Postprint: Spatial Differentiation and Risk of County-Level Land Use Carbon Emissions in Ningxia

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Abstract

Land use change is one of the key factors influencing regional carbon emissions. Investigating the spatiotemporal patterns of land use carbon emissions holds significant importance for rational land resource allocation, improving land use efficiency, and achieving energy conservation and emission reduction objectives. Based on land use and energy data from 22 county-level units in Ningxia spanning 1990–2020, this study comprehensively employs the carbon emission risk index and carbon footprint pressure index to analyze land use change, spatial differentiation of carbon emissions, and land use carbon emission risks across Ningxia's counties. The results indicate: (1) Land use change in Ningxia was relatively intensive during 1990–2020, with construction land exhibiting the highest dynamic degree, increasing in area by 1578.48 km^2. (2) Over the past 30 years, net land use carbon emissions in Ningxia increased by 4969.25\$×10^{4}\$ t, with construction land carbon emissions accounting for over 86% of total emissions; carbon sequestration increased by 23.76\$×10^{4}\$ t, dominated by forest land sequestration which comprised over 75% of total sequestration, displaying a pattern of local agglomeration and overall dispersion. (3) Land use carbon emissions across Ningxia's counties and districts show an increasing trend, though with substantial variation, spatially forming a distribution pattern where counties along the Yellow River exhibit higher carbon emissions than those in central and southern regions. (4) The risks and pressures of land use carbon emissions in Ningxia's counties and districts are considerable, with ecosystem carbon balance being disrupted.

Full Text

Spatial Differentiation and Risk Assessment of Land Use Carbon Emissions at the County Level in Ningxia

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Abstract

Land use change represents a critical factor influencing regional carbon emissions, and investigating the spatiotemporal patterns of land use carbon emissions holds significant importance for rational land resource allocation, improved land use efficiency, and achieving energy conservation and emission reduction goals. Based on land use and energy data from 22 county-level units in Ningxia during 1990–2020, this study comprehensively applied the carbon emission risk index and carbon footprint pressure index to analyze land use changes, spatial differentiation of carbon emissions, and associated risks across Ningxia's counties. The results indicate: (1) Land use changes in Ningxia were substantial from 1990 to 2020, with construction land exhibiting the largest dynamic degree, increasing by 1578.48 km^2. (2) Net carbon emissions from land use in Ningxia increased by 4969.25$×10^{4}$ t, with an average annual growth rate of 15.71% during 2000–2020, nearly doubling each decade. Carbon emissions from construction land accounted for over 86% of total emissions. Carbon absorption increased by 23.76$×10^{4}$ t, dominated by forest carbon absorption (>75% of total absorption), displaying a pattern of local agglomeration and overall dispersion. (3) County-level land use carbon emissions showed an increasing trend but with considerable variation, forming a spatial pattern where counties along the Yellow River exhibited higher emissions than central and southern counties. (4) All counties face high risks and pressures from land use carbon emissions, with severe imbalance between carbon emissions and absorption, leading to disrupted ecosystem carbon equilibrium.

Keywords: land use; carbon emission; carbon emission risk; pressure index; Ningxia

Introduction

Land use change is recognized as a significant factor affecting carbon emissions since the Industrial Revolution, second only to fossil fuel combustion and industrial processes [1]. The academic community has subsequently developed models such as STIRPAT and Laspeyres to investigate the mechanisms of land use carbon emissions, revealing notable differences in how various land use type structures influence terrestrial ecosystem carbon emissions [2]. In particular, changes in construction land contribute up to 33.55% of the marginal increase in net carbon emissions, representing the primary driver of carbon emission growth from land use type transformations [3]. This demonstrates that land use change constitutes a key cause of increasing carbon emissions and climate warming [4], exerting major impacts on carbon cycling processes [5] and maintaining close relationships with ecological environments [6]. Consequently, studying the carbon emission effects of land use represents an essential undertaking for addressing global climate change and constructing low-carbon land use structures.

Ningxia, located in the underdeveloped northwestern region of China, serves a vital ecological security barrier function and represents an important province for national ecological construction. Simultaneously, it constitutes a key component of the national comprehensive energy base in the "Hohhot-Baotou-Yinchuan-Yulin" economic zone. In recent years, rapid regional economic development has driven significant land use changes [7], with GDP reaching 3920.55$×10^{8}$ yuan and urbanization rate climbing to 64.96%. This accelerated economic growth and urbanization has triggered substantial increases in energy consumption. Statistical data reveal that the region's energy consumption grew from 707.3$×10^{4}$ t to 8581.8$×10^{4}$ t of standard coal equivalent—an 11.1-fold increase. Zheng Yongchao et al. [8] found that land use carbon emissions in Ningxia increased by 199.11% from 1990 to 2018, though their study did not examine county-level differences in land use carbon emissions, hindering the formulation of differentiated emission reduction measures. This paper focuses on Ningxia's counties, utilizing land use data from 1990–2020 to quantitatively analyze carbon emissions induced by land use changes through methods including the carbon emission risk index and carbon footprint pressure index. The study provides an in-depth examination of county-level spatial differentiation and risks of carbon emissions, aiming to inform decision-making for constructing low-carbon land use structures in the pursuit of China's "dual carbon" goals.

1. Study Area Overview

Ningxia Hui Autonomous Region is situated in the upper reaches of the Yellow River, bordering Shaanxi to the east, Gansu to the south, and Inner Mongolia to the north. The region comprises 22 county-level administrative units covering a total land area of 6.64$×10^{4}$ km^2. Ningxia experiences a continental climate with an average annual temperature ranging from 5.3 to 9.9°C and annual precipitation between 195–268 mm. The northern part belongs to the Inner Mongolia Plateau, surrounded by the Tengger, Ulan Buh, and Mu Us deserts, while the southern region lies on the Loess Plateau. The terrain, with elevations above 1000 m, slopes downward from south to north in a stepwise pattern. The region extends approximately 450 km from north to south, divided from south to north into six geomorphic units: Liupan Mountain area, southern Ningxia loess hills, Lingwu-Yanchi platform, central Ningxia mountains and intermontane plains, Yinchuan Plain, and Helan Mountain area (Figure 1). The

Yellow River traverses the region, creating a network of canals and ditches in the plain areas with numerous lakes and marshes, resulting in fertile land. Land use types include cultivated land, forestland, grassland, water bodies, construction land, and unused land, accounting for 44.53%, 5.64%, 9.14%, 2.41%, 4.73%, and 33.55% of the total area, respectively.

2.1 Data Sources and Processing

Land use data for 1990, 2000, 2010, and 2020 were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn), with a spatial resolution of 30 m × 30 m. The land use classification includes six primary types: cultivated land, forestland, grassland, water bodies, construction land, and unused land. Energy consumption data were sourced from the *Ningxia Statistical Yearbook* and municipal/county statistical yearbooks from 1990–2020. County administrative boundaries were standardized to the 2020 boundaries, with indirect carbon emission data for counties that underwent administrative adjustments apportioned according to their respective shares in the year of adjustment.

2.2.1 Land Use Carbon Emission Calculation Following the accounting methods provided in the *IPCC 2006 Guidelines for National Greenhouse Gas Inventories* [21], this study estimated carbon emissions from cultivated land, forestland, grassland, water bodies, and unused land using the direct emission method, while carbon emissions from construction land were calculated indirectly through energy consumption.

(1) Direct carbon emission calculation formula [22]:

$$C = \sum_{i=1}^{n} (S_i \times E_i)$$

where C represents total carbon emissions (t), S_i is the area of land use type i (hm^2), E_i is the carbon emission coefficient for land use type i (t · hm^{-2} · a^{-1}), and n is the number of land use types. Based on Ningxia's actual conditions and existing research, carbon emissions were calculated using the coefficients listed in Table 1.

(2) Indirect carbon emission calculation formula [23]:

$$C_e = \sum_{i=1}^{n} (B_i \times D_i \times E_i)$$

where C_e represents total carbon emissions from construction land (t), B_i is the consumption quantity of energy type i (t), D_i is the standard coal conversion coefficient for energy type i, E_i is the carbon emission coefficient for energy type i, n is the number of energy types, and i is the energy type. Considering data reliability and Ningxia's actual conditions, energy consumption includes coal, petroleum, natural gas, primary electricity, and other energy types, all converted to standard coal equivalent. The calculation only considered the carbon emission coefficient for coal, set at $0.68\ \mathrm{t \cdot t^{-1}}$.

2.2.2 Carbon Emission Risk Calculation **(1) Carbon Emission Risk Index** The carbon emission risk index characterizes risk using per-unit-area carbon emissions from land use types. The magnitude of county-level land use carbon emission intensity indicates regional carbon emission risk levels—higher values correspond to greater risk. The calculation formula [25] is:

$$R_j = \frac{\sum_{i=1}^{n} C_{ji}}{\sum_{i=1}^{n} S_{ji}}$$

where R_j is the carbon emission risk index for county j, C_{ji} is carbon emissions from land use type i in county j (t), S_{ji} is the area of land use type i in county j (hm^2), and n is the number of land use types.

(2) Carbon Footprint Pressure Index The carbon footprint pressure index reflects the disturbance of human activities on regional ecological environments [26]. The calculation formula is:

$$P = \frac{C_e}{C_a}$$

where P is the carbon footprint pressure index, C_e is total regional carbon emissions (t), and C_a is total regional carbon absorption (t). When $P < 1$, county land use carbon emissions are less than carbon absorption, indicating ecosystem carbon balance; when $P > 1$, emissions exceed absorption, indicating ecosystem carbon imbalance and substantial pressure on the carbon cycle.

3.1 Land Use Change Analysis

In terms of land use type area proportions and dynamic degree changes (Table 2), grassland accounted for the largest proportion, followed by cultivated land, with their combined share exceeding 75% of total land area in all periods, indicating that grassland and cultivated land are the dominant land use types in Ningxia. Other land types maintained relatively small proportions throughout the study period.

From 1990–2000, cultivated land, construction land, and forestland showed dynamic degrees greater than zero, indicating continuous area expansion. Cultivated land exhibited the largest dynamic degree, followed by construction land, with area increases of 2241.33 km^2 and 117.62 km^2, respectively. Meanwhile, grassland and unused land areas decreased, with grassland showing the greatest reduction rate, reflecting intensified land development.

During 2000–2010, construction land demonstrated the largest dynamic degree, showing strong growth momentum and rapid urban expansion. Forestland ranked second, with its growth rate significantly accelerating compared to the previous period, adding 381.19 km^2. The dynamic degrees of cultivated land, grassland, and unused land decreased.

From 2010–2020, construction land, forestland, and water bodies showed the most significant area increases, with water bodies exhibiting a particularly pronounced dynamic degree far exceeding previous periods, adding 58.42 km^2.

Overall, land use changes were substantial during the study period, characterized by significant increases in construction land, forestland, and water areas. Construction land expansion was most prominent, with a net increase of 1578.48 km^2. Cultivated land area first increased then decreased, while grassland and unused land areas continuously declined. These changes primarily resulted from accelerated water conservancy facilities construction, Yellow River irrigation projects, ecological shelterbelt development, the Grain for Green program, population growth, and urbanization. During the expansion of construction land, forestland, and water bodies, encroachment on cultivated land, grassland, and unused land occurred, demonstrating strong land development intensity.

3.2.1 Overall Characteristics of Land Use Carbon Emissions

Based on formula (1), land use carbon emissions, carbon absorption, and their proportions were calculated (Table 3). From 1990–2020, carbon emissions showed a significant increasing trend, with net emissions rising by 4969.25$\times10^{4}$ t. The average annual growth rate reached 15.71% during 2000–2020, with the largest increase occurring in the 2010–2020 period. Construction land carbon emissions accounted for 86.15% of total carbon source emissions. The proportion of cultivated land emissions gradually decreased while construction land emissions increased, indicating that cultivated land's role as a carbon source weakened while energy consumption became the primary emission source. Construction land replaced cultivated land as the main carbon source after 2000, accounting for over 86% of emissions by 2020. This shift primarily resulted from rapid economic and social development in Ningxia, where construction land encroached upon cultivated land, grassland, and unused land. The energy consumption during land development and construction grew rapidly, leading to substantial emission increases.

Regarding carbon absorption, total absorption increased by 23.76$\times10^{4}$ t from 1990–2020. Forest carbon absorption proportion increased annually, exceeding 75% of total absorption and becoming the dominant absorption type. Grassland carbon absorption proportion gradually decreased, while water bodies and unused land contributed minimally to carbon absorption.

Spatially (Figure 2), cultivated land carbon emissions were mainly distributed in the Ningxia Plain and southern loess hills, showing contiguous distribution. Construction land emissions were dispersed, concentrated in cities along the Yellow River, with sporadic distribution in central and southern areas. Grassland carbon absorption appeared as continuous patches primarily in central and southern wind-sand transition zones and loess hills. Forest carbon absorption was mainly distributed in the Liupan Mountain National Forest Park, Luoshan Nature Reserve, Baijitan Nature Reserve, and Helan Mountain National Forest Park, exhibiting a pattern of local agglomeration and overall dispersion with uneven spatial distribution.

Since the 1980s, Ningxia has been a key region for the "Three-North" Shelterbelt Program, with enhanced small watershed management and desertification control, leading to significant forest area increases. Since the 21st century, ecological civilization construction and the Grain for Green program have sustained forest expansion, with forest coverage reaching 15.8% and forest stock volume increasing by 903.25% by 2020, gradually enhancing carbon absorption capacity. Although grassland accounts for approximately 33% of total land area, Ningxia's arid and semi-arid climate supports primarily desert grassland with weak carbon absorption capacity, resulting in limited contributions to total carbon absorption.

3.2.2 Spatiotemporal Evolution of County-Level Land Use Carbon Emissions

County-level carbon emissions and absorption by land use type are illustrated in Figure 3. Net carbon emissions varied considerably across counties, all showing increasing trends. Particularly after 2000, net emissions generally increased in all counties. For example, Xingqing District exhibited the largest net emissions in 2020 at 2401.59$×10^{4}$ t, nearly doubling since 2010 and representing the highest among all counties. As the core area of Yinchuan's economy, commerce, and finance, Xingqing District's rapid economic development and intensified land development drove emission growth. Lingwu City showed the largest net emissions in 2010 at 100.78$×10^{4}$ t, primarily because the Ningdong Energy and Chemical Industry Base, developed since 2003, converted cultivated land, grassland, and unused land to construction land, with energy consumption during development causing rapid emission increases.

Figure 4 presents the spatial patterns of land use carbon emissions in Ningxia's counties for 1990, 2000, 2010, and 2020. In 1990, emissions were relatively low, showing a banded continuous distribution along the Yellow River and in southern regions (Figure 5a). By 2000, emissions increased in counties along the Yellow River, forming a pattern where counties along the river showed higher emissions than central and southern counties (Figure 5b). This pattern intensified in 2010 and 2020, with central and northern counties exhibiting particularly significant emission increases (Figures 5c and 5d). This spatial configuration directly relates to the interaction between economic development and land use changes.

Since 2000, Ningxia implemented the Yellow River Urban Belt development strategy, increasing land development intensity. The Yellow River Urban Belt lies on the "Hohhot-Baotou-Yinchuan-Lanzhou" economic corridor, with abundant resources and developed transportation, concentrating 92.43% of the region's energy consumption. Central and southern counties possess fewer resources, relatively weaker economic development, and lower energy consumption. Geographically located in the loess hills, these counties have increased forest area through afforestation and soil erosion control, enhancing carbon absorption capacity and resulting in generally lower emissions than the economically developed counties along the Yellow River.

3.3 Land Use Carbon Emission Risk

Carbon emission risk indices and pressure indices were calculated using formulas (2) and (3) (Table 4). From 1990–2020, both indices showed increasing trends, indicating growing risks and pressures from land use carbon emissions. Counties including Xingqing, Lingwu, Huinong, Pingluo, Qingtongxia, Hongsibu, Shapotou, Zhongning, Yuanzhou, and Jingyuan exhibited continuously increasing risk and pressure indices, suggesting persistently growing carbon emission risks and pressures. Other counties reached peak values around 2010 before declining, indicating reduced risks and alleviating pressures. However, throughout the study period, all counties maintained pressure indices greater than 1, demonstrating that carbon emissions exceeded absorption in every county, with ecosystem carbon balance severely disrupted.

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4. Discussion

Land use change represents a crucial factor influencing carbon emission distribution, and its complexity introduces uncertainty regarding the magnitude and patterns of land use carbon emissions. Elucidating the spatial patterns and changes in land use carbon emissions is not only necessary for achieving carbon neutrality but also essential for accurately understanding carbon cycling. Through analysis of spatiotemporal patterns and risks of county-level land use carbon emissions in Ningxia, this study highlights spatial differentiation and risks, providing a reference for formulating differentiated land use emission reduction measures.

The results reveal that land use carbon emissions in Ningxia's counties have increased with significant spatial variation. The growth rate is most pronounced in northern counties, particularly along the Yellow River, where development activities in energy, industry, construction, and transportation have become primary carbon sources. Therefore, this study recommends promoting coordinated urban-rural development in future urbanization processes, integrating construction land scale, structure, and layout to form spatially adjacent and connected urban-rural patterns that reduce energy and logistics consumption. Urban industrial layout should be optimized by reducing or eliminating high-energy-consumption industrial land and minimizing fossil fuel dependence in production processes. Coordinating non-agricultural industrial land with infrastructure land will promote intensive, connotative, and green urban development, helping to reduce carbon emission intensity.

County-level forestland and grassland show uneven spatial distribution with small carbon absorption capacity, large net carbon emissions, and high carbon emission risks and pressures. When formulating emission reduction policies, counties should fully consider regional water resource carrying capacity, develop characteristic economic forests on unused land and slopes, advance afforestation with high quality to enhance forest carbon absorption, strengthen protection of wetlands and lakes in the Ningxia Plain, improve saline soil, and intensify ecological restoration and management to promote ecosystem carbon cycling and balance.

5. Conclusions

Based on land use and energy data from 22 county-level units in Ningxia from 1990–2020, this study analyzed spatial differentiation and risks of land use carbon emissions, yielding the following conclusions:

(1) Land use changes in Ningxia were substantial from 1990–2020, with intensified land development. Construction land, forestland, and water areas increased significantly, while cultivated land and grassland areas decreased, most notably through rapid construction land expansion (1578.48 km^2 increase).

(2) Net land use carbon emissions increased by 4969.25$×10^{4}$ t, with an average annual growth rate of 15.71%. The 2010–2020 period witnessed the largest increase. Construction land carbon emissions accounted for over 86% of total carbon source emissions. Spatially, emissions were concentrated in cities along the Yellow River, showing a dispersed distribution pattern. Carbon absorption increased by 23.76$×10^{4}$ t, dominated by forest absorption (>75% of total), exhibiting a pattern of local agglomeration and overall dispersion.

(3) County-level land use carbon emissions showed increasing trends with considerable variation. Northern counties experienced the most significant growth rates, forming a spatial pattern where counties along the Yellow

River exhibited higher emissions than central and southern counties.

(4) All counties face high risks and pressures from land use carbon emissions, with severe imbalance between carbon emissions and absorption, resulting in disrupted ecosystem carbon equilibrium.

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