Vertical Distribution Characteristics of Land Use Change in Karst Mountainous Areas (Postprint)

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Abstract

Land use change in karst mountainous areas is influenced by complex terrain. Previous large-scale studies have conducted statistical analyses of topographic characteristics across entire study areas, while research on spatial characteristics and differences of local land use change has been limited. This paper takes the karst mountains of Guizhou and Guangxi as an example, constructs a land use dynamic vertical gradient index, and characterizes and reveals the vertical distribution characteristics of land use change in the study area. The results show that: from 1990 to 2010, the net change area of land use in karst mountainous areas was relatively small, but the mutual conversion among various land use types was intense. Cropland was encroached upon by construction land, while forestland and grassland were reclaimed as cropland; ecological restoration projects led to significant increases in forestland, grassland, and water bodies. The increased and decreased cropland were clearly misaligned in vertical distribution: decreased cropland was mainly distributed in low-altitude (0-200 m) and gentle-slope (0°-5°) areas, whereas increased cropland was primarily located in high-altitude (600-1,400 m) and steep-slope (8°-25°) areas; increased and decreased forestland and grassland corresponded to each other in distribution, with peaks occurring at 800-1,400 m and 8°-25°, respectively; increases in water bodies and construction land were mostly situated in low-altitude (0-800 m) and gentle-slope (0°-5°) areas. Application of the land use dynamic vertical gradient index revealed that although newly added construction land from 2000 to 2010 was concentrated in the lowest altitude and gentlest slope classes, at the local scale, new construction land tended to be distributed toward relatively higher altitudes and steeper slopes. Limited land resources have driven a trend of land use development toward higher altitudes and steeper slopes in karst mountainous areas. The land use dynamic vertical gradient index can both further support conclusions derived from global statistical analysis methods and analyze and uncover local relative differences in the vertical distribution characteristics of land use change.

Full Text

Vertical Distribution Characteristics of Land Use Change in Karst Mountainous Regions

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Abstract

Land use change in karst mountainous regions is significantly influenced by complex terrain. Previous large-scale studies have typically conducted statistical analyses of topographic characteristics across entire study areas, while research on local spatial features and variations in land use change remains limited. Taking the Guizhou-Guangxi karst mountainous region as a case study, this paper constructs a dynamic vertical gradient index for land use change to characterize and reveal the vertical distribution patterns of land use change in the study area. Results indicate that from 1990 to 2010, although the net change area of land use in the karst mountainous region was relatively small, mutual conversions among various land use types were intense. Arable land was encroached upon by construction land, while forests and grasslands were simultaneously reclaimed as cultivated land. Ecological restoration projects led to significant increases in forestland, grassland, and water bodies. The vertical distribution of increased and decreased arable land showed clear spatial mismatch: decreased arable land was mainly distributed in low-elevation (0–200 m) and gentle-slope (0°–5°) areas, whereas increased arable land was primarily located in high-elevation (600–1,400 m) and steep-slope (8°–25°) zones. Increased and decreased forestland and grassland showed corresponding distributions, both peaking at 800–1,400 m elevation and 8°–25° slope. Increases in water bodies and construction land were concentrated in low-elevation (0–800 m) and gentle-slope (0°–5°) areas. Application of the dynamic vertical gradient index for land use change revealed that although newly added construction land from 2000 to 2010 was concentrated in the lowest elevation and gentlest slope classes, at the local scale it tended to be distributed in relatively higher elevations and steeper slopes. Limited land resources in karst mountainous areas are driving land use development toward higher elevations and steeper slopes. The dynamic vertical gradient index for land use change can both support conclusions derived from global statistical analysis methods and analyze and explore local relative differences in the vertical distribution characteristics of land use change.

Keywords: Land use change; Elevation distribution; Slope distribution; Vertical gradient index; Karst mountainous region

Introduction

Through the utilization of land-related natural resources, humans have altered Earth’ s land surface cover to meet demands and obtain material products and services. With rapid industrialization, urbanization, and economic development, competition and conflicts among various land use types have intensified. For instance, urban and industrial land has encroached upon cultivated land, forests and grasslands have been reclaimed for cultivation, and large-scale programs for returning farmland to forests and grasslands have been implemented. Faced with rapid cultivated land loss, China has implemented the strictest land use control and farmland protection systems, with the balance between occupied and compensated arable land being a crucial component. However, this balance often reflects quantitative rather than qualitative equivalence of cultivated land, with phenomena such as replacing high-quality flatland farmland with poor-quality mountainous land. In mountainous regions, special geographical structures and land resource conditions result in insufficient cultivated land reserves, high requirements for land development and consolidation, and an unfavorable balance situation, particularly as vertical distribution changes in cultivated land significantly affect qualitative balance. Complex terrain features with large surface undulations influence land use direction and patterns, significantly impacting land use/cover. Meanwhile, vertical distribution differences in land use affect land quality and utilization direction. Therefore, analyzing land use changes along terrain gradients can reveal patterns and contribute to scientific regional land use planning and structural adjustment.

Previous studies have shown that different land use types exhibit varying change trends with changes in topographic factors such as elevation, slope, and aspect. In China’ s karst mountainous regions, limited land resources and dense populations make land use competition and conflicts particularly prominent, yet large-scale studies on the vertical distribution characteristics of land use change in these areas remain scarce. Previous research has typically conducted hierarchical statistics on various topographic factors to analyze change trends and vertical distribution characteristics in regions including farming-pastoral ecotones, karst mountainous areas, Taihang Mountains, and loess hilly regions. Some scholars have introduced terrain niche index and distribution index to describe topographic differences. However, mountainous terrain exhibits significant local variations, and unified hierarchical statistics may overlook local spatial information on land use change. Therefore, this study takes the Guizhou-Guangxi karst mountainous region as an example, analyzes overall land use change characteristics from 1990 to 2010, and constructs a dynamic vertical gradient index for land use change at the county level to explore spatial distribution differences along terrain gradients.

1.1 Study Area

The Guizhou-Guangxi karst mountainous region selected for this study primarily references the South China karst topography map and Asian karst distribution map in China' s National Natural Atlas. The study area is located between 42°15 -44°55 N and 80°5 -84°5 E [Figure 1: see original paper], covering 214,100 km². The elevation ranges from 0 to 2,848 m, gradually decreasing from northwest to southeast. Landforms are dominated by medium and small mountains, transitioning from mid-mountain hills to low-mountain basins. Vegetation types include subtropical deciduous forests, broadleaf forests, mixed forests, with some tropical rainforests and alpine vegetation. Soil types are primarily limestone soil, yellow soil, and red soil, with other types sporadically distributed. Administratively, the region mainly includes central and southern Guizhou Province and central Guangxi Province.

1.2 Data Sources

Land use vector data (for 1990, 2000, and 2010) [Figure 2: see original paper] were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences. The data include six primary categories: arable land, forestland, grassland, water body, urban/rural/industrial/mining and residential land (hereinafter referred to as construction land), and unused land (bare rock in the study area). This vector data format achieves a comprehensive classification accuracy of over 94.3% at the primary land use level, meeting 1:100,000 scale mapping precision requirements. Using terrain analysis tools (ArcGIS 10.1) and GDEM digital elevation model data (from Geospatial Data Cloud, http://www.gscloud.cn/), this study extracted elevation and slope distribution maps for subsequent analysis.

1.3.2 Terrain Classification Criteria and Division

Based on the elevation distribution characteristics of the study area, this study established 10 elevation classes at 200 m intervals. Slope was classified according to the "General Rules for Comprehensive Planning of Soil and Water Conservation" (GB/T15772-1995) into six categories: micro-slope, gentle slope, moderate slope, relatively steep slope, steep slope, and very steep slope .

1.3.3 Dynamic Vertical (Elevation and Slope) Gradient Index for Land Use Change

Vertical distribution differences in land use change are constrained by local conditions and occur within certain elevation or slope ranges. For example, low-elevation farmland in alpine regions may still be higher than high-elevation farmland in hilly regions. Unified hierarchical statistics across the entire region following the classification in section 1.3.2 would obscure relative differences in farmland change among different areas. Therefore, this study uses the average elevation (slope) of each land use type at the county level as a reference for standardized calculation, representing whether the elevation (slope) of land use change areas during the study period is higher or lower than the average elevation (slope) of the corresponding land use type at the period' s beginning. This index can analyze relative spatial differences in the vertical distribution of land use change. The calculation formula is:

Where iF and S_iF are the dynamic elevation and slope vertical gradient indices for land use; i represents a specific land use type (six categories in this study: arable land, forestland, grassland, water body, construction land, and unused land); E_i and S_i represent the elevation and slope of changed grid cells (with grid cells as the minimum calculation unit); a and b represent the beginning and end of the study period; and $\overline{E_i}$ and $\overline{S_i}$ represent the average elevation and slope of land use type i within the county unit at the study period's beginning. If $iF = 1$, the changed grid unit has elevation and slope equivalent to the corresponding land use type' s average; if $iF > 1$ (larger values indicating stronger tendency), the changed land use grid unit tends toward higher elevation or steeper slope; conversely, if $iF < 1$ (smaller values indicating stronger tendency), it tends toward lower elevation or gentler slope.

1.3.1 Land Use Dynamic Degree

Land use dynamic degree refers to the rate of quantitative change in a specific land use type within a certain time range in the study area. The formula [27] is:

Where K is the dynamic degree of a specific land use type during the study period (expressed as the annual change rate in this study); U_a and U_b are the quantities of the specific land use type at the beginning and end of the study period; and T is the study period length.

2 Results and Analysis

2.1 Overall Characteristics of Land Use Change

From 1990 to 2010, forestland had the largest area in the Guizhou-Guangxi karst mountainous region, accounting for over 50%; arable land, grassland, construction land, and water body ranked second to fifth; unused land was minimal at only 0.01% . Over the 20-year period, net quantitative changes in land use were relatively small, with maximum annual change rates below 1%. Land use change magnitude was smaller during 1990–2000 than during 2000–2010. Water body and construction land had the highest change rates, with increases of 0.384% and 0.797% respectively in the first period, and 0.651% and 0.899% in the second period, resulting in net increases of 19,600 ha and 43,900 ha. Arable land showed decreasing trends in both periods, with reductions of 2,200 ha and 24,200 ha respectively, with the second period' s reduction rate (0.043%) far exceeding the first period' s (0.004%). Forestland first decreased then increased, with a net increase of 60,000 ha over 20 years. Grassland showed a continuous decreasing trend, with a net reduction of 97,000 ha.

Mutual conversions among land use types were intense [Figure 3: see original paper]. For example, during 1990–2000, arable land decreased by 22,200 ha and increased by 24,400 ha, while during 2000-2010 it decreased by 62,700 ha and increased by 38,500 ha—both far exceeding net change areas (2,200 ha and 24,200 ha). During 1990-2000, conversions among arable land, forestland, and grassland were substantial, while construction land expansion and water body changes were quantitatively lower. Increased arable land primarily came from forestland (14,500 ha, 65.24% of total conversion) and grassland (7,000 ha, 31.53%), indicating frequent deforestation for cultivation. Decreased arable land was mainly occupied by construction land expansion (65.76% of total conversion). Forestland changes were most extensive, with frequent mutual conversion between forest and grassland (37,600 ha of forest to grassland and 35,600 ha of grassland to forest). Water body increases mainly came from arable land and forestland, with minimal contraction.

During 2000-2010, conversions among arable land, forestland, and grassland remained intense, with grassland showing the largest change area. Increased arable land mainly came from grassland (27,500 ha) and forestland (10,600 ha), primarily due to land development and consolidation. Although construction land increase still mainly occupied arable land, the primary reduction in arable land shifted to conversion to forestland (35,400 ha, 56.4% of total conversion), highlighting the effectiveness of the Grain for Green Program. Grassland conversion to forestland reached 89,900 ha, far exceeding other type conversions. Water body increases mainly came from arable land and forestland.

Regional cultivated land reduction resulted from construction land expansion and implementation of the Grain for Green Program, while the balance policy simultaneously led to extensive new cultivated land reclamation, resulting in a slight overall decrease over 20 years. Construction land increased dramatically to meet population growth and rapid urbanization and economic development needs. Meanwhile, ecological projects including the Pearl (Yangtze) River Shelter Forest, Natural Forest Protection, Grain for Green, nature reserve construction, wetland protection and restoration, and rocky desertification comprehensive management significantly increased ecologically important land use types such as forestland, grassland, and water bodies.

2.2 Overall Vertical Distribution Characteristics of Land Use Change

Using GIS spatial analysis technology to overlay terrain factors with land use maps, we analyzed land use change patterns across elevation and slope classes [FIGURE:4 and FIGURE:5]. During 1990-2000, increased and decreased land use areas showed spatial mismatch in elevation distribution [Figure 4: see original paper]. In the 0-200 m elevation zone, arable land decrease far exceeded increase (15,900 ha vs. 5,500 ha). In contrast, in the 200-1,400 m zone, arable land increase exceeded decrease (8,200 ha vs. 16,100 ha). Forestland increase was mainly in 0-600 m (35,500 ha, nearly 60% of total increase), while decrease was primarily in 800-1,400 m (over 50% of total decrease). Conversely, grassland decrease concentrated in 0-600 m, while increase was mainly in 800-1,400 m. Water body and construction land increases were concentrated in low-elevation areas.

During 2000-2010, consistency in elevation distribution between increased and decreased areas strengthened [Figure 4: see original paper]. Only arable land still showed much greater decrease than increase in 0-200 m (15,000 ha vs. 1,000 ha), with a first peak of decreased arable land in 0-200 m and peaks of both increased and decreased arable land in 800-1,400 m. Grassland and forestland peaked in 800-1,400 m, showing corresponding vertical distribution characteristics. Increased and decreased water bodies were concentrated in 0-800 m, accounting for 86.78% and 90.65% of change areas respectively. Construction land increase concentrated in low-elevation 0-200 m zones.

During 1990-2000, increased and decreased arable land also showed spatial mismatch in slope distribution: arable land decrease far exceeded increase in 0°-5° (16,300 ha vs. 6,900 ha), while increase exceeded decrease in 8°-25° (8,100 ha vs. 15,100 ha). Other land use types showed stronger consistency [Figure 5: see original paper]. Forestland and grassland peaked in 8°-25°, with over 50% of change areas in this range. Water body and construction land changes concentrated in low-slope 0°-5° areas, accounting for 55.13%, 42.50%, and 70.32% of increased water body, decreased water body, and increased construction land respectively. During 2000-2010, arable land decrease still far exceeded increase in 0°-5° (18,800 ha vs. 8,100 ha), with decrease slightly exceeding increase in other intervals. Other land use types showed similar slope distribution patterns to 1990-2000 [Figure 5: see original paper].

In summary, increased and decreased arable land areas in karst mountainous regions showed spatial mismatch in vertical distribution: decreased arable land was mainly in low-elevation, gentle-slope paddy fields around cities, while increased arable land was primarily high-elevation, steep-slope dry land. Under the balance policy, although total cultivated land slightly decreased, the quality of new farmland was far lower than that of lost farmland. Forestland and grassland converted frequently, with increased and decreased areas showing corresponding vertical distribution characteristics, peaking at 800-1,400 m elevation and 8°-25° slope. Water body and construction land increases tended toward low-elevation and flat terrain areas.

2.3 Analysis of Dynamic Vertical Gradient Index for Land Use Change

To further explore local-scale vertical distribution differences in karst mountainous land use change, we calculated the dynamic vertical gradient index (including elevation and slope indices) for each land use type using formulas (2) and (3). Considering that land use change amounts remain small relative to total regional area, affecting visualization effectiveness, we ultimately calculated average gradient index values within county units. Due to space limitations, we present only the elevation and slope gradient indices for increased construction land during 2000-2010 as examples [Figure 6: see original paper]. Nearly half of counties had elevation gradient indices greater than 1, mainly distributed in

Zunyi (northern Guizhou), Liupanshui and Qianxinan (western Guizhou), and Baise and Hechi in Guangxi. Over two-thirds of counties had slope gradient indices greater than 1, mainly distributed across most of Guizhou and Liuzhou, Laibin, and Baise in Guangxi. Thus, although newly added construction land was concentrated in the lowest elevation and gentlest slope classes (0–200 m and 0°–5°) [FIGURE:4 and FIGURE:5], at the local scale it tended toward relatively higher elevations and steeper slopes. Limited available land resources, rapid urban population growth, and dramatic land expansion have created prominent human-land conflicts, with some towns exhibiting "building cities on mountains" phenomena.

presents average values of vertical gradient indices for various land use changes. Arable land decrease showed elevation and slope gradient indices of 0.90 and 0.91 during 1990–2000, indicating tendency toward low-elevation, gentle-slope areas. However, the slope gradient index during 2000–2010 reached 1.24, indicating that arable land decrease tended toward relatively steeper areas. All values for arable land increase exceeded 1, especially the slope gradient index (1.32 and 1.40), significantly higher than 1, indicating extensive development and utilization of steep slopes. Forestland increase values were around 1, while decrease values were around 0.9, indicating that relatively low-elevation, gentle-slope forest resources were vulnerable to conversion. Grassland decrease values were around 1, while increase values (except elevation gradient index for 2000–2010) exceeded 1, showing that new grassland tended toward relatively higher elevations and steeper slopes. Except for water body increase during 1990–2000 (elevation gradient index of 0.97), all other values exceeded 1, especially slope gradient indices far greater than 1, indicating water body changes also tended toward relatively higher elevations and steeper slopes. Construction land increase during 1990–2000 was in relatively low-elevation, steep-slope locations (elevation and slope gradient indices of 0.97 and 1.15 respectively), while during 2000–2010 it tended toward relatively high-elevation, steep-slope areas (both indices exceeding 1).

3 Discussion and Recommendations

This study proposes and calculates the dynamic vertical gradient index for land use change, whose magnitude can intuitively demonstrate distribution differences and trend strengths of land use change within administrative units [Figure 6: see original paper]. This can further support conclusions from global statistical analysis methods [FIGURE:4 and FIGURE:5] while also analyzing and mining local relative differences in vertical distribution characteristics. For example, conclusions about vertical distribution characteristics of arable land decrease and increase are generally consistent: except for slope decrease tending toward steep areas during 2000–2010 [FIGURE:5, TABLE:3], decreased arable land was mainly in low-elevation, gentle-slope areas, while increased arable land was primarily in high-elevation, steep-slope areas. Conventional methods can identify overall vertical distribution mismatch between decreased and increased arable land, while the vertical gradient index can display relative differences in vertical distribution and quickly assess change intensity through mean values. For instance, the slope gradient index for arable land increase far exceeding 1 indicates extensive steep slope cultivation.

Furthermore, the vertical gradient index can uncover patterns undetected by conventional methods. While conventional research shows construction land increase and water body changes mainly occurred in low-elevation, gentle-slope areas [FIGURE:4, FIGURE:5], the dynamic vertical gradient index reveals that urban expansion and water body changes during 2000–2010 tended toward relatively high-elevation, steep-slope areas . Thus, this method characterizes and mines local relative changes in vertical distribution that are easily overlooked by global statistical analysis, though its applicability and conclusions require further discussion and validation.

This study reveals vertical distribution characteristics of land use from two perspectives: global statistical analysis and local relative differences. Results show that over 20 years, mutual conversions among different land use types in karst mountainous regions were intense, with arable land occupied by construction land and forests/grasslands reclaimed as farmland, while ecological restoration projects significantly increased forestland, grassland, and water bodies. Under multiple demands and contradictions including urbanization development, food security, and ecological protection, human-land conflicts remain acute, requiring overall land use regulation and coordination.

Given limited land resources, we recommend focusing on improving land use efficiency and optimizing spatial regulation from vertical distribution perspectives. Particularly in counties/cities with high development of land resources in relatively high-elevation, steep-slope areas, considering that new farmland quality is far lower than lost farmland quality, the region must further protect relatively high-quality cultivated land resources and continue implementing the Grain for Green policy on slope farmland unsuitable for cultivation. Regarding construction land, the study area has experienced dramatic expansion over 20 years, with some towns expanding toward relatively high-elevation, steep-slope areas. However, fragile ecological environments and limited resource carrying capacity in mountainous areas make large-scale urbanization inappropriate. Development should focus on small and medium-sized cities with emphasis on small town system construction, preventing excessive concentration, improving low-level sprawl in mountainous urban built-up areas, and enhancing construction land use efficiency and quality during urbanization.

This study applied GIS spatial analysis technology to construct a dynamic vertical gradient index for land use change, characterizing and analyzing vertical distribution characteristics of land use change in the Guizhou-Guangxi karst mountainous region. Results show: (1) From 1990 to 2010, although net land use change area was relatively small, mutual conversions among land use types were frequent, with the most intense conversions among arable land, forestland, and grassland. Forestland had the largest change area, decreasing in the first decade and significantly increasing in the second. Arable land had equivalent increase and decrease in the first decade but substantial decrease in the second. Grassland consistently decreased, while water bodies and construction land expanded significantly. Human-land conflicts remain acute, with construction land dramatically increasing and occupying large amounts of cultivated land, while forests and grasslands were reclaimed as farmland, and ecological restoration projects significantly increased forestland, grassland, and water bodies. (2) Increased and decreased arable land areas showed obvious spatial mismatch in vertical distribution: decreased arable land was mainly in low-elevation (0-200 m) and gentle-slope (0°-5°) areas, while increased arable land was primarily in high-elevation (600–1,400 m) and steep-slope (8°–25°) areas. Forestland and grassland converted frequently, with increased forestland and decreased grassland, and decreased forestland and increased grassland showing consistent vertical distribution characteristics, peaking at 800–1,400 m elevation and 8°-25° slope. Water body and construction land increases mainly occurred in low-elevation (0–800 m) and gentle-slope (0°-5°) areas. (3) The dynamic vertical gradient index was constructed to deeply mine local vertical distribution characteristics of land use change. Results show that during 1990-2000, arable land decrease tended toward relatively low-elevation, gentle-slope areas, while during 2000–2010, decreased arable land tended toward relatively steep areas. During 1990–2000, arable land increase, grassland increase, water body change, and construction land increase tended toward high-elevation, steep-slope distribution. Over 20 years, forestland decrease tended toward relatively low-elevation, gentle-slope areas. Limited available land resources in the study area are driving urban expansion and farmland reclamation toward higher elevations and steeper slopes.

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