# Postprint: Forest Ecological Security Assessment and Center of Gravity Evolution Analysis in Hubei Province Based on Ecological Location Coefficient

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## Abstract

Forests are crucial components of the Earth' s ecosystem. However, with the rapid development of human economy and society, forest ecosystems are becoming increasingly vulnerable, which impacts the sustainable development of humanity. Therefore, research on forest ecological security holds significant practical importance. Based on panel data from Hubei Province spanning 1999 to 2014, this study first calculated the forest ecological security index using the entropy weight method and fuzzy matter-element method, then computed the ecological location coefficient by integrating meteorological and topographic indicators, adjusted the forest ecological security index using this coefficient, and further incorporated ArcGIS software and a gravity center analysis model. The following conclusions were drawn: (1) Regions with the highest ecological location coefficients are primarily distributed in the eastern and select central areas of Hubei Province, while the lowest coefficients are mainly found in western Hubei, with the ecological location coefficient demonstrating certain coupling with economic development levels; (2) Over the 16-year period, the number of counties classified in the worst forest ecological security level increased by 100%, indicating that the overall forest ecological security situation in Hubei is not optimistic; (3) The forest ecological security indices of Danjiangkou City and Songzi City maintained a consistent upward trend throughout these 16 years; (4) The forest ecological security gravity center migrated from northwest to southeast between 1999 and 2007, and from east to west between 2007 and 2014, with relatively rapid movement.

# Full Text

## Preamble

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**Forest Ecological Security Evaluation Based on Ecological Location Coefficient and Gravity Center Transfer Analysis in Hubei Province**

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## Abstract

Forests constitute a vital component of Earth' s ecosystems, producing oxygen through photosynthesis to sustain human, animal, and plant life [1-3]. Forest ecosystems provide essential nutrients and food for various species, thereby maintaining biodiversity [4-6]. They also serve critical functions in carbon sequestration, climate regulation, windbreak and sand fixation, and air purification [7-8]. However, rapid economic and social development has intensified deforestation and land encroachment, rendering forest ecosystems increasingly fragile [9]. Forest ecological security refers to the health and integrity of forest ecosystems and their capacity to tolerate ecological destruction and environmental pollution while meeting human survival and development needs. A high forest ecological security index indicates a complete ecosystem and strong sustainable development capacity, whereas a low index suggests unsustainable development [10].

This study evaluates forest ecological security in Hubei Province using panel data from 1999 to 2014. The entropy weight method and fuzzy matter-element method were employed to calculate the forest ecological security index, which was then adjusted using an ecological location coefficient derived from meteorological and terrain indicators. ArcGIS software and a gravity center analysis model revealed four key findings: (1) Areas with the highest ecological location coefficients were concentrated in central and eastern Hubei, while the lowest coefficients appeared in western regions, showing a certain correlation with economic development levels. (2) Over the 16-year study period, counties classified in the worst forest ecological security grade increased by 100%, indicating an overall pessimistic outlook for forest ecological security in Hubei. (3) The forest ecological security indices of Danjiangkou and Songzi maintained an upward trend throughout the study period. (4) The gravity center of forest ecological security migrated from northwest to southeast between 1999 and 2007, then shifted rapidly from east to west until 2014.

**Keywords:** ecological location coefficient; forest ecological security index; status index; pressure index; gravity center transfer

## Introduction

Forests are essential yet fragile components of global ecosystems. The rapid development of human economies and societies increasingly threatens forest ecosystems, compromising their ability to support sustainable development. Consequently, studying forest ecological security holds significant practical importance. Forest ecological security is dynamic and regionally variable, as threats differ across locations. Hubei Province, situated in the middle reaches of the Yangtze River and home to the Three Gorges Dam and Danjiangkou Reservoir (the water source for the South-to-North Water Transfer Project), occupies a critical ecological position. This study designs a forest ecological security index to dynamically assess the health and integrity of Hubei’ s forest ecosystem by integrating forest status and human economic activities.

International research on forest ecological security began early, with studies evaluating Amazon rainforest security [11] and ecological security in northwest Washington [12]. Domestic research remains limited. Mao Xupeng et al. assessed forest ecological security in Hunan and Xiangtan [13-14], while Feng Yan et al. analyzed spatial correlations in Jilin Province [15]. Evaluations of 100 pilot counties ranked Changbai County (Jilin) and Suichang County (Zhejiang) highest, with Gangcha County (Qinghai) and Gong’ an County (Hubei) lowest [16]. However, these studies inadequately incorporated natural condition indicators, relying primarily on annual precipitation, accumulated temperature, and sunshine hours while neglecting altitude, slope, and wind direction. The resulting forest ecological security indices failed to objectively reflect actual conditions. This study addresses this gap by introducing an ecological location coefficient to adjust the index.

Methodologically, most forest ecological security analyses rely on basic statistical methods. This study enhances analytical rigor by introducing spatial gravity center analysis, a technique rarely applied in this field. While previous studies used gravity center methods to compare ecological civilization and economic centers [17] and analyze tourism impacts [18], this research pioneers its application to forest ecological security dynamics in Hubei.

## 1. Evaluation Index System Construction

### 1.1 Forest Ecological Security Index System

The index system was constructed through literature review, frequency analysis, and expert consultation. Recognizing that conventional frameworks neglect natural condition indicators, this study developed a system incorporating meteorological and terrain factors to calculate an ecological location coefficient. This coefficient reflects regional variations in vegetation productivity and species distribution, which significantly impact forest ecological security. By using it as an adjustment factor, the scientific validity of the evaluation system is enhanced.

The forest ecological security index (ESI) comprises forest status index and social pressure index. The forest status index integrates resource conditions and disaster indicators, while the social pressure index combines pressure and response indicators from the PSR model, reflecting both human pressures on forests and conservation efforts. The final system includes 14 indicators after a rigorous screening process.

**Table 1 Forestry Ecological Security Index System**

| Index Name | Formula | Weight | Structure |
|---|---|---|---|
| Forest Coverage Rate | (Forest Area/Total Land Area) × 100% | 0.0709 | Forest Status Index |
| Forest Stock Volume per Unit Area | Forest Stock Volume/Forest Area | 0.0574 | Forest Status Index |
| Forest Species Richness Index | Arbor Forest Area/Total Forest Area | 0.0583 | Forest Status Index |
| Forest Fire Disaster Rate | (Disaster Area/Total Forest Area) × 100% | 0.0751 | Forest Status Index |
| Forest Pest and Disease Disaster Rate | (Disaster Area/Total Forest Area) × 100% | 0.0749 | Forest Status Index |
| Industrial Output Value per Unit Area | GDP/Construction Land Area | 0.0745 | Social Pressure Index |
| Land Occupation Intensity by Human Engineering | Urban Population/Total County Population × 100% | 0.0748 | Social Pressure Index |
| $SO_2$ Emission Intensity | $SO_2$ Emissions/GDP | 0.0750 | Social Pressure Index |
| Industrial Wastewater Emission Intensity | Industrial Wastewater Emissions/GDP | 0.0751 | Social Pressure Index |

| Index Name | Formula | Weight | Structure |
|---|---|---|---|
| Forest Ecological Construction and Protection Investment Intensity | Investment/GDP | 0.0749 | Social Pressure Index |
| Annual Afforestation Ratio | Annual Afforestation Area/Total Land Area × 100% | 0.0749 | Social Pressure Index |

### 1.2 Forest Status Index

Resource condition indicators include forest coverage rate (F01), forest stock volume per unit area (F02), and forest species richness index (F03), all positively correlated with forest ecological security [24-25]. Higher values indicate better forest growth and biodiversity. Disaster indicators comprise forest fire disaster rate (F04) and pest/disease disaster rate (F05), which are negatively correlated as they reflect forest vulnerability [26].

### 1.3 Social Pressure Index

General behavior indicators (Y01-Y04) include industrial output value per unit area and land occupation intensity, all negatively correlated with forest security [27]. Behavior pressure indicators (Y05-Y07) encompass $SO_2$ emission intensity and industrial wastewater intensity, also negatively correlated. Maintenance activity indicators (Y08-Y09) include forest ecological construction investment intensity and annual afforestation ratio, which are positively correlated as they reflect conservation efforts.

### 1.4 Ecological Location Coefficient

The ecological location coefficient comprehensively reflects regional natural conditions (meteorological and terrain factors) that influence species distribution and vegetation productivity. Based on frequency analysis of existing literature and forest ecosystem characteristics, six high-frequency, applicable, and data-accessible indicators were selected: annual precipitation, accumulated temperature, average temperature, sunshine hours, average wind speed, average altitude, and slope aspect.

**Table 2 Ecological Location Coefficient Rating Table**

| Target Layer | Criterion Layer | Index Layer | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|---|---|
| Ecological Location Coefficient | Meteorological Location Coefficient | Annual Precipitation (mm) | $ $1000 | 800-1000 | 600-800 | 400-600 | $ $400 |
| | | Accumulated Temperature (°C) | $ $3500 | 3000-3500 | 2500-3000 | 2000-2500 | $ $2000 |
| | | Average Temperature (°C) | $ $20.8 | 10.8-20.8 | 3.4-10.8 | -3.4-3.4 | ≤-3.4 |
| | | Sunshine Hours (h) | $ $1600 | 1200-1600 | 800-1200 | 400-800 | $ $400 |
| | | Average Wind Speed (m/s) | $ $1.6 | 1.6-3.4 | 3.4-5.4 | 5.4-10.8 | $ $10.8 |
| | Terrain Location Coefficient | Average Altitude (m) | $ $200 | 200-500 | 500-1000 | 1000-2000 | $ $2000 |
| | | Slope Aspect | South-facing | Southwest/Southeast | East/West | Northeast/Northwest | North-facing |

Higher levels indicate more favorable conditions for forest growth. In Hubei (Northern Hemisphere), south-facing slopes receive optimal sunlight, while north-facing slopes are least favorable.

## 2. Methods and Models

### 2.1 Forest Ecological Security Index: Fuzzy Matter-Element Method

Based on fuzzy matter-element theory, a composite matter-element $R_{mn}$ was constructed for Hubei' s counties:

$$R_{mn} = \begin{bmatrix} M_1 & M_2 & \cdots & M_m & \\ C_1 & x_{11} & x_{21} & \cdots & x_{m1} \\ C_2 & x_{12} & x_{22} & \cdots & x_{m2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & x_{1n} & x_{2n} & \cdots & x_{mn} \end{bmatrix}$$

where $M_j$ represents the $j$th county, $C_i$ represents the $i$th characteristic, and $x_{ji}$

is the characteristic value. Indicators include both positive and negative types, requiring calculation of relative membership degrees.

For positive indicators (larger-is-better):

$$u_{ji} = \frac{x_{ji} - \min(x_{ji})}{\max(x_{ji}) - \min(x_{ji})}$$

For negative indicators (smaller-is-better):

$$u_{ji} = \frac{\max(x_{ji}) - x_{ji}}{\max(x_{ji}) - \min(x_{ji})}$$

A new fuzzy matter-element $R_{mn}$ is then established with membership degrees $u_{ji}$. The standard fuzzy matter-element $R_{0n}$ is derived from the maximum values of $u_{ji}$. The difference-square fuzzy matter-element $R_\Delta$ is calculated as:

$$\Delta_{ji} = (1 - u_{ji})^2$$

The composite fuzzy matter-element $R_{PH}$ is computed using the entropy weight method:

$$R_{PH} = \begin{bmatrix} M_1 & M_2 & \cdots & M_m \\ PH_1 & PH_2 & \cdots & PH_m \end{bmatrix}$$

where $PH_j = 1 - \sum_{i=1}^{n} w_i \Delta_{ji}$ represents the unadjusted forest ecological security value.

### 2.2 Euclidean Closeness and Forest Ecological Security

This study adopts Euclidean closeness $M(PH_j)$ as the evaluation criterion, where $PH_j = \sqrt{\sum_{i=1}^{n} w_i \Delta_{ji}}$ represents the forest ecological security value before ecological location coefficient adjustment.

### 2.3 Ecological Location Coefficient Calculation

Six ecological location indicators were rasterized and graded using ArcGIS. Expert scoring determined weights of 0.625 for meteorological coefficients and 0.375 for terrain coefficients. The calculation proceeds through three levels:

1. **Index layer coefficient score**: $F_{ij} = \sum_{k=1}^{n} S_{ijk} \times W_{ijk}$
2. **Criterion layer coefficient score**: $F_i = \sum_{j=1}^{n} F_{ij} \times W_{ij}$
3. **Target layer comprehensive score**: $F = \sum_{i=1}^{n} F_i \times W_i$

where $S_{ijk}$ is the rating value, $W_{ijk}$ is the index weight, and $n$ is the number of indicators.

### 2.4 Modified Forest Ecological Security Index

After calculating $PH_j$ and comprehensive location coefficient $F$, the adjusted forest ecological security value is:

$$ESI_j = PH_j \times \frac{F}{\bar{F}}$$

where $ESI_j$ is the adjusted value, $PH_j$ is the original value, $F$ is the location coefficient, and $\bar{F}$ is the provincial average.

### 2.5 Gravity Center Analysis Model

County center coordinates $(x_i, y_i)$ were obtained from statistical yearbooks. The gravity center coordinates of Hubei' s forest ecological security are:

$$X = \frac{\sum_{i=1}^{n} ESI_i x_i}{\sum_{i=1}^{n} ESI_i}, \quad Y = \frac{\sum_{i=1}^{n} ESI_i y_i}{\sum_{i=1}^{n} ESI_i}$$

Annual migration distance is calculated using the Pythagorean theorem:

$$D_{i-j} = R \times \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

where $R = 111.111$ km is the constant converting degrees to kilometers.

## 3. Study Area and Data Sources

### 3.1 Study Area

Hubei Province, located in the middle Yangtze River basin, covers 185,900 km$^2$ with a forest area of 73,627 km$^2$ (39.61% coverage, 17.98% above the national average). Given its critical role in flood prevention and soil conservation for both the province and downstream Yangtze regions, assessing forest ecological security holds significant practical importance. Based on data availability, 76 counties were selected as study samples.

### 3.2 Data Sources

All data originated from the Forest Ecological Security Index Research Project, covering 1999-2014. Data collection involved two phases: initial distribution of data forms to county forestry bureaus in March 2015, followed by statistical analysis and supplementation through telephone consultations and yearbook queries. Counties with complete data loss were excluded; those with partial missing data were retained after supplementation.

## 4. Results

### 4.1 Entropy Weight Calculation Results

The entropy method yielded weights for 14 indicators (Table 1). Industrial wastewater emission intensity (Y07) had the highest weight (0.0752), followed by forest fire disaster rate (F04), industrial output value per unit area (Y04), and $SO_2$ emission intensity (Y05), all at 0.0751. Forest stock volume per unit area (F02) had the lowest weight (0.0574), while forest species richness index (F03) was slightly higher at 0.0583.

### 4.2 Ecological Location Coefficient Results

Based on six indicators and data from 76 counties, the ecological location coefficient was calculated and visualized using ArcGIS with natural breaks classification into five levels.

**Figure 1 [Figure 1: see original paper] Ecological Location Coefficient Map of Hubei Province**

The highest coefficient areas (31.22001–32.42000) were distributed in eastern and central Hubei, particularly around Wuhan. The lowest coefficient areas (22.91000–26.03000) were concentrated in western regions like Shennongjia Forest District, Xingshan County, and Baokang County. The provincial average was 29.94719.

Notably, Shennongjia, despite its ecological importance, ranked last in location coefficient, indicating suboptimal natural conditions for forest growth. The highest coefficient appeared in Hong’ an County (northeast) at 32.42000. Economic developed areas around Wuhan showed high coefficients, while economically lagging western regions showed low coefficients, demonstrating a coupling between location coefficient and economic development.

### 4.3 Modified Forest Ecological Security Index

After calculating initial forest ecological security values using entropy weights, fuzzy matter-element, and Euclidean closeness, the ecological location coefficient was applied as a correction factor. The adjusted values for 1999, 2004, 2009, and 2014 were mapped using ArcGIS.

**Figure 2 [Figure 2: see original paper] Forestry Ecological Security Distribution in Hubei Province**

In 1999, high-security areas were concentrated in northwestern and southwestern Hubei, with low-security areas scattered in eastern, central, and western regions including Huangzhou, Yunmeng, Shennongjia, Laifeng, and Yidu. By 2004, the second-highest security grade expanded significantly, adding Danjiangkou and Zengdu District in the north, and Xishui County in the west. The worst-grade areas remained unchanged.

By 2009, high-security areas added Xiangyang County in the north and Wuhan City in the east, while worst-grade areas expanded dramatically, adding Wuhan (east), Xiangyang (north), and Xingshan (west). Shennongjia’ s security value improved from worst to poor grade. By 2014, Songzi and Danjiangkou maintained consistent upward trends. Danjiangkou’ s forest ecological security value rose from middle to highest grade due to sustained afforestation efforts, reaching 11,000 $hm^2$ in 2009. However, Wuhan’ s rapid economic development caused its security value to drop from middle to worst grade.

### 4.4 Forest Ecological Security Status Index

The status index was calculated separately for clearer analysis. **Figure 3** [**Figure 3: see original paper**] shows its spatial distribution. Highest-status areas in 1999 were concentrated in western Hubei. By 2004, this region expanded to include Jianshi County. By 2009, the pattern remained similar, with better areas distributed in western and southeastern Hubei. The worst-status areas were consistently found in Yunmeng County and Huangzhou District.

### 4.5 Forest Ecological Security Pressure Index

After standardizing negative indicators, higher pressure index values indicate smaller pressures. **Figure 4** [**Figure 4: see original paper**] illustrates pressure index changes. Minimum-pressure areas in 1999 were distributed in central Hubei (Jingshan County), northwest (Zhushan County), and southwest (Enshi City). By 2004, this area expanded to include Yunxi, Nanzhang, and Yicheng, but reduced in the southwest. By 2009, minimum-pressure areas shrank significantly, while maximum-pressure areas (darkest colors) expanded dramatically, particularly in eastern Xialu District, Wuhan, and surrounding regions, reflecting mounting economic pressure on forests.

### 4.6 Gravity Center Analysis

Using the gravity center model, coordinates were calculated for 1999-2014 (Table 3). **Figure 5** [**Figure 5: see original paper**] shows the migration trajectory.

**Table 3 Forest Ecological Security Gravity Center in Hubei Province**

| Year | Longitude | Latitude |
|---|---|---|
| 1999 | 112°46 15 E | 30°50 30 N |
| 2004 | 112°45 36 E | 30°50 31 N |
| 2009 | 112°45 52 E | 30°50 30 N |
| 2014 | 112°45 55 E | 30°50 42 N |

The gravity center migration divides into two phases: (1) 1999-2007: northwest to southeast migration (1.6 km total, 0.2 km/year average), driven by improved forest ecological security in southeastern counties like Chibi City (61.79% forest coverage increase through returning farmland to forest). (2) 2007–2014: east to west migration (1.75 km total, 0.25 km/year average), reflecting significant improvements in western counties like Nanzhang and Shayang (annual afforestation >2,000 $hm^2$).

**Table 4 Gravity Center Variation Statistics (1999–2014)**

| Phase | Direction | North-South Distance (km) | East-West Distance (km) | Total Distance (km) | Average Annual Distance (km) |
|---|---|---|---|---|---|
| 1999-2007 | NW-SE | 0.67 | 1.46 | 1.6 | 0.2 |
| 2007-2014 | E-W | 0.2 | 1.74 | 1.75 | 0.25 |

## 5. Conclusion

This study calculated Hubei’ s county-level forest ecological security indices using entropy weight and fuzzy matter-element methods, adjusted them with ecological location coefficients, and analyzed spatial dynamics using ArcGIS and gravity center models. Key findings include:

1. Highest ecological location coefficients were concentrated in central and eastern Hubei, while lowest coefficients were in western regions, showing coupling with economic development levels.
2. The worst-grade forest ecological security areas increased by 100% from 1999-2014, with new worst-grade areas appearing in Wuhan (east), Xiangyang (north), and Xingshan (west), indicating a pessimistic overall situation.
3. Danjiangkou and Songzi maintained consistently rising security indices due to strong afforestation and protection investments.
4. The gravity center migrated northwest-to-southeast (1999-2007) then east-to-west (2007-2014) at an accelerated pace, reflecting stronger forest ecological improvements in western regions during the second phase.

## 6. Discussion

The results reveal a paradox: areas with highest ecological location coefficients (central/eastern Hubei, especially around Wuhan) exhibit the worst forest ecological security values due to rapid economic growth and pollution emissions. Local governments and industries should prioritize afforestation and environmental governance to reduce forest ecosystem damage.

Methodologically, this study employed entropy weighting, which emphasizes indicator differences but cannot assess ecological importance, unlike subjective methods (AHP, expert scoring) that do the opposite [33-34]. Future research should combine these approaches [35-38] and incorporate principal component analysis for indicator screening [39-41]. The current ecological location coefficient considers only meteorological and terrain factors, omitting geology, soil, and hydrology. Future improvements should include: - **Geological indicators:** Lithology, geological structure (affecting landforms and community distribution) - **Soil indicators:** Organic matter, microorganisms, moisture (essential nutrients) - **Hydrological indicators:** Flood season runoff (affecting water availability)

These enhancements would provide a more comprehensive assessment of forest ecological security.

## References

[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41]

*Note: Figure translations are in progress. See original paper for figures.*

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