Postprint: Urban Ecological Red Line Delimitation Method Based on Bayesian Networks

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Abstract

Ecological red line delineation is a critical approach for safeguarding ecological security and reconciling conflicts between urban construction, basic farmland protection, and ecological conservation. Currently, most ecological red line delineation methods rely on ecological suitability evaluation, overlooking the exploration of land use change dynamics and exhibiting insufficient coordination with urban development, which leads to frequent encroachment on ecological land and suboptimal protection outcomes. Through comprehensive analysis of historical ecological land change processes and ecological suitability conditions, this study proposes a Bayesian network-based methodology for urban ecological red line delineation, with Ezhou City serving as the study area to validate the model' s delineation effectiveness. Results demonstrate that the proposed method conforms to Ezhou City' s urban development trajectory and the spatial distribution patterns of ecological land, facilitating the inclusion of stable regions with high ecological service value into the red line while ensuring the on-the-ground implementation of ecological red line zones. Compared with traditional ecological evaluation methods, the Bayesian network model delineation approach exhibits greater practical efficacy and can offer valuable insights and serve as a reference for research on urban ecological red line delineation methodologies.

Full Text

A Method for Delineating Urban Ecological Red Line Protection Areas Based on Bayesian Networks

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Abstract

Delimiting ecological red lines is a critical approach for protecting ecological security and coordinating the conflicts among urban construction, basic farmland protection, and ecological conservation. Existing methods for ecological red line delineation primarily rely on ecological suitability evaluation while neglecting the investigation of land-use changes and lacking coordination with urban development trends, resulting in frequent occupation of ecological land and poor protection effectiveness. This study proposes a novel urban ecological red line delineation method based on Bayesian networks by comprehensively analyzing both historical change processes and ecological suitability conditions of ecological land. The proposed model was applied to Ezhou City, Hubei Province, to validate its effectiveness. The results demonstrate that only 65.5% of ecological land in Ezhou remained stable from 2004 to 2013. Among the dynamic factors, farmland occupation exhibited the greatest influence, accounting for 43.6% of the variance, while urban encroachment accounted for 10.2%. Sensitivity analysis further revealed that farmland occupation had the highest impact on ecological land potential value, with a variance reduction of 29.5%, followed by eco-environmental sensitivity (8.55%) and ecosystem service importance (1.84%). The variance reductions for distance to water bodies and ecological forest protection were greater than those for distance to roads or railways, changes in traffic facilities, and urban construction, all of which had minimal effect on ecological land potential. Diagnostic analysis established causal links between influencing factors and the target variable through backward propagation. Under the condition that ecological land potential value was "yes," the probabilities of "extremely important" factors for ecosystem services and water conservation increased by 6% and 2.7%, respectively, indicating enhanced contributions from forest and aquatic ecosystem service values. Furthermore, the probabilities of "highly sensitive" and "extremely sensitive" factors for ecological sensitivity decreased by 13.4% and 1.8%, respectively, confirming improved natural conditions through ecological land protection. Using 2013 ecological suitability factor values, forward reasoning with the trained network yielded the relative potential value of each ecological land parcel for red line delineation. The results align with Ezhou' s urban development trends and spatial distribution of ecological land, ensuring both the inclusion of stable, high ecological service value areas and effective spatial implementation of ecological red lines. Compared with traditional ecological evaluation methods, the Bayesian network approach demonstrates stronger practical effectiveness and can provide valuable reference for urban ecological red line delineation.

Keywords: ecological red line; Bayesian network; spatial optimization; delineation model

Introduction

Ecological red lines refer to areas with special and critical ecological functions within ecological spaces that require mandatory and strict protection, representing the bottom line for safeguarding national ecological security. As an institutional innovation in ecological civilization construction, delineating urban ecological red lines is a fundamental measure for protecting urban ecology and coordinating urban ecological environments with economic development, holding significant importance for sustainable urban development. Since China' s reform and opening-up, rapid urbanization and industrial expansion have continuously encroached upon urban ecological spaces, fragmenting regional ecological landscape patterns and severely threatening urban ecological security. In response, China first proposed the ecological protection strategy of delineating ecological red lines in 2011, and by 2014, ecological red line work had been elevated from a regional ecological management system to a national ecological protection strategy. However, current ecological red line delineation practices lack comprehensive consideration for coordination with urban construction and development, and the delineated ecological protection lands are frequently occupied, yielding poor results. Therefore, in-depth research on ecological red line delineation methods is essential.

Ecological red line delineation is not merely about protecting ecological land; it represents ecological conservation based on comprehensive consideration of urban construction and farmland protection. Scientific and rational ecological red line delineation should include two aspects: first, selecting parcels with high ecological potential and value based on ecological suitability evaluation to protect ecosystem service functions and ecological landscape security patterns; second, considering regional ecological land evolution patterns while ensuring ecological service value to guarantee the stability of included parcels and ensure effective spatial implementation of ecological red lines. Existing studies on ecological red line delineation in China mostly follow national policies. Researchers such as Ding Yuchen and Fan Ningde have explored ecological red line delineation based on ecological spatial layout and ecosystem service values. Jiang Dalin et al. discussed ecological protection zone delineation using ecological vulnerability and ecosystem service functions. Liu Jie et al. investigated ecological red line delineation through ecological network planning. Xu Yan, Zeng Jiangning, and Huang Wei et al. delineated marine ecological red line boundaries from perspectives of ecological function importance, sensitivity, and ecological disaster risk. Ma Shifa et al. proposed a top-down participatory delineation method from the perspective of ecological security pattern maintenance. Chen Minghui et al. used discrete particle swarm algorithms for multi-scenario simulation of ecological red line zones. However, these studies are all based on ecological suitability or functional evaluation, ignoring the learning of land-use change patterns, which cannot guarantee that delineation results will adapt to regional land-use change trends, leaving them at high risk of occupation.

This study addresses both ecological land historical change patterns and ecological suitability conditions by proposing a Bayesian network (BN)-based approach. Bayesian networks are probabilistic network models based on Bayesian causal probability reasoning. They construct initial probability models through prior data and experience, then improve these models using new observational data. As non-black box models, they can integrate land dynamic changes with current influencing factors for comprehensive ecological red line delineation, express qualitative causal relationships among factors, and support quantitative analyses for both predictive and diagnostic purposes.

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1. Framework of the Ecological Red Line Delineation Model

The model integrates land historical change patterns and ecological suitability conditions. The framework primarily includes: selection of ecological suitability factors, analysis of ecological land dynamic change processes, model structure learning, parameter learning, ecological red line delineation, sensitivity analysis, and diagnostic analysis. The structure of the BN-based ecological red line delineation model is shown in [Figure 1: see original paper].

The model simulation process comprehensively considers two aspects: (1) **Historical dynamics of ecological land**: By overlaying and comparing ecological land conditions from two time periods, the model learns land historical change patterns within the study area and combines them with current influencing factors to predict the probability of parcels being zoned as ecological red line areas, yielding more realistic and accurate simulation results. (2) **Hierarchical nature of ecological suitability factors**: By extracting ecological suitability conditions at the parcel level from land-use status maps and incorporating them into the ecological red line delineation index system with factor classification, the scientific rationality of simulation results is enhanced. Through BN learning and inference, the potential value of each parcel is obtained and sorted to achieve the target ecological red line area.

Ecological suitability factors reflect the natural conditions and location characteristics of ecological land. Natural conditions include terrain (slope, relief amplitude), soil and water conservation (water conservation capacity, soil erosion degree, distance to water bodies, distance to ecological public welfare forests), and land quality. These factors demonstrate parcel ecological potential and resistance to farmland occupation. Location factors include distance to roads, railways, and town centers, reflecting the impact of construction land and transportation facilities on ecological land occupation.

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2. Evolution Process of Ecological Land

Analyzing the historical change process of ecological land can identify driving factors behind these changes. Incorporating land evolution into the ecological red line delineation index system not only helps ensure the stability of included parcels but also coordinates ecological protection with urban construction. Ecological land evolution occurs in two forms: (1) farmland occupation of ecological land, and (2) construction land occupation of ecological land.

The index system for the BN-based ecological red line delineation model comprises three components: ecological suitability factors, ecological land historical change factors, and target variables, totaling 13 indicators (Table 1).

Table 1 Index system of ecological red line protection zoning model

Index Type	Specific Indicators
Ecological Suitability Factors	Eco-environmental sensitivity, Distance to ecological forest, Ecosystem service importance, Slope, Water conservation importance, Relief amplitude, Distance to water body, Distance to railway, Soil erosion degree, Distance to town center, Distance to road
Ecological Land Historical Change Factors	Urban encroachment, Farmland occupation
Target Variable	Ecological land potential

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3. Bayesian Network Model Structure Construction and Parameter Learning

Network structure construction and node parameter learning are essential for building the BN model. The purpose of network structure construction is to reflect both qualitative and quantitative relationships among factors. Traditional algorithms such as the three-stage analysis algorithm and SGS (Spirtes, Glymour, Scheines) algorithm can obtain statistical relationships among factors but cannot capture causal relationships. This study adopts the expert experience method, establishing network structure based on causal relationships among factors and refining it using relevant land-use change models.

The model structure construction was implemented using Matlab programming. The construction results are shown in [Figure 2: see original paper], where ecological land potential, as the target variable, is directly influenced by ecological sensitivity, ecosystem service importance, farmland occupation, and construction occupation, demonstrating the combined effects of ecological suitability and historical change factors on ecological red line delineation.

Specifically, farmland occupation is jointly influenced by distance to water bodies and slope, simulating farmland occupation of ecological land under irrigation and terrain conditions. Construction occupation is influenced by accessibility factors such as distance to roads and town centers, reflecting impacts from transportation facilities and urban development. Eco-environmental sensitivity is affected by soil erosion, relief amplitude, and distance to water bodies, simulating land quality. Ecosystem service function is influenced by water conservation capacity and distance to ecological public welfare forests, reflecting the contribution of forests to ecosystem service values. Soil erosion degree is affected by slope, elevation, and distance to water bodies.

Parameter learning for the BN model involves obtaining conditional probability tables for each factor from observational data. Learning methods include maximum likelihood estimation and Bayesian methods for complete data, and expectation-maximization and Gibbs sampling algorithms for incomplete data. This experiment used complete training data and adopted the maximum likelihood method for parameter learning. Using Matlab' s BN toolbox, ecological suitability factors and ecological land dynamic change factors were used as training data for network parameter learning. The resulting model contains inter-factor relationships and conditional probability distributions for ecological land potential, providing a foundation for subsequent model inference.

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4. Sensitivity and Diagnostic Analysis of the Bayesian Network Model

Both sensitivity analysis and diagnostic analysis are methods for quantifying factor dependencies within the BN model. Conducting sensitivity analysis on the target variable (ecological land potential) reveals the influence magnitude of each factor, where larger variance reduction values indicate greater influence of input factors. Conversely, diagnostic analysis observes changes in influencing factor probability distributions by assigning a specific state to the target variable, with greater probability changes indicating stronger relationships.

Using Netica software, sensitivity and diagnostic analyses were performed on the target variable. Sensitivity analysis results are expressed as variance reduction percentages.

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1. Study Area Overview

This study selected Ezhou City in Hubei Province as the research area. Located in southeastern Hubei (114°32 –115°05 E, 30°00 –30°06 N) along the middle reaches of the Yangtze River and adjacent to Wuhan City, Ezhou possesses abundant ecological resources and serves as a nationally important water conservation area and a typical region for ecological protection research. It is a crucial city for maintaining water environmental security in the middle reaches of the Yangtze River and an important node city in the Wuhan Urban Agglomeration. Ezhou has experienced rapid development, with urban construction land increasing from 54.48 km^2 to 93.04 km^2, intensifying land supply contradictions and highlighting conflicts between ecological protection and urban construction. Some lakes have been filled and occupied, causing further ecological damage. Under these circumstances, delineating ecological red lines in Ezhou is of great significance for ensuring urban ecological security and maintaining the health of the middle Yangtze River ecosystem.

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2. Data Sources and Processing

Research data included Ezhou' s land-use status vector maps for 2004 and 2013, ecological red line control zones from land-use planning, soil erosion distribution maps, administrative division maps, and elevation data obtained from remote sensing imagery. Using ArcGIS spatial analysis and distance tools, water conservation distribution maps, ecosystem service importance maps, ecological sensitivity maps, relief amplitude raster maps, and ecological red line delineation base maps were generated [Figure 4: see original paper].

Using 2004 Ezhou ecological land as the generation range, 20,000 random sample points were generated proportionally by area. These sample points were overlaid with base data raster maps to extract variable values for each point and attribute ecological information. These sample points served as training data for model parameter learning. Variable values required further discretization, which works well for processing discrete data in BN models. The discrete classification of variables is shown in Table 2.

Considering model accuracy and complexity, continuous variables were discretized into two to four grades based on relevant policies and expert knowledge. Following the Second National Land Survey Technical Regulations, slope was classified into four grades: "0-2°" , "2-5°" , "5-15°" , and " 15°" . Ecological land potential was classified as "yes" or "no" . Other variable grades were set according to land-use change conditions.

Table 2 Discretization and classification of variables

Variable Names	Classification Code	Value Type
Gradient / °	<5, 5-15, 15	Discrete
Altitude / m	<50, 50-200, 200	Discrete
Relief amplitude / °	<2, 2-5, 5-15, 15	Discrete
Distance to water body / m	<500, 500-1000, 1000-2000, 2000	Discrete
Distance to railway / m	<1000, 1000-2000, 2000-4000, 4000	Discrete

Variable Names	Classification Code	Value Type
Distance to road / m	<500, 500-1000, 1000-2000, 2000	Discrete
Distance to township / m	<2000, 2000-4000, 4000-6000, 6000	Discrete
Distance to ecological forest / m	<500, 500-1000, 1000-2000, 2000	Discrete
Importance of water conservation	General, Moderately important, Important, Extremely important	Discrete
Soil erosion degree	Slight, Moderate, Severe, Extremely severe	Discrete
Eco-environmental sensitivity	Insensitive, Mildly sensitive, Moderately sensitive, Highly sensitive, Extremely sensitive	Discrete
Importance of ecosystem services	General, Moderately important, Important, Extremely important	Discrete
Urban encroachment	Yes, No	Discrete
Farmland occupation	Yes, No	Discrete
Ecological land potential	Yes, No	Discrete

3. Bayesian Network Model Training

After constructing the network structure, the discretized sample point data were used as training data, and the maximum likelihood method was employed for model parameter learning. The trained BN model revealed dynamic changes between two land-use types and probability distributions of various factors. Farmland occupation was severe, with 65.5% of ecological land transforming to other types and only 34.5% remaining stable. Among land dynamic change factors, farmland occupation accounted for 43.6% and construction occupation for 10.2%. Moderate or higher eco-environmental sensitivity reached 71.2%, indicating high ecosystem disturbance and prominent ecological problems. Moderate or higher soil erosion accounted for 27.3%, showing significant soil erosion. Moderate or higher ecosystem service importance reached 73.4%, indicating high contribution value of ecosystem services.

4. Sensitivity Analysis

Using the target variable "ecological land potential" for sensitivity analysis reveals the influence of historical change factors and ecological suitability factors. Sensitivity analysis results are expressed as variance reduction percentages, where variance reduction reflects the influence magnitude of specific variables on the target variable.

Table 3 Sensitivity analysis results

Variable Type	Variable	Variance Reduction
Ecological land historical change factors	Farmland occupation	29.5%
	Construction occupation	10.2%
Ecological suitability factors	Eco-environmental sensitivity	8.55%
	Importance of ecosystem services	1.84%
	Distance to water body	0.62%
	Importance of water conservation	0.26%
	Relief amplitude	0.07%
	Distance to ecological forest	0.06%
	Soil erosion degree	0.06%

The results show that farmland occupation has the greatest impact on ecological land potential with a variance reduction of 29.5%, indicating severe farmland occupation of ecological land. Construction occupation shows a variance reduction of 10.2%. Among ecological suitability factors, eco-environmental sensitivity and ecosystem service importance show variance reductions of 8.55% and 1.84%, respectively—both crucial for regional ecological security patterns, underscoring the importance of ecological sensitivity and service function evaluation in red line delineation. Distance to water bodies and water conservation importance show variance reductions of 0.62% and 0.26%, respectively, reflecting the significant role of water bodies in ecological sustainability. Lower values for soil erosion degree and relief amplitude indicate that soil and terrain conditions are not primary obstacles to ecological protection in Ezhou.

5. Diagnostic Analysis

Diagnostic analysis quantitatively reveals causal relationships between influencing factors and target variables by selecting influential factors and observing changes in factor probability tables through Bayesian network backward reasoning when the target variable "ecological land potential" is set to "yes."

Table 4 Diagnostic analysis results

Variable	States	Probability Change
Importance of ecosystem services	Extremely important	+6.0%
	Highly important	-13.4%
Eco-environmental sensitivity	Extremely sensitive	-1.8%
	Highly sensitive	-13.4%
Distance to ecological forest	<0.5 km	+14.7%
	0.5-1 km	-13.4%
	1-2 km	-1.8%
Importance of water conservation	Extremely important	+2.7%
Soil erosion degree	Severe	+3.7%
Distance to water body	<0.5 km	+2.2%

When ecological land potential is set to "yes" (assuming parcels are included in ecological red lines), the probability of "extremely important" ecosystem services increases by 6.0%, and water conservation importance increases by 2.7%, indicating enhanced ecological service value contributions from protected green and water ecosystems. The probabilities of "highly sensitive" and "extremely sensitive" ecological sensitivity factors decrease by 13.4% and 1.8%, respectively, with probability distributions shifting toward low and moderate sensitivity—confirming improved natural conditions and reduced human disturbance in red line areas. Probabilities for distance to ecological forests and water bodies increase, demonstrating effective protection and enhanced stability of forests and water bodies within red lines. The probability of severe soil erosion increases by 3.7% under the condition of inclusion in ecological red lines, indicating improved soil erosion conditions.

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6. Delineation Results and Analysis

Using Ezhou' s 2013 land-use status data, ecological red lines were specifically delineated. Overlay analysis obtained attribute values of various suitability evaluation factors for each parcel, which were input as observed data into the trained BN model. Forward reasoning yielded the target variable "ecological land potential" as the basis for including ecological land parcels in red lines. Parcels were sorted by posterior probability from high to low, and ecological land parcels were selected until the total area matched Ezhou' s planned ecological red line area (41,669 hm²). The final ecological red line zones are shown in [Figure 6: see original paper].

To validate the model' s accuracy, traditional ecological suitability evaluation was used to delineate Ezhou' s ecological red lines using the same data, ignoring ecological land historical changes [Figure 7: see original paper]. Comparison revealed multiple conflict areas between the two methods, with main conflict areas magnified in [Figure 8: see original paper].

The BN model did not include scattered ecological land parcels around Tujia' ao and Taihe towns, as these areas face severe farmland occupation pressure and poor stability. Area A, located between Shawo Township and Zelin Town, is a priority development zone in Ezhou's planning. Area B, distributed along major transportation routes in Bishi Town, lacks spatial compactness and integration with other plans when delineated using traditional methods, offering no practical guidance. The BN method primarily added four concentrated areas (C, D, E, F): Area C is the Yangtze River beach wetland in Yangye Town, crucial for protecting surrounding water and green ecosystems; Area D is the Yangtze River coast in northern Duan Dian Town, with concentrated distribution and high ecological service value; Areas E and F are edges of Yanjia Lake and Wusi Lake, with high resource potential and ecological utilization value due to their beach pond characteristics; Area G is an ecological forest distribution area in southwestern Shawo Township. While traditional methods partially included this area, the BN method comprehensively mapped the complete ecological red line distribution range.

These results demonstrate that compared with traditional ecological red line delineation methods, the BN-based approach comprehensively considers ecological suitability conditions and ecological land evolution factors. Under the premise of equal ecological importance, it includes parcels with greater potential and stability in ecological land, yielding more scientific and rational delineation results.

Conclusions and Discussion

Ecological red line delineation is crucial for coordinating ecological protection, urban construction, and basic farmland preservation. This study proposes a Bayesian network-based urban ecological red line delineation method by comprehensively analyzing ecological land historical change processes and ecological suitability conditions. Compared with traditional ecological evaluation methods, the BN model better maintains urban ecosystem health, avoids frequent adjustments caused by human occupation, and ensures the stability and sustainability of ecological red lines, presenting a favorable scenario of coordinated ecological construction, urban development, and economic development.

The Bayesian network model demonstrates effective application in ecological red line delineation through two key capabilities: (1) Integrating prior knowledge with current evidence, combining current observational data with dynamic change data to learn land change patterns and simulate realistic land development dynamics, enhancing objective effectiveness of delineation results; (2) Possessing causal reasoning capabilities to obtain target variable probability values through forward and backward reasoning as scientific bases for red line zoning, enabling acquisition of both qualitative and quantitative relationships among variables.

However, limitations exist. Ecological red line delineation is a multi-level decision-making process, and further research is needed on integrating multi-level simulation into BN models. This study did not consider spatial heterogeneity impacts on ecological red line delineation. Urban ecological red lines should be delineated based on clear understanding of regional resource-environment carrying capacity and development potential in different areas. Future research should focus on incorporating zoning concepts and combining BN models with the main functional area concept for urban ecological red line delineation.

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