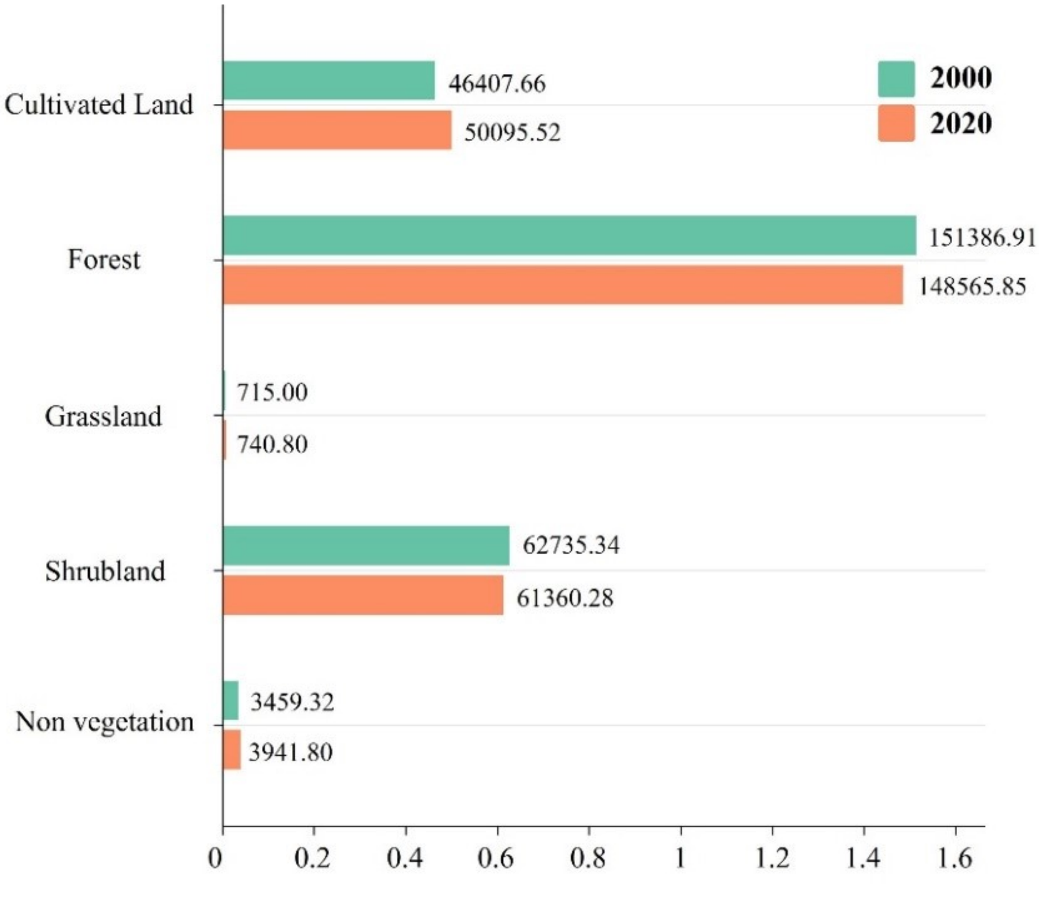

Figure 2. Area of various vegetation types and non-vegetation areas in Laos from 2000 to 2020（10^5 km^2）

Figure 3 illustrates the spatial distribution of vegetation types in Laos from 2000 to 2020. Overall, there was a notable reduction in vegetation area and an increase in non-vegetation area, indicating significant damage to Laos' vegetation during this period. Forests are the most significant and predominant vegetation type in the study area, distinguished by their wide distribution. Cultivated land is primarily located in flat terrain and areas with adequate water resources along the Mekong

River, as well as in the central mountain valleys with mild climates. Moreover, rapid urban development has led to the encroachment of adjacent vegetation types. Population growth has also forced the continuous increase in cultivated land area, especially in the areas around the city center. In particular, the cultivated land type in the area around Vientiane, the capital of Laos, has shown an expanding trend. The primary cause of this trend is the conversion of non-vegetation types, such as barren land, which has led to a decline in the overall vegetation area and significant regional vegetation degradation.

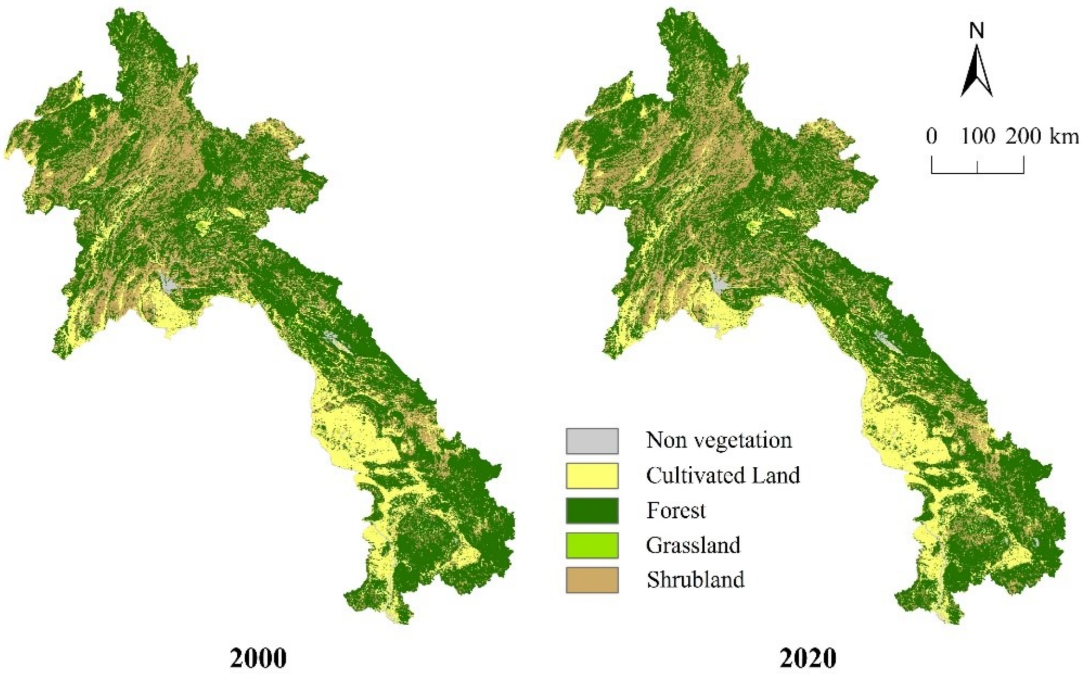

Figure 3. Spatial distribution of vegetation types and non-vegetation in Laos from 2000 to 2020

3.1.2 Vegetation restoration and degradation identification

To examine vegetation restoration and degradation in Laos, we defined the increase in vegetation area from 2000 to 2020 as vegetation restoration, while the decrease in vegetation area during the same period was classified as vegetation degradation. We drew a Sankey diagram based on the vegetation type transfer matrix in Laos from 2000 to 2020 (Figure 4). Over the past 20 years, vegetation transfer in Laos mainly occurred between shrubland, forest, and cultivated land, with a smaller area of grassland transfer.

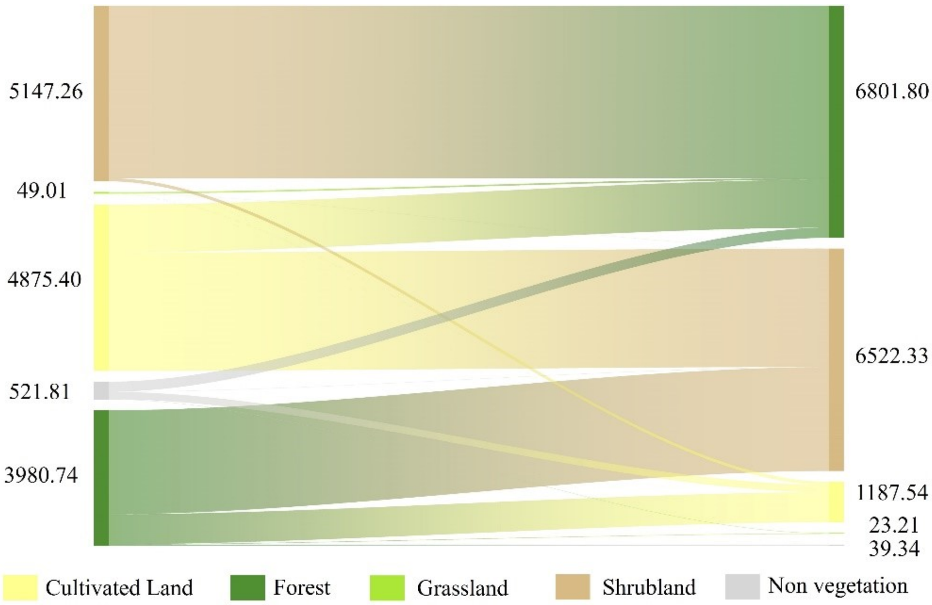

Figure 4. Sankey diagram of vegetation types and non-vegetation transfer areas in Laos from 2000 to 2020（km²）

Figure 5 illustrates the spatial distribution of vegetation changes in Laos. Vegetation recovery is particularly focused around the capital city of Vientiane and in the central and southern regions, especially in the bare land areas both within and surrounding the city. In contrast, vegetation degradation displays a concentrated pattern, predominantly occurring north of Vientiane, which may be linked to local construction activities. Over the past 20 years, the vegetation status in most areas of Laos has remained relatively stable, with the total area of vegetation recovery exceeding that of degradation, indicating an overall positive trend.

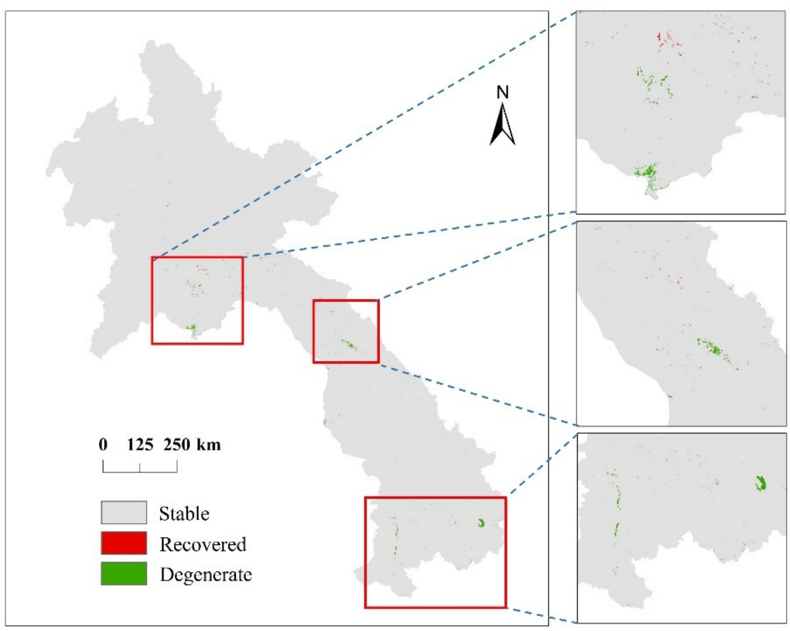

Figure 5. Vegetation restoration and degradation in Laos from 2000 to 2020

3.1.3 Vegetation change attribution analysis

Table 3 presents the findings from the vegetation change factor analysis in Laos. The *P* values of all influencing factors are 0, indicating a significant impact on vegetation changes in Laos. Among them, the three driving factors of average annual temperature, average annual precipitation, and human footprint rank in the top three in explaining vegetation change, and are the main driving factors affecting vegetation change in Laos. This was followed by nighttime light, land use type, GDP, soil type, DEM, average annual evaporation, population density, and slope. Except for the q-values of the four influencing factors of average annual temperature, average annual precipitation, human footprint, and night light, which are greater than 0.1, the q-values of the other influencing factors are all less than 0.1, indicating that although the impact of these factors on vegetation change is significant but the impact is weak. In particular, the q values of population density and slope were only 0.03 and 0.02, which means that population density and slope had almost no effect on vegetation change in Laos. This finding highlights the significant influence of climate and hydrological conditions on regional vegetation growth in Laos. Temperature and precipitation have a direct influence on water input and surface hydrological processes, which in turn affect vegetation growth. Furthermore, alterations in the area of various vegetation types can influence transpiration rates, resulting in changes to the regional water balance as well as to forest and soil ecosystems.

Table 3. **Results of vegetation change factor analysis**

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
q	0.057	0.075	0.147	0.139	0.091	0.056	0.030	0.240	0.024	0.456	0.068
p	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note:（X_1 is DEM, X_2 is GDP, X_3 is human footprint, X_4 is night lights, X_5 is land use type, X_6 is annual average evaporation, X_7 is population density, X_8 is annual average precipitation, X_9 is slope, X_{10} is annual average temperature, X_{11} is soil type）

Figure 6 presents the results of the interaction detection between vegetation change and its driving factors in Laos. The *q* values for the interactions among the 11 driving factors exceed those observed for individual factors. A larger *q* value signifies a greater impact of the interaction on vegetation change. The results of the interaction detection are all enhancement types (double factor enhancement and nonlinear enhancement), there are no independent and weakening types, and there are more bilinear enhancement types. The two factors with the largest interaction effects are annual average temperature ∩ soil type and annual average temperature ∩ night light, both of which have a value of 0.61. The second is annual average temperature ∩ GDP and annual average temperature ∩ human footprint. The interaction types of double factor enhancement are the interaction type between GDP and two factors (human footprint and land use type), the interaction type between human footprint and two factors (night light and annual average temperature), and night light ∩ land use and land use ∩ annual average temperature. The interaction types between the remaining factors are nonlinear enhancement. Furthermore, the *q* values for the interaction between annual average temperature and other driving factors are all greater than 0.5, demonstrating the significant influence of annual average temperature on vegetation changes in Laos. The interaction detection structure of each factor also shows that each driving factor does not act independently, and the interaction between these factors significantly affects vegetation changes.

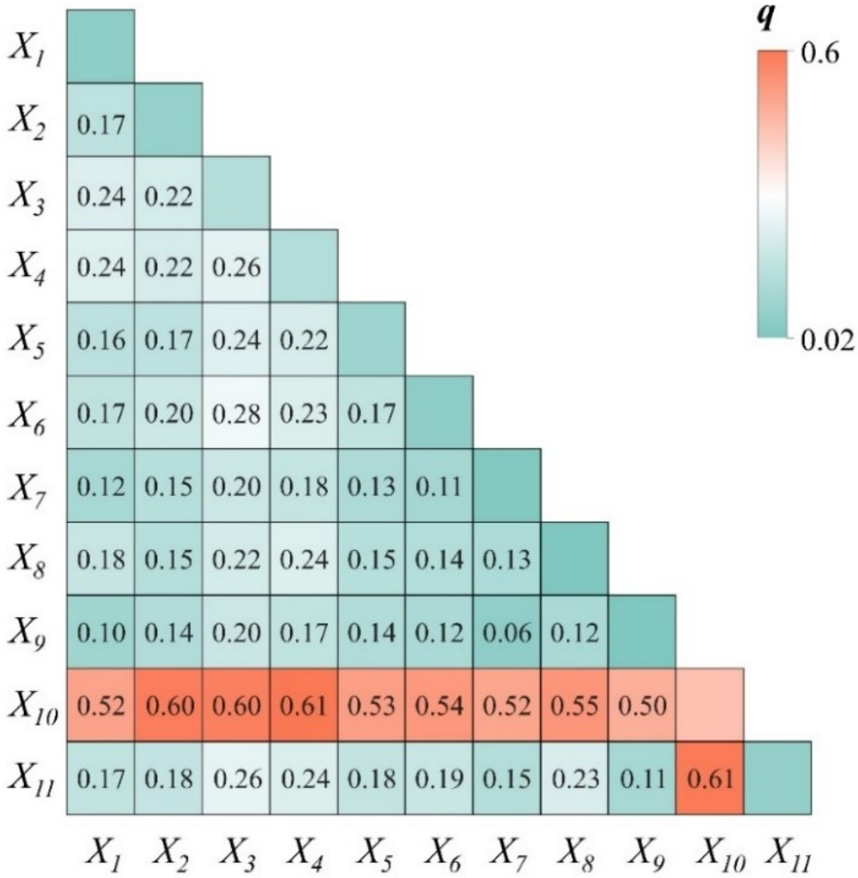

Figure 6. Results of interaction detection of 11 driving factors. (X_1 is DEM, X_2 is GDP, X_3 is human footprint, X_4 is night lights, X_5 is land use type, X_6 is annual average evaporation, X_7 is population density, X_8 is annual average precipitation, X_9 is slope, X_{10} is annual average temperature, X_{11} is soil type)

3.2 Spatiotemporal analysis of ecosystem service systems

The spatial distribution patterns of the four key ecosystem service functions—carbon storage, habitat quality, soil conservation, and water yield—in Laos from 2000 to 2020 are influenced by a range of natural and socio-economic factors (Figure 7).

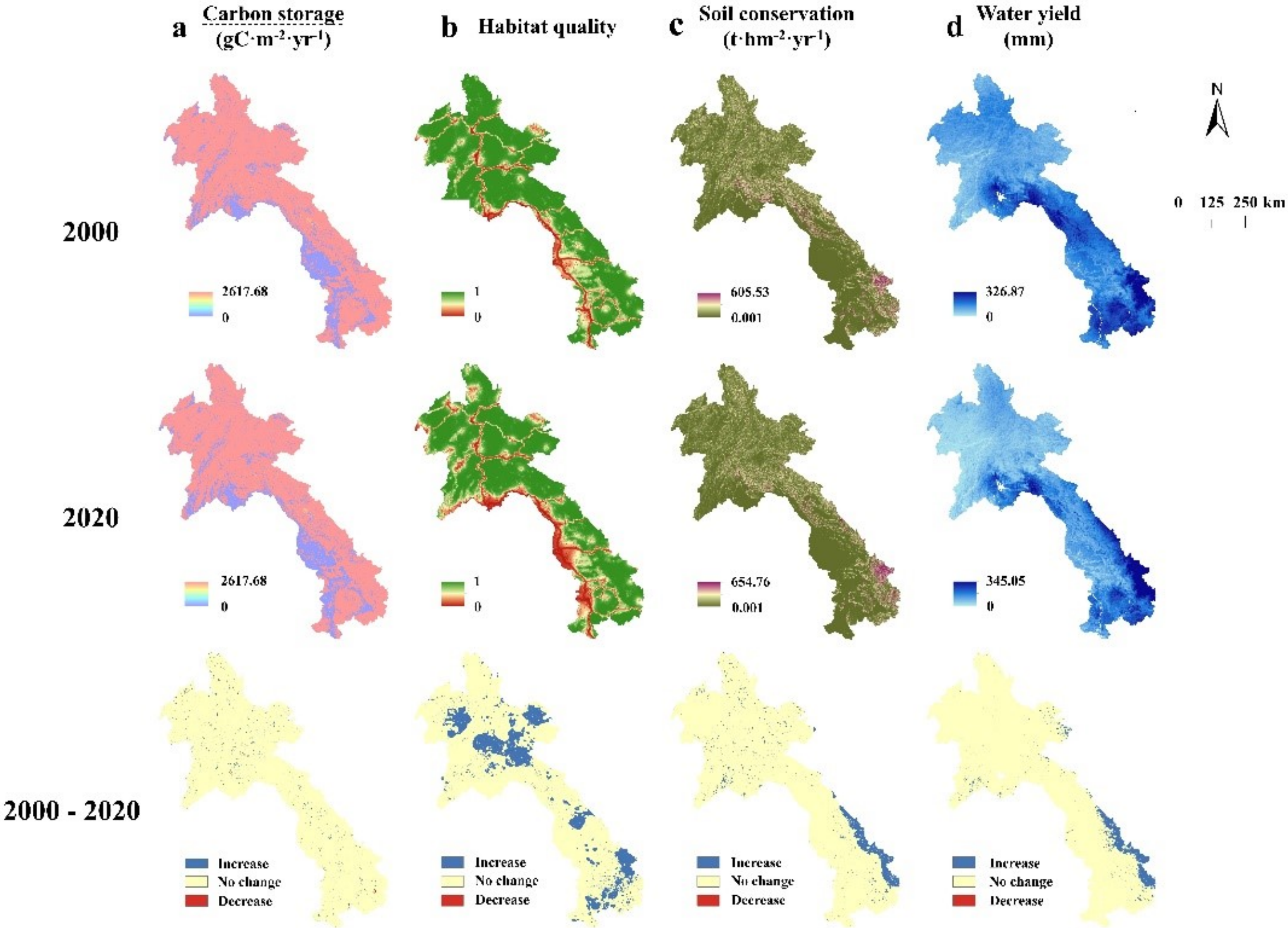

Figure 7. Spatial distribution of ecosystem services in Laos from 2000 to 2020

From 2000 to 2020, the carbon storage in Laos has generally shown an upward trend. The overall pattern of carbon storage in Laos is characterized by higher levels in the northeast and lower levels in the southwest. High-value carbon storage areas are primarily found in the mountainous regions dominated by broad-leaved forests and shrubs in the east, while low-value carbon storage areas are mainly situated in the non-vegetated regions along the Mekong River. Notably, there has been a decline in carbon storage in the southeastern region of Laos, primarily attributed to the destruction and degradation of vegetation resulting from local engineering projects.

From 2000 to 2020, the average habitat quality in the primary forest areas of Laos demonstrated a clear upward trend, marked by a significant rise in the habitat quality index and a reduction in standard deviation. This indicates a reduction in the disparity of habitat quality among these areas and suggests that the improvement in habitat quality is becoming more uniformly distributed. The spatial distribution of increased habitat quality exhibited a patchy pattern across the northern, central, and southern regions. Notably, the most significant improvement in habitat quality occurred in the northern region, where the increase in habitat area was markedly greater than that in the central and southern regions. This is mainly because the area is dominated by plateau mountains and hilly landforms, with diverse vegetation types, including broadleaf forests, shrubs, and grasslands. These vegetation types exhibit high NDVI, vegetation cover, and biomass, creating highly suitable habitats for a diverse array of species. Other areas, including the Mekong River, have relatively stable habitat quality because these areas are dominated by agricultural land, shrubs, and non-vegetation types.

From 2000 to 2020, the soil conservation service function remained stable in most areas of Laos. Notably, the southwest region bordering Vietnam exhibited high soil conservation service levels, with significant improvements, indicating reduced soil erosion and a lower risk of geological disasters such as landslides. In contrast, the soil conservation service function along the Mekong River was relatively low, with some areas displaying concentrated and continuous patterns of degradation. Therefore, it is essential to enhance ecological governance and promote vegetation restoration to mitigate the risk of water loss.

Between 2000 to 2020, the overall average water yield in Laos remained stable. The water conservation and soil conservation service functions at the junction of the southwest and Vietnam border were similar, with high water yield and a significant increase, indicating that the water conservation and soil conservation functions in this region are relatively good. The difference in water yield between this region and other places has gradually widened. In general, the spatial distribution of water yield shows a gradual increase from the northeast to the southwest, with the central region exhibiting higher water yield levels compared to the northern mountainous areas. It's noteworthy that the water yield in the middle reaches of the Mekong River in Laos exceeds that of the lower reaches.

3.3 Impact of vegetation change on the balance of ecosystem services

Over the past two decades, the conversion of vegetation types in Laos has significantly impacted the balance of ecosystem services (Figure 8). The transformation of forests and grasslands into cultivated land has resulted in a decline in ecosystem services, particularly affecting water yield and habitat quality. Carbon storage and soil conservation functions are greatly affected by the transition from forest to grassland. The transition between other vegetation types has little impact on soil conservation functions. Grasslands and cultivated land were converted into forests and additional cultivated areas. The ecosystem services associated with land types converted to grassland showed an increase, with the most notable changes observed in supporting services and regulating services. Transforming cultivated land into grassland, shrubland, and forest significantly enhances carbon storage services. In contrast, converting forested areas to grassland, shrubland, or agricultural land results in a reduction in the habitat quality index, with the most substantial decline observed when forests are converted to cultivated land. Additionally, the most notable increase in water yield is observed when cultivated land is converted to grassland compared to other vegetation types. However, transforming forests into other land types leads to a decrease in water yield, especially when converting to grassland, the water yield decreases significantly. Results showed that forest type was the most effective in improving ecosystem services through targeted vegetation restoration, followed by shrubland and grassland (Figure. 8a).

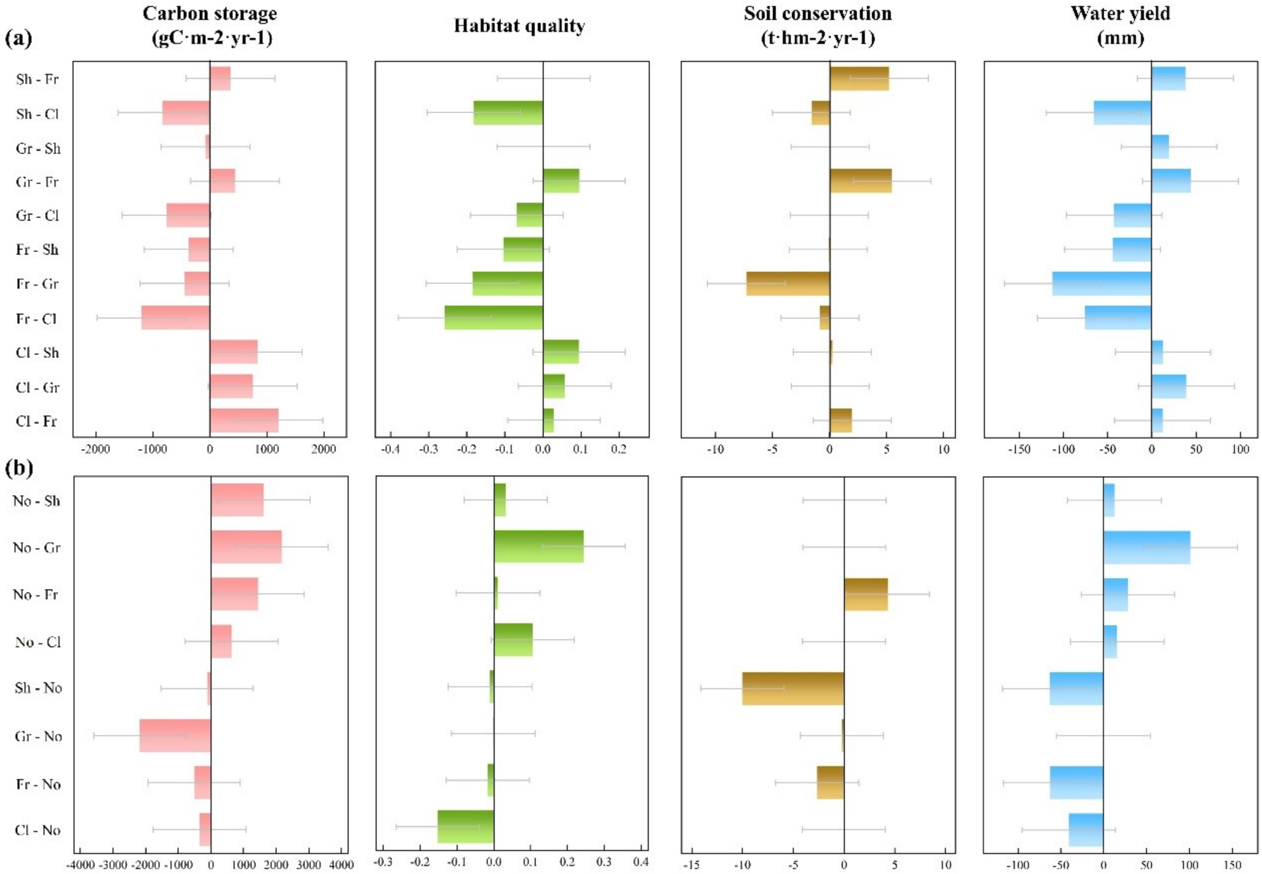

Figure 8. Impacts of changes in vegetated and non-vegetated land types on ecosystem services in Laos. (a) Changes in ecosystem services caused by conversions between different vegetation types in Laos from 2000 to 2020; (b) Changes in ecosystem services caused by conversions between vegetation and non-vegetated land types in Laos from 2000 to 2020). Note：Sh: Shrubland, Fr：Forest, Cl: Cultivated land, Gr: Grassland, No: Non vegetation

Figure 8b illustrates the alterations in ecosystem services resulting from the conversion of vegetation and non-vegetated land types in Laos between 2000 and 2020. The results indicate that converting forest, shrubland, and cultivated land to non-vegetated land types resulted in decreases in water yield of 62.36 mm, 63.16 mm, and 40.67 mm, respectively. This conversion also led to declines in carbon storage, habitat quality, and soil conservation services. Conversely, converting non-vegetated land to forest, shrubland, grassland, or cultivated land resulted in increases in carbon storage, habitat quality, and soil conservation services. Among them, the increase in carbon storage was the most significant, increasing by 1444.14 gC•m $^{-2}$, 1613.25 gC•m $^{-2}$, 2174.58 gC•m $^{-2}$ and 634.90 gC•m $^{-2}$, respectively. It is worth noting that vegetation restoration improved almost all ecosystem services in Laos.

4. Conclusion

This study analyzed and evaluated the spatiotemporal variation of vegetation in Laos from 2000 to 2020, identifying its driving mechanisms and quantitatively assessing carbon storage, habitat quality, soil conservation, and water yield associated with vegetation over the past two decades. Additionally, we explored how changes in different vegetation types and the conversion between vegetation and non-vegetation types affect the balance of ecosystem services. The results reveal that, between 2000 and 2020, the overall area of vegetation recovery in Laos exceeded the degraded area, resulting in a net increase of 482.47 km², indicating a recovery trend. The primary drivers of vegetation change in Laos are average annual temperature, average annual precipitation, and human footprint. Notably, our findings demonstrate that restoring forestland significantly enhances carbon storage, habitat quality, water yield, and soil conservation services. The restoration of vegetated areas positively impacts nearly all vegetation-related ecosystem services. This study provides valuable insights for vegetation restoration and protection efforts in Laos, aiding in the sustainable development of the region's ecological environment.

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