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Article

# Investigating the spatiotemporal evolution characteristics of forests and identifying the contributions of driving factors using GIS technology and machine learning models: A case study of Yibin City, China

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**Abstract:** This study employs a transfer matrix, dynamic degree, stability index, and the PLUS model to analyze the spatiotemporal changes in forest land and their driving factors in Yibin City from 2000 to 2022. The results reveal the following: (1) The land use in Yibin City is predominantly characterized by cultivated land and forest land (accounting for over 95% of the total area). The area of cultivated land initially increased and then decreased, while forest land continued to decline and construction land expanded significantly. The rate of forest land loss has slowed (with the dynamic degree decreasing from −0.62% to −0.04%), and ecosystem stability has improved (the *F*-value increased from 2.27 to 2.9). The conversion of cultivated land to forest land is the primary driver of forest recovery, whereas the conversion of forest land to cultivated land is the main cause of reduction; (2) cultivated land is concentrated in the central and northeastern regions, while forest land is distributed in the western and southern mountainous areas. Construction land is predominantly located in urban areas and along transportation routes. Areas of forest land reduction are mainly found in the central and southern regions with rapid economic development, while areas of forest land increase are concentrated in high-altitude zones or key ecological protection areas. Stable forest land is distributed in the western and southern ecological conservation zones; (3) changes in forest land are primarily influenced by annual precipitation, elevation, and distance to rivers. Road accessibility and GDP have significant impacts, while slope, annual average temperature, and population density exert moderate influences. Distance to railways, aspect, and soil type have relatively minor effects. The findings of this study provide a scientific basis for the sustainable management of forest resources and ecological conservation in Yibin City.

**Keywords:** forests; spatiotemporal evolution; driving factors; Yibin City

## 1. Introduction

Forests, as one of the planet's most vital ecosystems, play crucial roles in carbon cycling, hydrological regulation, and biodiversity conservation [1,2]. However, under the dual effects of environmental changes and anthropogenic interventions, their spatial distribution and evolutionary processes have grown increasingly complex. The dynamic changes in spatiotemporal patterns profoundly influence regional ecological security [3], carbon neutrality achievement [4], and sustainable development policymaking [5]. Investigating forest spatiotemporal evolution characteristics and driving factors not only enhances understanding of forest landscape transitions but also provides scientific foundations for optimizing forest resource management, ecological restoration, and land-use planning. Current dynamics in forest coverage involve multiple natural and anthropogenic drivers, including climate change [6], topographic constraints [7,8], socioeconomic development [9,10], and policy interventions. Precise identification of these factors' mechanisms proves essential for improving targeted forest conservation and management strategies. Beyond local implications, such investigations contribute to broader forest ecology and sustainability science by offering transferable methodologies and insights into managing forest ecosystems under competing pressures of economic growth and ecological protection, a challenge faced by many mountainous and urbanizing regions globally.

Current research on forest spatiotemporal evolution predominantly employs remote sensing, field surveys, and spatial statistical analysis, though these conventional methods face limitations in data processing efficiency and spatial resolution. Recent advancements in Geographic Information System (GIS) technology have significantly refined forest evolution studies. GIS enables high spatiotemporal-resolution monitoring of forest cover and facilitates multi-scale, multi-temporal dynamic analysis through integration with remote sensing data, thereby elucidating forest pattern evolution trends. Furthermore, GIS spatial analysis capabilities support systematic evaluation of terrain, climate, and land-use impacts on forest dynamics, establishing robust data foundations for mechanistic studies. For instance, a study conducted by Kan et al. [11] in 2022 utilized Geographic Information Systems (GIS) and multi-source remote sensing data to map changes in forest cover in the Qinling Mountains, exploring the coupling relationship between forest utilization changes and temperature as well as precipitation. In driving factor identification, traditional statistical approaches (e.g., regression analysis, principal component analysis) reveal partial environmental influences but struggle to resolve complex nonlinear relationships inherent in multidimensional datasets. Emerging machine learning models (e.g., Random Forest, support vector machine) have demonstrated superior performance in ecological research by effectively processing high-dimensional, heterogeneous data [12]. These models quantitatively determine individual driver contributions [13,14], offering enhanced reliability for causal analysis of forest spatiotemporal changes. Recent reviews, such as that by Sun et al., underscore the growing application of ensemble machine learning models like Random Forest in dissecting the nonlinear interactions between forest dynamics and socio-ecological drivers, particularly in rapidly urbanizing regions [15]. The synergistic integration of GIS-based pattern analysis and machine learning-driven factor attribution represents an innovative technical pathway for advancing forest evolution research.

This study selects Yibin City in Sichuan Province, China, as the study area based on three principal considerations: Firstly, its strategic position within the upper Yangtze River's ecological barrier zone, characterized by abundant forest resources and typical mountainous forest landscapes, renders forest dynamics critical to regional ecological security and watershed water conservation [16]. Secondly, the city's concurrent exposure to multiple natural (climate variability, topographic complexity) and anthropogenic (urban expansion, economic development) drivers establishes it as an exemplary region for investigating forest dynamics and their driving mechanisms. Thirdly, recent implementation of national and local ecological policies (e.g., Natural Forest Protection Program, Grain-for-Green Project) provides a tangible policy context for analyzing human-environment interactions. A recent investigation by Liu et al. into the Grain-for-Green Project's long-term impacts in Southwest China revealed significant forest recovery in mountainous regions, aligning with Yibin's ecological restoration trends and reinforcing the relevance of policy-driven analysis in this study [17]. Utilizing land-use data from 2000, 2011, and 2022, this research employs a dual analytical approach: GIS-based spatiotemporal analysis to quantify forest cover dynamics across 2000–2022, combined with Random Forest algorithm implementation to identify contribution magnitudes of driving factors. The quantitative investigation of forest evolution patterns and driving mechanisms in Yibin not only informs localized forest management strategies but also establishes transferable methodologies for sustainable ecosystem governance in comparable ecological regions across China.

## 2. Materials and methods

### 2.1. Study area

Yibin City is located on the southern edge of the Sichuan Basin (103°–105° E, 27°–29° N) in the upper reaches of the Yangtze River, covering a total area of approximately 13,000 $km^2$ (**Figure 1**). It serves as a core node of the ecological barrier in the upper Yangtze River region. The area features the confluence of the Yangtze River, Minjiang River, and Jinsha River, making it a crucial water system hub. The study area is predominantly mountainous, with a general topographic pattern of "high in the southwest and low in the northeast" and an elevation range of 236–2008 m. The region experiences a subtropical monsoon climate, with an average annual temperature of 16.5 °C–18.5 °C and an average annual precipitation of 900–1200 mm, providing suitable hydrothermal conditions for forest growth. The vegetation is primarily subtropical evergreen broad-leaved forest, with a forest coverage rate of nearly 50%, making it an important water conservation area in the upper Yangtze River. Economically, Yibin plays a pivotal role as a hub connecting the Chengdu-Chongqing economic circle and serves as a significant industrial cluster and production base for Wuliangye in the Yangtze River Economic Belt. Ecologically, it contributes to water conservation, carbon sequestration, oxygen release, and ecological restoration, serving as a natural laboratory for studying human-land relationships in mountainous cities.

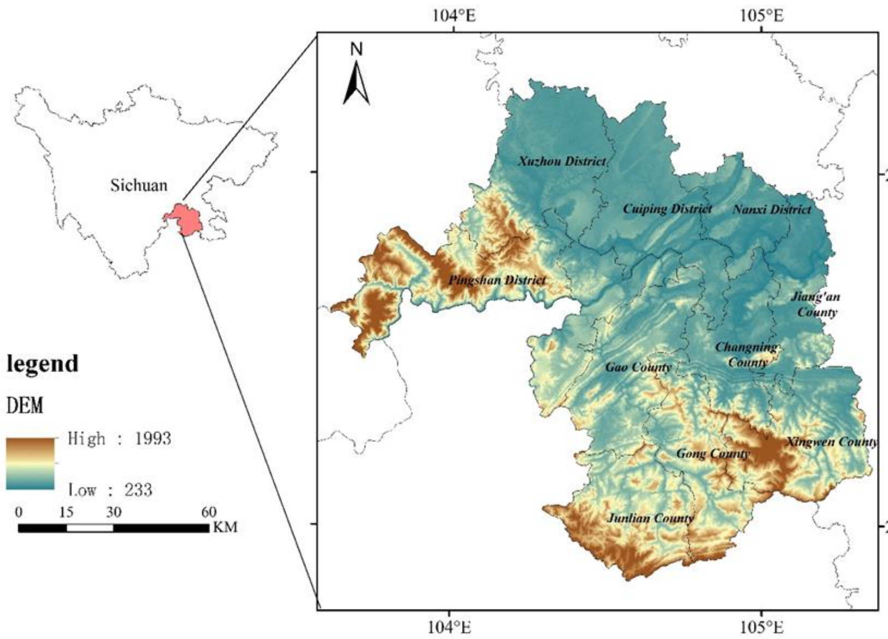


**Figure 1.** Location of the study area.

## 2.2. Methods

### 2.2.1. Land use transfer matrix

The transition matrix, as a quantitative analysis tool, can effectively reveal the dynamic conversion relationships between different land use types and the characteristics of spatial pattern evolution over a specific time period [18]. Its expression is as follows:

$$S_{ij} = \begin{pmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{pmatrix} \quad (1)$$

In this context, *n* represents the total number of land use types within the study area; *i* and *j* correspond to the land use categories at the beginning and end of the study period, respectively. The matrix element $S_{ij}$ quantitatively characterizes the spatial area of conversion from land use type *i* to land use type *j*.

### 2.2.2. Land use dynamic degree

Land use dynamic analysis methods provide essential tools for assessing the evolution of regional land resources. Among these, the single-type dynamic index (*K*) quantitatively characterizes the intensity and trend of changes in a specific land type over the study period [19]. Its expression is as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (2)$$

In the equation, $U_a$ and $U_b$ represent the land use area at the beginning and end of the study period, respectively, and *T* denotes the duration of the study. A positive value of *K* indicates an expansion trend of the land use type, whereas a negative value signifies a contraction.

The land use stability index (*F*) serves as a crucial metric for assessing the degree to which a specific land use type remains unchanged during the study period [20]. Its calculation formula is as follows:

$$F = \frac{\Delta U_{\text{a-b}} + \Delta U_{\text{b-a}}}{U_a} \times \frac{1}{m} \times 100\% \quad (3)$$

Here, $\Delta U_{a\to b}$ represents the area converted from type *a* to other types (b), $\Delta U_{b\to a}$ denotes the area converted from other types to type *a*, and *m* signifies the duration of the study. The *F* value exhibits a non-negative characteristic ($F \geq 0$), with its magnitude positively correlated to the intensity of land use change. Specifically, a smaller *F* value indicates greater spatial stability of the land use type.

Comparative analysis reveals that the *K* index primarily reflects the directional change in the scale of land use types (expansion or contraction), whereas the *F* index emphasizes the spatial stability of land use types. When the area of conversion into and out of a land use type reaches equilibrium, its *K* value approaches zero, indicating that land use change is primarily characterized by spatial reorganization rather than scale expansion or contraction.

### 2.2.3. Random Forest regression algorithm

Random Forest (RF) is an ensemble machine learning algorithm composed of multiple independent decision trees (CARTs), which effectively reduces overfitting and enhances prediction accuracy in both classification and regression tasks [21]. As a significant branch of machine learning models, Random Forest improves the stability of individual decision trees through ensemble learning strategies, making it particularly effective in high-dimensional data analysis and nonlinear relationship modeling. This study employs the Random Forest regression algorithm to quantify the influence of various driving factors on forest evolution. The core optimization objective of this algorithm is to minimize the mean squared error (MSE), whose mathematical expression is as follows:

$$\underbrace{min}_{A,s}\left[\underbrace{min}_{c_1}\sum_{x_i\in D_{1(A,s)}}(y_i-c_i)^2+\underbrace{min}_{c_2}\sum_{x_i\in D_{2(A,s)}}(y_i-c_2)^2\right] \quad (4)$$

here, $c_1$ represents the sample output value of dataset $D_1$, $c_2$ denotes the output value of dataset $D_2$, A is an arbitrary partitioning feature, *s* is an arbitrary partitioning point, $x_i$ is the independent variable, and $y_i$ is the dependent variable.

This study employed the Random Forest regression algorithm within the Land Expansion Analysis System (LEAS) module of the PLUS model to quantify the contributions of driving factors to forest changes in Yibin City. The model parameters were configured as follows: Number of regression trees = 20, sampling rate = 0.01, and number of randomly selected features at each split (mTry) = 11, corresponding to the total number of considered driving factors (e.g., annual precipitation, elevation, distance to roads). These parameter selections balanced computational efficiency with model performance. The study utilized 30-meter resolution land use data from three periods (2000, 2011, and 2022) covering Yibin

City's 13,000 $km^2$ study area. The relatively low tree number (20) and sampling rate (0.01) were chosen to reduce training time while maintaining predictive stability, whereas setting mTry equal to the total feature count ensured comprehensive evaluation of all driving factors during node splitting, thereby maximizing the model's capacity to capture their relative contributions.

To assess model robustness, we implemented 5-fold cross-validation during training. Model performance was evaluated using root mean square error (RMSE), a commonly adopted predictive accuracy metric in PLUS model applications. Cross-validation yielded an RMSE of 0.1627 (based on standardized forest change data), indicating low prediction error. This RMSE value aligns with findings from comparable studies [22], confirming the reliability of Random Forest in characterizing relationships between forest changes and driving factors.

Although GIS-Random Forest integration has become relatively common in ecological and land use studies, this research demonstrates its tailored application within Yibin City's distinctive ecological and socioeconomic context. As a critical ecological barrier in the upper Yangtze River basin, Yibin City faces dual challenges of mountainous ecosystems and complex human-environment interactions. The Random Forest algorithm effectively handles high-dimensional nonlinear relationships between forest changes and multiple drivers (e.g., topographic, climatic, and anthropogenic factors), providing a robust analytical framework for identifying dominant drivers of forest dynamics in mountainous regions. This methodological approach enhances the precision of factor contribution analysis, offering scientific support for developing targeted forest management strategies in Yibin City.

## 3. Results and discussion

### 3.1. Spatiotemporal change characteristics of forests in Yibin City

#### 3.1.1. Temporal change characteristics of forests in Yibin City

By analyzing the temporal changes in land use types and their proportions in Yibin City (**Table 1**), it was found that the land use structure of Yibin City is dominated by cropland and forestland, which together account for more than 95% of the total area. However, the trends in changes among different land use types exhibit significant variations. Specifically, the proportion of cropland area showed a fluctuating trend of initial increase followed by a decrease, rising from 58.62% in 2000 to 61.02% in 2011 and then declining to 60.49% in 2022. The proportion of forestland area exhibited a continuous downward trend, decreasing from 39.63% in 2000 to 36.71% in 2022. The proportions of grassland and water bodies changed relatively little, remaining at approximately 0.02% and 1%, respectively. The proportion of construction land area increased significantly, rising from 0.69% in 2000 to 1.66% in 2022. The proportion of unused land area was extremely low, consistently remaining below 0.001%.

**Table 1.** Proportion of various land use types in Yibin City.

| **Land Use Types** | **proportion** | | |
|---|---|---|---|
| | **2000** | **2011** | **2022** |
| Cultivated Land | 58.62% | 61.02% | 60.49% |
| Forest Land | 39.63% | 36.91% | 36.71% |
| Grassland | 0.02% | 0.01% | 0.02% |
| Water area | 1.04% | 1.08% | 1.11% |
| Construction Land | 0.69% | 0.98% | 1.66% |
| Unused Land | 0.0005% | 0.0002% | 0.0002% |

From the perspective of the rate of change in forestland area (**Figure 2**), the forestland area in Yibin City exhibited distinct phased characteristics during the study period. At the beginning of the study (2000), the dynamic degree of forestland was −0.62%, indicating a decreasing trend in forestland area and a relatively rapid loss of forest resources. By the end of the study period (2022), the dynamic degree of forestland significantly decreased to −0.04%, suggesting that the decline in forestland resources was effectively controlled and the rate of resource loss slowed. In terms of forestland stability, the *F*-value increased from 2.27 to 2.9, reflecting a positive trend that indicates enhanced stability of forestland and an improvement in ecosystem quality, demonstrating a favorable developmental trajectory.

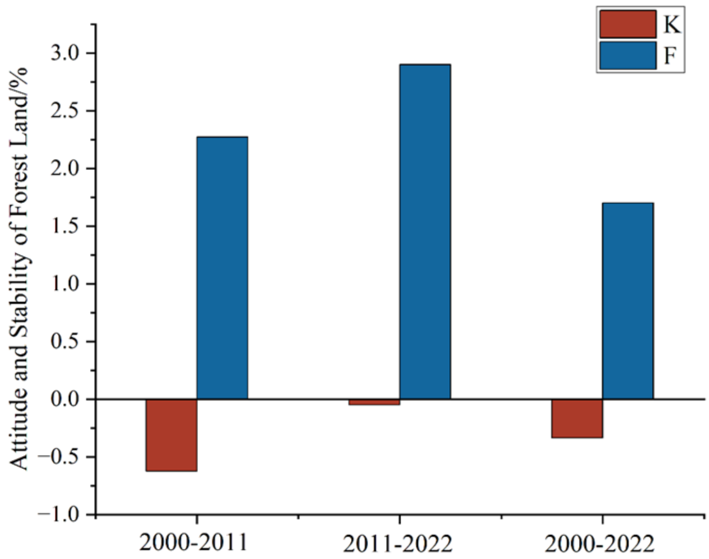


**Figure 2.** Forest land dynamic degree and stability in Yibin City.

From the data on the mutual transitions between forestland and other land types (**Figure 3**), in terms of forestland gain, the conversion of cropland to forestland was the primary method of forest area restoration. From 2000 to 2022, the area converted was 787.97 km$^2$, accounting for 99.8% of the total increase in forestland in the city, demonstrating the targeted focus of ecological restoration projects on cropland. Additionally, 0.99 km$^2$ of grassland and 0.94 km$^2$ of water bodies were converted to forestland, with their combined contribution being less than 0.2%, representing a minor supplementary source. The conversion of forestland to cropland was the main cause of forestland area reduction, with 1170.54 km$^2$ of forestland being converted back to cropland over the 22-year period, accounting for approximately 99.5% of the total converted area. Furthermore, small amounts of forestland were converted to grassland, water bodies, and construction land, with areas of 0.42 km$^2$, 1.83 km$^2$, and 3.65 km$^2$, respectively. Although the area of forestland converted to construction land accounted for only 0.3%, it reflects a trend of construction land encroaching on forestland.

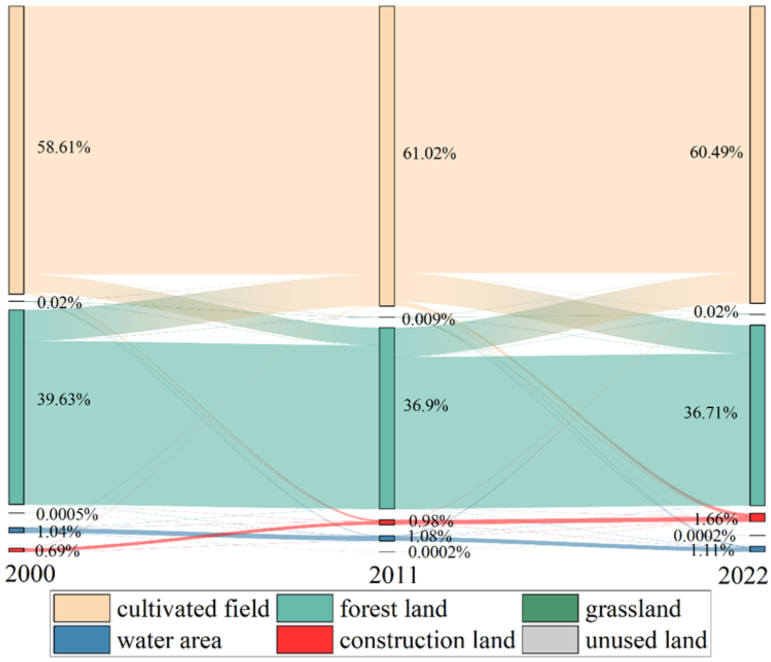


**Figure 3.** Land use transition matrix of Yibin City from 2000 to 2022.

### 3.1.2. Spatial change characteristics of forests in Yibin City

The spatial distribution of various land use types in Yibin City exhibits significant regional differences (**Figure 4**), with distinct temporal changes observed over time. Cropland is predominantly concentrated in the central and northeastern regions of Yibin City, including flatlands and hilly areas in Cuiping District, Nanxi District, Jiang'an County, and Xuzhou District. Forestland is mainly distributed in the western and southern mountainous areas of Yibin City, including Xingwen County, Gong County, and Junlian County, forming a spatially complementary pattern with cropland. Grassland, which accounts for the smallest proportion, is scattered in high-altitude mountainous areas and along riverbanks, such as in Pingshan County and Xingwen County. Water bodies are primarily distributed along rivers such as the Yangtze River, Minjiang River, and Jinsha River. Construction land is concentrated in urban built-up areas, along transportation routes, and around industrial and mining enterprises, such as in Cuiping District, Xuzhou District, and Nanxi District, exhibiting a "point-like diffusion" pattern. Unused land is mainly found in high-altitude mountainous areas, steep slopes, and abandoned industrial and mining sites.

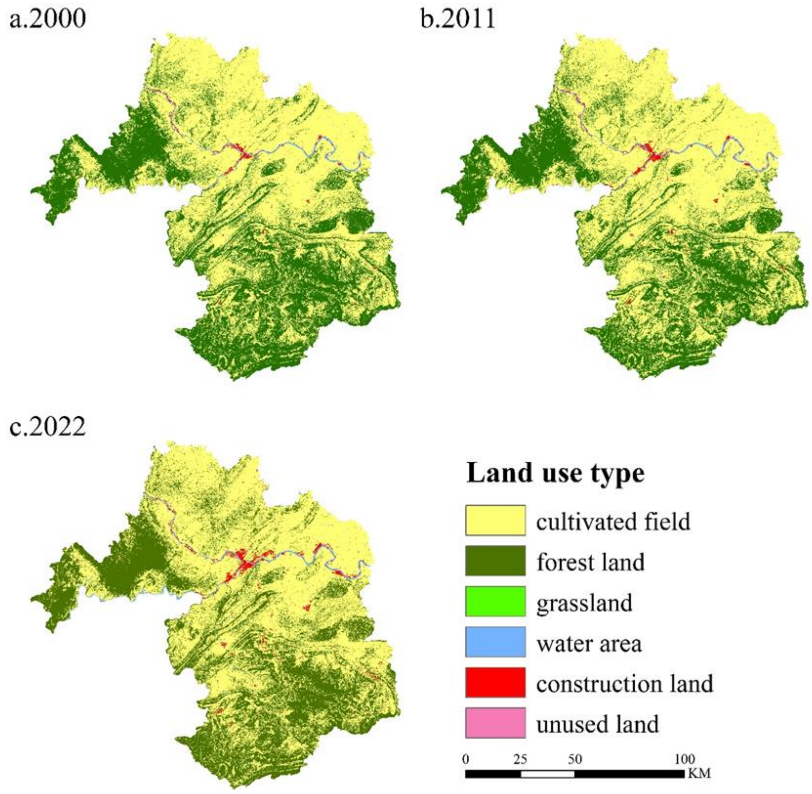


**Figure 4.** Spatial distribution of land use in Yibin City from 2000 to 2022. **(a)** Land Use Distribution in the Study Area, 2000; **(b)** Land Use Distribution in the Study Area, 2011; **(c)** Land Use Distribution in the Study Area, 2022.

Through the analysis of forest spatial changes in Yibin City from 2000 to 2022 (**Figure 5**), significant changes in the spatial distribution of forestland area can be observed. The areas of forestland reduction are relatively scattered, primarily concentrated in the central and southern regions of Yibin City, including counties such as Gao County, Gong County, and Changning County, where urbanization has progressed rapidly, agricultural development is intensive, and human activities have had a pronounced impact on low-altitude hilly and plain areas. The intensification of economic development and human activities has led to a notable decrease in forestland area in these regions. Areas of forestland increase are mainly distributed in counties such as Xuzhou District, Cuiping District, and Xingwen County, where elevations are higher, terrain is more rugged, and slopes are steeper. These regions, being key ecological protection zones with minimal human disturbance, provide favorable conditions for the implementation of ecological restoration policies. Areas where forestland area remained relatively stable are primarily located in the western Pingshan County and Xuzhou District, as well as in the southern counties of Junlian County, Gong County, and Xingwen County, which are either ecological protection zones or regions with slower economic development. In these areas, the extent of forestland change was minimal.

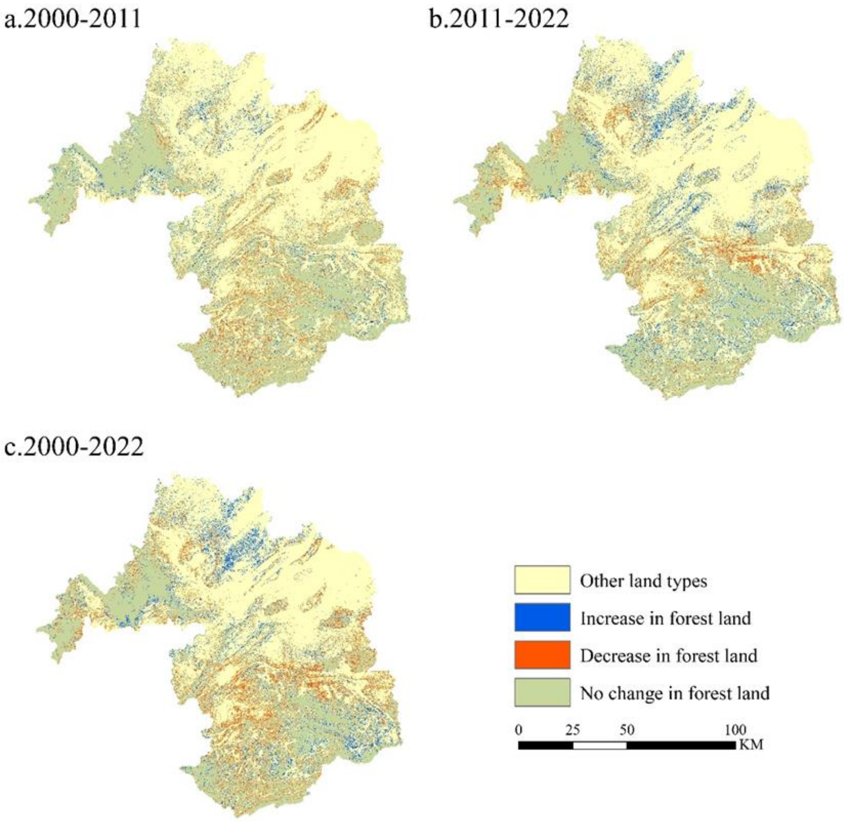


**Figure 5.** Regions of spatial change in forest area in Yibin City. **(a)** Spatiotemporal Distribution of Forest Land in the Study Area, 2000–2011; **(b)** Spatiotemporal Distribution of Forest Land in the Study Area, 2011–2022; **(c)** Spatiotemporal Distribution of Forest Land in the Study Area, 2000–2022.

## 3.2. Analysis of driving factors for spatiotemporal changes in forests in Yibin City

Building on the analysis of the spatiotemporal changes in forests in Yibin City, this study focuses on exploring the driving factors behind forestland evolution from multiple dimensions. The Land Use Expansion Analysis System (LEAS module) within the PLUS model was utilized to analyze the driving factors of forestland changes. Based on previous research experience and the characteristics of Yibin City, 11 driving factors were selected (**Figure 6**). The reclassified land use data from 2000 and 2022 were input into the PLUS model, and expansion areas were extracted. The raster data of the driving factors were processed with a unified coordinate system and pixel size before being imported into the LEAS module to analyze the driving roles of natural and social factors in land use changes.

The results (**Figure 7**) indicate that both natural and socio-economic factors jointly influence the spatiotemporal distribution pattern of forestland. Among these, annual precipitation (0.156), DEM (0.131), and distance to rivers (0.118) are the primary driving factors affecting forestland changes, highlighting the decisive role of climatic, hydrological, and topographic elements in shaping forestland distribution patterns. Road accessibility (0.115) and GDP (0.099) exhibit significant driving effects on forestland distribution, underscoring the substantial constraints imposed by human activities on forestland resource distribution. Slope (0.092), annual average temperature (0.08), and population density (0.086) have moderate impacts on forestland distribution as socio-economic and natural factors. Additionally, distance to railways (0.061) and aspect (0.053) exert relatively minor influences on forestland resource distribution patterns, while soil type (0.03) contributes the least to the forestland distribution pattern.

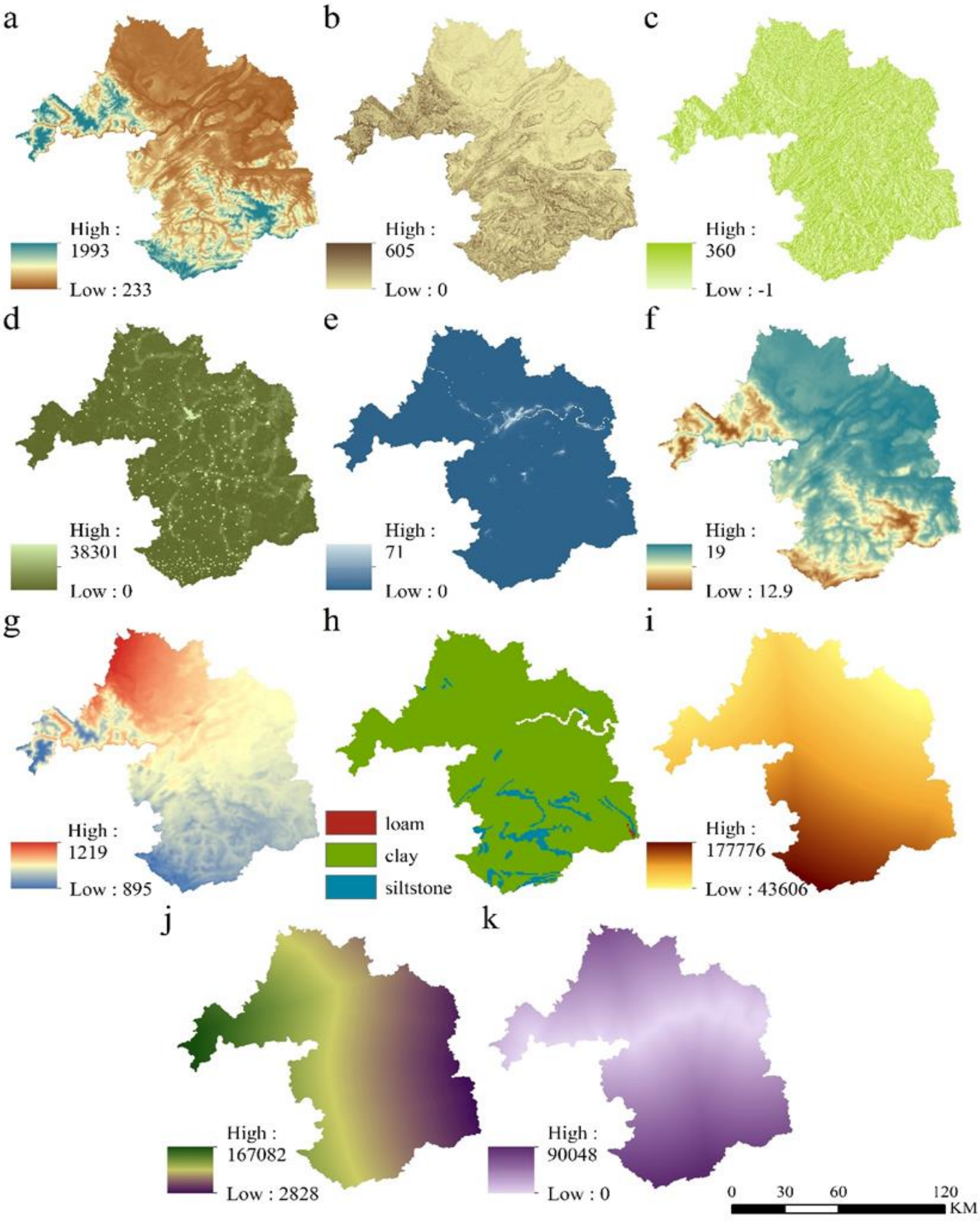


**Figure 6.** Driving factors of land use change in Yibin City: (a) DEM; **(b)** slope; **(c)** aspect; **(d)** population density; **(e)** GDP; **(f)** average annual temperature; **(g)** average annual precipitation; **(h)** soil type; **(i)** distance to railway; **(j)** distance to road; **(k)** distance to river.

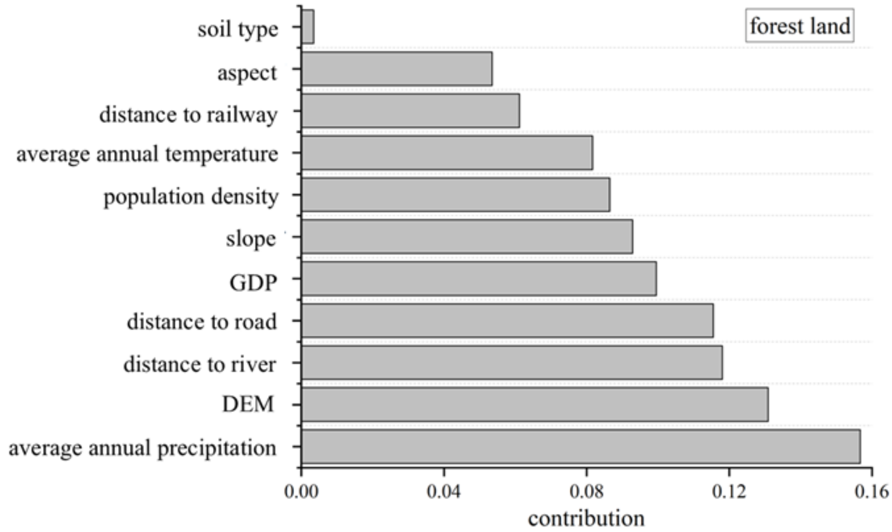


**Figure 7.** Contribution of driving factors to the growth of forest area in Yibin City.

### 3.3. Causal mechanism analysis of driving factors

Forest changes are driven by a combination of multiple natural and anthropogenic factors, among which precipitation, GDP growth, and road accessibility are the key variables influencing forest dynamics in Yibin City. This section delves into how these factors affect forest changes from a causal mechanism perspective and analyzes the complexity of their interactions.

Annual precipitation (0.156) is the most critical natural factor influencing forest dynamics. Increased precipitation can promote forest recovery by improving water availability, while in some cases, it may exacerbate soil erosion, thereby affecting forest growth [23]. Adequate precipitation enhances soil moisture, strengthens vegetation growth capacity, and accelerates the natural recovery of forests, particularly in high-altitude mountainous areas of Yibin (e.g., Xingwen County, Junlian County), where precipitation is higher and evaporation is lower, resulting in more significant forest recovery. Conversely, excessive precipitation may lead to soil erosion, especially in areas with steep slopes (e.g., hilly regions of Changning County), where soil and water loss can hinder forest recovery Remote sensing data analysis reveals that areas with annual precipitation exceeding 1100 mm experience faster forest recovery, while regions with annual precipitation below 1000 mm (e.g., areas surrounding urban centers) show relatively slower recovery. This trend aligns with the findings of Koehn et al. [24], which highlight the positive role of precipitation in subtropical forest recovery.

GDP (0.099) exerts a dual effect on forest changes, potentially causing both forest loss and forest restoration. On one hand, economic growth drives urban expansion and infrastructure development, leading to a reduction in forest area. For example, in Cuiping District, some forests have been converted into urban green spaces and industrial land, while the expansion of cash crops (e.g., sorghum cultivation) has replaced parts of the forest with agricultural land. On the other hand, as the government places greater emphasis on ecological protection, fiscal revenues generated by GDP growth have facilitated the implementation of ecological compensation policies, such as subsidies for the Grain for Green Program and the construction of ecological public welfare forests [25]. In high-altitude areas of Yibin City, these policies have effectively promoted forest recovery. For instance, the government has established special compensation funds in ecological functional zones to support forest farmers in vegetation restoration and increase forest coverage. Additionally, with the development of Yibin's green economy (e.g., bamboo industry and eco-tourism), forest resources have been more effectively protected and restored. This trend is consistent with the findings of Lu et al. [26], which indicate that GDP growth in the upper reaches of the Yangtze River initially leads to forest loss but results in increased forest coverage in later stages due to policy interventions.

The impact of distance from roads (0.115) on forest change is primarily manifested in two aspects: Forest fragmentation and ecological restoration. Areas in close proximity to roads experience faster forest loss, while regions farther from roads exhibit relatively better forest recovery [27]. The expansion of the transportation network in Yibin City, particularly along the Yibin-Luzhou Expressway, has enhanced accessibility, leading to intensified forest fragmentation. Infrastructure development along the roads, such as industrial parks and logistics centers, has significantly contributed to forest loss in areas near the roads. However, in regions distant from roads, government-led initiatives like the Grain for Green Project have effectively promoted forest restoration. For instance, national ecological conservation policies tend to favor large-scale forest restoration programs in areas with limited accessibility and minimal human disturbance. This suggests that roads not only facilitate forest destruction but also provide opportunities for ecological restoration. Forest change is not determined by a single factor but rather by the interplay of multiple factors. GDP growth often accompanies road construction, and infrastructure expansion tends to exacerbate forest fragmentation, yet it may also foster forest restoration through ecological investments driven by economic growth. Additionally, the interaction between precipitation and topography cannot be overlooked. In high-altitude regions, precipitation plays a more significant role in forest restoration, whereas in low-altitude urbanized areas, economic factors exert a more pronounced influence. The implementation of ecological policies is also closely linked to economic development. In economically advanced regions, such as the central urban area of Yibin City, policies often focus on curbing forest destruction, while in remote mountainous areas, the emphasis is primarily on promoting forest expansion.

Forest changes are not determined by a single factor but result from the interaction of multiple factors [28]. GDP growth is often accompanied by road construction, and infrastructure expansion tends to exacerbate forest fragmentation, while also potentially promoting forest restoration through ecological investments driven by economic growth. Furthermore, the interaction between precipitation and topography cannot be overlooked. In high-altitude areas, precipitation plays a stronger role in forest recovery, while in low-altitude urbanized regions, economic factors have a more significant impact. The implementation of ecological policies is also closely related to economic development. In economically developed areas (e.g., the central urban area of Yibin City), policies often focus on curbing forest destruction, whereas in remote mountainous areas, they primarily promote forest expansion.

This study demonstrates that forest changes are not the result of a single variable but are shaped by the combined effects of natural conditions, economic development, and policy interventions. Therefore, policymakers should integrate ecological compensation, transportation planning, and industrial adjustments when formulating forest management strategies to achieve sustainable restoration and utilization of forest resources.

## 4. Discussion

### 4.1. Spatiotemporal change patterns of forests in Yibin City

The land use in Yibin City is predominantly characterized by cropland and forestland, consistent with previous research findings [29,30]. This pattern is closely related to its geographical location on the southern edge of the Sichuan Basin, where hilly and mountainous terrain predominates. However, the changing trends of various land use types reflect the complex relationship between economic development and ecological protection. The area of cropland initially increased and then decreased, with the earlier growth likely linked to agricultural development policies, while the subsequent decline resulted from urban expansion and the implementation of ecological policies such as returning farmland to forest, highlighting the conflict between cropland protection and the demand for construction land [31,32]. The area of forestland continued to decline, despite policies such as returning farmland to forest and natural forest protection. The demand for timber resources driven by economic development and the conversion of forestland to cropland remain primary pressures. The significant increase in construction land [33] indicates accelerated urbanization but also brings challenges such as land resource scarcity and the compression of ecological space. The areas of grassland and water bodies changed minimally, yet their ecological functions should not be overlooked. The extremely low proportion of unused land reflects the high utilization rate of land resources in Yibin City.

The analysis of the rate and stability of forestland changes reveals that the dynamic degree of forestland in 2000 was −0.62%, indicating a rapid loss of forestland, primarily driven by agricultural expansion and urbanization [34]. By 2022, the dynamic degree decreased to −0.04%, showing a significant slowdown in the rate of loss, while the forestland stability index ($F$-value) increased from 2.27 to 2.9, indicating an improvement in ecosystem quality and reflecting the positive outcomes of ecological protection policies. The changes in forestland area were mainly driven by the mutual conversion between cropland and forestland: The conversion of cropland to forestland was the primary pathway for forest restoration, highlighting the effectiveness of ecological restoration projects [35]. In contrast, the conversion of forestland to cropland accounted for 99.5% of the total, representing the main cause of forestland reduction and reflecting the ongoing pressure of agricultural development on forest resources. Additionally, although the conversion of forestland to construction land accounted for only 0.3%, its increasing trend suggests that the potential threat of urbanization to forestland cannot be overlooked.

In terms of spatial distribution, cropland is concentrated in the flatlands and hilly areas of the central and northeastern regions, while forestland is distributed in the mountainous areas of the west and south, forming a spatially complementary pattern with cropland. Grassland is scattered in high-altitude mountainous areas and along riverbanks; water bodies are distributed along the Yangtze River, Minjiang River, and Jinsha River; construction land is concentrated in urban built-up areas and along transportation routes; and unused land is found in high-altitude mountainous areas and steep slopes. Areas of forestland reduction are mainly located in the low-altitude hilly and plain regions of the central and southern parts, where urbanization is rapid and agricultural development is intensive. Areas of forestland increase are concentrated in high-altitude zones or key ecological protection areas, benefiting from policies such as returning farmland to forest [36]. Areas of stable forestland are distributed in the ecological protection zones of the west and south, indicating the significant effectiveness of ecological protection policies.

In the future, Yibin City should strengthen the coordination between ecological restoration and land use planning in low-altitude hilly and plain regions to reduce further encroachment of human activities on forestland. In high-altitude mountainous areas, the continuation of ecological protection policies is essential to consolidate the achievements of forestland restoration. Simultaneously, efforts should be made to promote a balanced development between economic growth and ecological protection, ensuring the sustainable utilization of forest resources and the long-term safeguarding of regional ecological security.

## 4.2. Interaction between natural factors and human activities

Forest changes are influenced by both natural factors and human activities, which do not operate independently but interact and constrain each other, collectively shaping the spatiotemporal evolution of forests in Yibin City. This section, based on the empirical results of this study, explores how economic growth affects forest changes and analyzes its interactions with ecological policies and natural environmental factors.

### 4.2.1. Dual effects of economic growth on forest changes

Economic growth in Yibin City has accelerated over the past two decades, with GDP increasing from 42.35 billion yuan in 2000 to 187.69 billion yuan in 2022, reflecting significant urbanization and industrial expansion in the region. However, the impact of economic growth on forest changes is dual, potentially exacerbating forest loss while also promoting forest restoration, depending on the economic development model, government policy interventions, and natural conditions.

From a negative perspective, economic growth is often accompanied by urban expansion, accelerated industrialization, and infrastructure development, leading to a reduction in forest area. The study found that the proportion of construction land in Yibin City increased from 0.69% in 2000 to 1.66% in 2022, while the forest area decreased from 39.63% to 36.71% during the same period, indicating that urbanization has encroached on forest resources to some extent. In economically developed areas, such as Cuiping District and Xuzhou District, urban expansion and industrial development have led to the conversion of large areas of forest into construction land and high-value agricultural land (e.g., sorghum cultivation for liquor production), reflecting the squeezing effect of economic growth on forest resources. Additionally, infrastructure development (e.g., roads, logistics parks) has exacerbated forest fragmentation, particularly along the Yibin-Luzhou economic belt, where forests have been fragmented into smaller patches, reducing ecological connectivity.

However, economic growth can also promote forest restoration by facilitating the implementation of ecological policies and the development of green industries. With increased government investment in ecological protection, ecological compensation policies (e.g., the Grain for Green Program, the Natural Forest Protection Program) have been implemented under the impetus of economic growth, promoting forest restoration. For example, in high-altitude areas such as Xingwen County and Junlian County, fiscal revenues generated by economic growth have supported the construction of ecological public welfare forests, leading to an increase in forest area between 2011 and 2022. Moreover, the "bamboo industry + eco-tourism" model, promoted through government-enterprise cooperation, has become a typical case of economic growth driving forest restoration. In Gong County and Changning County, the expansion of bamboo planting has increased forest coverage while providing a sustainable development path for the local economy.

#### 4.2.2. Regulatory role of natural environment on economic activities and forest changes

Natural environmental factors play a regulatory role in the relationship between economic growth and forest changes, influencing the specific manifestations of economic activities on forests. For instance, precipitation and elevation are critical natural factors affecting forest changes, but their effects vary depending on the intensity of regional economic activities. The study found that in areas with annual precipitation exceeding 1100 mm (e.g., Junlian County, Gong County), forest recovery rates are higher, and forest loss is slower even in regions with higher GDP. This may be because these areas, with abundant water resources, have stronger ecological recovery capacities, and the destructive impacts of economic activities on forests are offset by the natural restorative effects of precipitation. In contrast, in areas with lower precipitation, such as the urban areas of Yibin City and low-altitude regions along the Jinsha River, economic activities (e.g., urban expansion, industrial development) have a more pronounced impact on forest resources, resulting in higher rates of forest loss. This demonstrates the significant regulatory role of natural conditions in the interaction between economic development models and forest changes.

Additionally, road accessibility plays a key role in the relationship between economic growth and forest changes. The study shows that the impact of roads on forest changes varies under different levels of economic development. In economically developed urban areas, forest loss is more pronounced in regions close to roads. For example, in Cuiping District, the rate of forest loss within 1 km of roads is significantly higher than in areas farther from roads. This indicates that the land demand driven by economic growth tends to prioritize areas with convenient transportation, leading to the exploitation and utilization of forests. In contrast, in less economically developed mountainous areas (e.g., Xingwen County, Pingshan County), roads act as drivers of ecological restoration. Due to government-implemented ecological compensation projects targeting remote areas, forest recovery rates are higher, particularly in regions more than 3 km from main roads, where forest area shows an increasing trend.

#### 4.2.3. Regulatory role of ecological policies

Ecological policies serve as a buffer mechanism in the relationship between economic growth and forest changes, mitigating the destructive impacts of economic expansion on forest resources to some extent and guiding economic development toward an eco-friendly direction. Since 2000, Yibin City has implemented a series of ecological protection policies, among which the Grain for Green Program and the Natural Forest Protection Program have had the most significant impact on forest changes. For example, in high-altitude areas (elevation > 800 m), the Grain for Green Program has significantly reduced farmland reclamation and promoted forest restoration. In urbanized areas, ecological protection policies primarily focus on the construction of urban green belts and ecological barriers, but their restoration rates are much lower than in remote mountainous areas. This indicates that the effects of ecological policies exhibit regional variability, with more pronounced impacts in areas with favorable natural conditions and lower economic pressures.

### 4.3. Driving factors of forest changes in Yibin City

This study, through a multi-dimensional analysis of driving factors, reveals the complex mechanisms underlying the spatiotemporal evolution of forestland in Yibin City, demonstrating that both natural elements and anthropogenic factors play significant roles in shaping the spatiotemporal distribution patterns of forestland [37,38].

Among the topographic factors, elevation and slope exert significant control over the spatial pattern of forestland, a finding consistent with the geomorphological characteristics of the ecological barrier zone in the upper reaches of the Yangtze River. Johnson et al. [39] also identified elevation and slope as critical factors influencing forestland distribution in their study of juniper woodlands in the western United States. The results indicate that topographic factors play a key role in shaping regional forestland distribution patterns by affecting the redistribution of hydrothermal conditions and the scope of human activities. Similarly, Reed et al. [40] found that topography is a significant factor influencing forestland distribution in their study of the Serengeti. The increase in forestland is more pronounced in higher elevation areas, primarily due to the “High Mountain Ecological Migration” policy implemented in Yibin City, which encourages residents in high-altitude regions to relocate to lower-altitude areas, effectively reducing human disturbance to high mountain forestland. Concurrently, the implementation of the Natural Forest Protection Project has led to a notable increase in forest coverage and resource reserves in areas above 800 m in elevation.

Among the climatic factors, the spatial variation in annual precipitation significantly influences the pattern of forestland restoration, which is closely related to the unique “high in the south and low in the north” topography of Yibin City, leading to distinct spatial precipitation distribution. Koehn et al. [23] also found that precipitation significantly affects forestland distribution in their study on the relationship between seasonal precipitation and soil moisture in forests and woodlands. The southern mountainous region of the study area receives abundant precipitation, providing favorable conditions for the natural restoration of forestland. Additionally, the “Bamboo Sea Project” has been implemented in this region, promoting bamboo-based economies in areas with annual precipitation exceeding 1100 mm, thereby balancing ecological protection and economic development. Annual average temperature has a positive impact on forestland changes, as Yibin City is located within the citrus industry belt of the upper Yangtze River, rich in economic forest resources. Moderate increases in temperature can facilitate the expansion of economic forests, particularly in areas below 500 m in elevation, where the expansion of citrus cultivation has contributed to an increase in forestland area.

The impact of human activities on the spatiotemporal patterns of forestland exhibits significant spatial heterogeneity, consistent with previous research findings [41]. The driving effect of road accessibility in Yibin City displays a unique “bimodal” characteristic: Forestland reduction is pronounced in areas closer to major roads, which aligns closely with the spatial distribution of the local liquor industry belt. The expansion of liquor enterprises such as Wuliangye has driven changes in land use and the improvement of infrastructure in surrounding areas, leading to the encroachment of forest resources near these enterprises. In contrast, forestland increase is notable in areas farther from roads, reflecting the success of the “liquor enterprise + farmer” cooperative afforestation model, where enterprises promote forestland restoration in surrounding regions through the establishment of raw material forest bases. Additionally, GDP has a significant influence on the spatiotemporal patterns of forestland, a result consistent with previous studies [25]. In areas with higher GDP values, forestland resources tend to decrease, while in areas with lower GDP values, forestland resources tend to increase, aligning with earlier conclusions. The influence of GDP reflects the notable success of Yibin City’s “industry supporting forestry” policy, where tax revenues from the liquor industry are reinvested into ecological construction, resulting in the formation of forestland restoration zones around the economic core areas.

In terms of policy-driven mechanisms, the innovative “Bamboo Sea+” model implemented in Yibin City has played a significant role. By integrating bamboo forest cultivation with eco-tourism and carbon trading, a unique bamboo landscape belt has been formed in areas with slopes of 15°–25°, effectively increasing forest coverage. Additionally, as the first city along the Yangtze River, Yibin City’s “Shoreline Restoration 2.0 Project” has reduced the forest fragmentation index within a 1 km range along the Jinsha River and Minjiang River by establishing a multi-layered protection system of trees, shrubs, and grasses, significantly enhancing the ecological functions of the river corridors.

It is noteworthy that the contribution of soil type is relatively low, revealing that forestland evolution in the study area is more strongly influenced by external driving factors. This may be related to the substrate homogeneity resulting from the widespread distribution of purple soil. This finding provides new insights for ecological restoration in karst-danxia landform regions.

### 4.4. Impact of the baijiu industry on forest dynamics

Yibin City, a renowned baijiu production base in China, has its economy significantly bolstered by the baijiu industry, which stands as one of its core economic pillars. In recent years, the expansion of the baijiu industry has not only propelled local economic development but also influenced the spatiotemporal evolution of forest resources to varying degrees. This study reveals that the baijiu industry exerts a dual impact on forest dynamics through land use changes, ecological compensation policies, and raw material supply chains, potentially fostering forest restoration while also exacerbating forest reduction.

Primarily, the expansion of the baijiu industry has led to the conversion of some forested areas into agricultural land. The production of baijiu in Yibin heavily relies on sorghum cultivation, and the increasing demand for brewing-specific sorghum has driven the reclamation of existing forest lands into farmlands in certain areas. Research data indicates that from 2000 to 2022, a total of 1170.54 $km^2$ of forest in Yibin was converted into arable land, particularly in regions such as Cuiping District, Nanxi District, and Jiang'an County, which are core areas of baijiu industry concentration. These regions, being suitable for sorghum cultivation, have seen a pronounced transformation of forest land into agricultural use. Moreover, the expansion of distilleries and related infrastructure developments, such as logistics centers and industrial parks, has further encroached upon forested areas. For instance, the expansion of construction land around the Wuliangye Group and its vicinity has impacted the integrity of surrounding forest resources.

On the other hand, the baijiu industry has also contributed to forest restoration, especially under the guidance of ecological compensation policies, leading to the development of an "ecological brewing" model. In recent years, the government has introduced several ecological protection policies, such as the Natural Forest Protection Program and the Grain for Green Program, encouraging enterprises to adopt sustainable ecological management strategies during industrial development. For example, Wuliangye Group has invested in bamboo forest bases in Xingwen County and Gong County, reducing reliance on wood fuel in the baijiu production process through artificial bamboo planting while also increasing forest coverage. Additionally, baijiu enterprises actively participate in carbon neutrality and ecological compensation mechanisms. In some raw material supply bases in Yibin, companies have implemented a "company + farmer" model, signing long-term contracts with farmers to encourage the planting of economic forests (such as bamboo and fruit trees) under the Grain for Green policy, thereby enhancing forest vegetation coverage and reducing the encroachment of traditional farming on forest resources.

In summary, the impact of the baijiu industry on forest dynamics in Yibin presents both negative and positive aspects. On one hand, the expansion of sorghum cultivation and infrastructure development has led to the conversion of some forests into agricultural and construction lands. On the other hand, guided by ecological compensation policies, enterprises are actively promoting the planting of economic forests and ecological protection, facilitating forest resource restoration. Future policy formulation should further strengthen ecological compensation mechanisms, guiding the coordinated development of the baijiu industry chain and forest resource management and promoting a sustainable industrial ecological model to achieve a win-win situation for economic growth and ecological conservation.

### 4.5. Methodological innovation and unique applications

This study demonstrates methodological innovation and unique applications by integrating Geographic Information System (GIS) technology with the Random Forest (RF) module in the PLUS model to analyze the driving factors of forest land changes in Yibin City. Although the combination of GIS and machine learning is relatively common in forest ecology research, this study deeply integrates the RF module of the PLUS model with GIS data processing capabilities, focusing on the identification and ranking of driving factors, thereby offering a distinct perspective that differentiates it from other studies. Specifically, we utilized GIS technology to process land use data from 2000, 2011, and 2022 at high spatiotemporal resolution, which was then input into the RF module of the PLUS model to quantify the contributions of 11 natural and socio-economic driving factors to forest changes. This approach avoids the limitations of traditional statistical methods (e.g., linear assumptions) and leverages the nonlinear modeling capabilities of RF to accurately reveal the dominant roles of annual precipitation (0.156), elevation (0.131), and river distance (0.118) as primary driving factors, while also highlighting the significant influence of socio-economic factors such as road distance (0.115) and GDP (0.099).

The innovation of this study lies in the targeted application of the RF module in the PLUS model and its optimized integration with GIS. Rather than using the PLUS model for land use change simulation, we focused on driving factor analysis and fine-tuned the RF algorithm based on the ecological-economic characteristics of Yibin City. For instance, by assigning dynamic weights to socio-economic factors (e.g., GDP and road distance) based on the local influence of the liquor industry, the model's sensitivity to anthropogenic disturbances was enhanced. This adjustment enabled RF to more precisely capture the driving effects of liquor enterprise expansion on forest loss in low-elevation areas (e.g., the conversion of 1170.54 $km^2$ of forest to farmland between 2000 and 2022) and the natural driving mechanisms of forest restoration in high-elevation ecological reserves (e.g., the conversion of 787.97 $km^2$ of farmland to forest). Compared to the conventional separate application of GIS and RF in studies such as Deng et al. (2009), this study established a streamlined analytical workflow through efficient GIS data preprocessing and localized optimization of the RF module, not only improving the accuracy of driving factor ranking but also providing new insights into forest dynamics under the interplay of policies (e.g., Grain for Green) and economic activities. This method is particularly suitable for regions experiencing rapid urbanization alongside ecological conservation, setting an efficient and locally adaptive example for driving factor analysis in forest ecology research.

### 4.6. Limitations and future prospects of the study

This study systematically analyzes the spatiotemporal evolution characteristics and driving mechanisms of land use in Yibin City, but it still has some limitations.

First, in terms of data acquisition, the study period is relatively short, and the use of remote sensing data with a 30-meter spatial resolution may not fully reflect the long-term evolution patterns of forestland, potentially introducing some spatial accuracy errors. The moderate resolution may lead to underestimation of small-scale forest patches or fragmented land-use changes, particularly in rugged mountainous areas where edge effects are pronounced. To address this, validation against high-resolution imagery was conducted, but future studies could further reduce bias by integrating sub-meter resolution data (e.g., from Sentinel-2 or commercial satellites) to capture finer details. Second, the selection of driving factors primarily integrates natural and anthropogenic factors, which may not fully encompass the unique influencing factors of Yibin City. It is recommended that subsequent studies include more localized indicators (e.g., the expansion intensity of the liquor industry, the contribution of the bamboo economy, etc.). Additionally, potential biases in socio-economic data, such as GDP and population density, may arise from inconsistent reporting standards across administrative units or temporal discrepancies in data collection. These were partially mitigated through interpolation and cross-verification with local records, but future research could employ time-series harmonization techniques to enhance consistency. Additionally, this study did not fully consider the time-lag effects of policy implementation, which may affect the accuracy of the driving mechanism analysis.

Furthermore, it is recommended to focus on the following aspects: (1) Deepen the research on the coupling mechanisms of “human-land-industry,” particularly the interaction between the liquor industry and forestland changes; (2) conduct multi-scale comparative analyses to reveal the heterogeneous patterns of forestland changes across different geographical units; (3) develop an integrated “natural-economic-social” assessment model to provide decision-making support for the coordinated development of ecological industries; and (4) strengthen climate change scenario simulations to evaluate the response mechanisms of forestland ecosystems under future climate conditions.

## 5. Policy recommendations

This study identifies the primary drivers of forest changes in Yibin City, including climatic conditions (precipitation, temperature), socio-economic factors (GDP), infrastructure (road accessibility), and natural factors (DEM, slope). Based on the findings, this section proposes targeted policy recommendations to promote sustainable forest restoration, optimize land use structure, and provide actionable pathways for relevant authorities.

### 5.1. Implement land use control to address forest loss due to urban expansion

The study reveals that the expansion of construction land is a significant driver of forest loss in Yibin City. From 2000 to 2022, the proportion of construction land increased from 0.69% to 1.66%, with a clear spatial overlap between urban expansion and forest reduction. To balance urban development and ecological conservation, land use control should be strengthened. In rapidly urbanizing areas such as Cuiping District and Xuzhou District, it is recommended to delineate “ecological protection redlines,” clearly define forest conservation zones, and restrict urban expansion into ecologically sensitive areas. Urban planning should prioritize high-density, low-land-occupancy development models to minimize the encroachment of urban expansion on surrounding forests and improve land use efficiency. Additionally, to compensate for forest loss, a forest compensation mechanism could be established, requiring developers whose infrastructure projects lead to forest reduction to pay ecological restoration funds and implement afforestation projects of equal or larger scale in adjacent areas.

### 5.2. Leverage ecological compensation mechanisms to achieve win-win outcomes for economic development and forest restoration

The study finds that GDP growth has a dual effect on forests: It exacerbates forest loss in urban areas but promotes forest restoration in high-altitude regions (e.g., Xingwen County, Junlian County) through ecological policies and compensation mechanisms. Therefore, ecological compensation policies should be further optimized to foster synergistic development between economic growth and forest restoration. The government could increase subsidies for ecological public welfare forests, particularly in mountainous areas with high forest restoration potential, such as Pingshan County and Changning County, to encourage farmers and enterprises to participate in afforestation and forest protection. Additionally, an “ecological industry + compensation” model could be explored, supporting leading baijiu enterprises (e.g., Wuliangye) in introducing ecological certification standards into their supply chains and encouraging increased forest cover in raw material planting areas. For example, promoting a “bamboo industry + eco-tourism” model could integrate forest restoration with industrial development. Aligning with China’s “carbon neutrality” strategy, Yibin City could pilot forest carbon sink trading, incorporating afforestation and natural forest protection into the carbon trading system, thereby transforming forest resources into market-valued assets and incentivizing greater social capital participation in forest restoration.

### 5.3. Adjust agricultural structure to reduce encroachment of farmland on forests

The results indicate that the conversion of forests to farmland is one of the primary pathways of forest loss in Yibin City, with 1170.54 $km^2$ of forest converted to farmland between 2000 and 2022. Agricultural expansion, particularly in low-altitude areas, exerts significant pressure on forests. Therefore, optimizing agricultural structures is essential to reduce forest resource loss. In mountainous regions, agroforestry and ecological farming practices could be promoted to reduce the demand for traditional farmland expansion. For instance, in Junlian County, where forest recovery is relatively rapid, the cultivation of medicinal herbs and edible fungi under forest cover could enhance the economic value of forest resources. In agriculturally intensive areas (e.g., Jiang’an County, Nanxi County), precision management techniques such as smart irrigation and drone spraying could reduce land demand and improve agricultural productivity, thereby mitigating farmland encroachment on forests. Additionally, in agricultural expansion zones, such as the agricultural belt along the Jinsha River in Yibin City, forest buffer zones and water conservation forests could be established to minimize the ecological damage caused by agricultural activities.

### 5.4. Integrate transportation infrastructure development to reduce forest fragmentation

The study highlights road accessibility as a critical factor influencing forest changes, with road construction exacerbating forest fragmentation, particularly within 1 km of roads. Therefore, in mountainous road planning, direct forest crossings should be minimized, and road routes should be designed to bypass nature reserves. Furthermore, eco-friendly road construction could be piloted in forest-dense areas of Yibin City (e.g., near the Shunan Bamboo Sea), incorporating ecological corridors and vertical greening along roadsides to reduce the ecological impact of transportation. For existing roads (e.g., along the Yibin-Luzhou Expressway), ecological restoration projects should be implemented, such as establishing ecological buffer zones on both sides of the road to mitigate the fragmentation effects of roads on forests.

## 6. Conclusion

(1) The land use in Yibin City is predominantly characterized by cropland and forestland (accounting for over 95% of the total area). The area of cropland initially increased and then decreased, while forestland continued to decline and construction land expanded significantly. The rate of forestland loss slowed (with the dynamic degree decreasing from −0.62% to −0.04%), and ecosystem stability improved (the $F$-value increased from 2.27 to 2.9). The conversion of cropland to forestland is the primary driver of forest recovery, whereas the conversion of forestland to cropland is the main cause of reduction.

(2) The spatial distribution of land use exhibits significant differences: Cropland is concentrated in the central and northeastern regions; forestland is distributed in the western and southern mountainous areas; grassland is scattered in high-altitude mountainous regions and along riverbanks; water bodies are distributed along the Yangtze River, Minjiang River, and Jinsha River; and construction land is concentrated in urban areas and along transportation routes. Areas of forestland reduction are mainly located in the central and southern regions with rapid economic development, while areas of forestland increase are concentrated in high-altitude zones or key ecological protection areas. Stable forestland areas are distributed in the western and southern ecological conservation zones.

(3) Changes in forestland are primarily influenced by annual precipitation, elevation, and distance to rivers; road accessibility and GDP have significant impacts; slope, annual average temperature, and population density exert moderate influences; while distance to railways, aspect, and soil type have relatively minor effects.

(4) Beyond its implications for Yibin City, this study contributes significantly to the broader fields of forest ecology and sustainable development. The integrated use

of GIS-based spatiotemporal analysis and Random Forest-driven factor identification provides a robust methodological framework that can be adapted to other regions facing similar ecological challenges, such as deforestation driven by agricultural expansion or urbanization in mountainous landscapes. For instance, the finding that policy-driven conversion of cropland to forestland is a primary mechanism for forest recovery offers valuable insights for regions implementing afforestation programs, such as the Loess Plateau in China or the Himalayan foothills, where balancing agricultural needs with ecological restoration is a persistent issue. Similarly, the identification of elevation and precipitation as dominant natural drivers, coupled with socio-economic factors like GDP and road proximity, highlights universal mechanisms that can inform forest management in other ecologically sensitive zones undergoing rapid development, such as the Andes or the Western Ghats. Moreover, the tailored application of the PLUS model to simulate policy-driven land-use scenarios enhances its utility as a predictive tool for sustainable planning, applicable to any region aiming to reconcile economic growth with forest conservation. By demonstrating how local ecological policies (e.g., Grain-for-Green, Bamboo Sea Project) can mitigate forest loss while supporting economic activities like the liquor industry, this study offers a transferable model for achieving sustainable development goals in biodiversity-rich, economically active regions worldwide.

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