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Study on Carbon Emissions from Land Cover Change and Its Decoupling Pattern with Economic Development in Henan Province Based on Multi-Source Data (1990–2020)

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Abstract. It is of profound significance to study the variation of land cover change carbon emissions (LCCCE) and its relationship with economic development for the optimization of regional land cover structure and the development of the green economy. Using carbon emissions estimation methods, Tapio decoupling model, and Sen's nonparametric method, this study analyzed the characteristics of land cover area and its carbon emissions in Henan Province, and discussed the relationship between LCCCE and economic development based on multi-source data. The results showed that: (1) From 1990 to 2020, different land cover types showed great differences in their area changes, among which the cropland and construction land continued to change at rates of -4260.13 km^2/10a and 3677.61 km^2/10a, respectively, while the forest land had a trend of "decreasing first and then increasing" with a turning point of 2000. (2) The net carbon emissions (NCE) of land cover in Henan Province showed a trend of slow rise (1990–1999)–rapid rise (1999–2011)–rapid decline (2011–2020) at rates of 2441.94×10^4t/10a, 16575.21×10^4t/10a, and -7493.35×10^4t/10a, respectively. Carbon emissions from construction land accounted for 94.747% of NCE in Henan Province. (3) The relationship between LCCCE and Gross Domestic Product (GDP) in Henan Province presented multiple stages of weak decoupling (1991–1999), expansive coupling (2000–2006), weak decoupling (2007–2011), and strong decoupling (2012–2020).

Keywords. Land cover, Carbon emissions, Multi-source Data, Decoupling model, Henan Province

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1. Introduction

The current global historical cumulative carbon dioxide (CO_2) emissions are approaching the emission budgets for the temperature targets of 1.5°C and 2.0°C, accounting for 4/5 of the carbon budget for the 1.5°C scenario and 2/3 of the carbon budget for the 2.0°C scenario [1]. The global challenge of greenhouse gas emissions, particularly CO_2, has escalated into a significant worldwide concern. This is due to the potential of these emissions to induce global warming, which subsequently leads to the occurrence of severe calamities such as droughts and floods. Land, as one of the important production factors for humanity, is an essential carrier that supports human production and socio-economic development. The IPCC report states that carbon emissions from land use (including land use change) and forestry reached 6.6 ± 4.6 billion tons in 2019 [2]. Land cover change can cause alterations in the carbon source and sink processes and their magnitudes, resulting in a broad and intense impact on the carbon cycle of terrestrial ecosystems [3]. Changes in land cover structure often serve regional economic development plans, and economic growth remains a significant factor for the growth of global carbon emissions from fossil fuel combustion. Therefore, researching land cover change carbon emissions (LCCCE) can provide the scientific basis for local governments to carry out rational land resources planning and development, and industrial structure adjustment in order to achieve a low-carbon economic development mode.

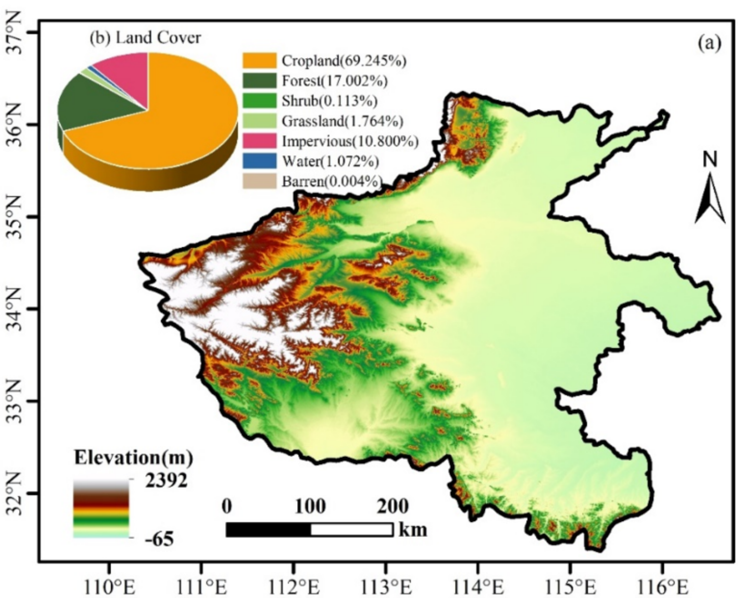

Figure 1. Map of Henan Province (a) and proportion of different land cover (b).

Located in central and eastern China, Henan Province (Figure 1a) is a populous, agricultural and industrial province, and one of the fastest-growing economies in China. Henan Province has a variety of land cover types, with cropland, forest, and impervious surface area (mainly refers to construction land) all accounting for more than 10% of the province's area, which are 69.245%, 17.002%, and 10.800%, respectively (Figure 1b). With the economic development and policy adjustment, the land cover of Henan Province has undergone continuous changes. Based on four-period remote sensing data, Zhang et al. found that forest, water area, and construction land in Henan Province increased during 2000–2020, while the area of cropland, grassland, and barren land decreased [4]. The research on LCCCE in Henan Province mainly focused on the municipal scale. For example, Feng clarified the characteristics of land cover structure changes in Zhengzhou city from 1995 to 2015, and then estimated the total LCCCE, which was found to be continuously increasing [5]. Gao et al. assessed the land cover carbon emissions and its economic value for key ecological functional areas of the Huaihe River Source [6]. However, there are few studies on the relationship between LCCCE and economic development in Henan Province at provincial and annual scales. Consequently, our objectives are to (1) reveal the temporal variation characteristics of land cover area in Henan Province from 1990 to 2020 based the annual China land cover dataset, (2) evaluate the change characteristics of LCCCE and net carbon emissions (NCE) in Henan Province, and (3) clarify the coupling relationship between LCCCE and regional economic development using Tapio decoupling model. Our results will be of great significance for transforming the economic development mode of high energy consumption, improving the ecological environment, and realizing low-carbon land use in Henan Province.

2. Materials and Mathematical Statistics Methods

2.1. Materials

2.1.1. Land Cover Dataset

China land cover dataset (CLCD) with a spatial resolution of 30m was downloaded from https://zenodo.org/record/5210928. It covers the period from 1990 to 2020. As a set of high-precision land cover product, CLCD was produced from Landsat images on the Google Earth Engine platform by coupling with the random forest classifier, spatial–temporal filtering, and logical reasoning. The overall accuracy of CLCD reached 79.31%, which was superior to MCD12Q1, ESACCI_LC, FROM_GLC and GlobaLand30 products [7]. In this dataset, there are seven land cover types in Henan Province, namely cropland, forest, shrub, grassland, water area, barren land, and impervious surface area (mainly refers to construction land).

2.1.2. Energy Consumption and Economic Data

Gross Domestic Product (GDP) and energy consumption data (mainly including raw coal, washed coal, other washed coal, coke, crude oil, petrol, kerosene, diesel, and fuel oil) of Henan Province during 1990–2020 were obtained from *Henan Statistical Yearbook* and *China Energy Statistical Yearbook*.

2.2. Mathematical Statistics Methods

2.2.1. Calculation of Land Cover Change Carbon Emissions

According to land cover type, the LCCCE can be calculated by direct and indirect estimation methods, respectively. The direct estimation method showed as equation (1) is used to calculate carbon emission/absorption of cropland, forest (including shrub), grassland, water area, and barren land.

$$C_i = A_i \times \alpha_i \tag{1}$$

Where C_i, A_i, and α_i are the carbon emission/absorption amount (unit: $\times 10^4$t), area ($\times 10^4$hm^2), and coefficient of carbon emission/absorption (t·hm^{-2}) for land cover i, respectively. Coefficients of carbon emission/absorption were determined according to reference [8].

The carbon emissions of construction land are calculated indirectly, which are mainly represented by the amount of carbon generated by fossil energy consumption in production and life. The estimation formula is as follows:

$$C_e = \sum E_j \times \theta_j \times \delta_j \tag{2}$$

Where C_e represents carbon emissions of construction land (unit: $\times 10^4$t), E_j represents the consumption of energy j ($\times 10^4$t), and θ_j represents the conversion coefficient of energy j to standard coal. δ_j represents the carbon emissions coefficient of energy j. θ_j and δ_j are mainly referred to *China Energy Statistical Yearbook* and reference [9].

NCE (C) for land cover change is defined as:

$$C = \sum C_i + C_e \tag{3}$$

2.2.2. Tapio Decoupling Model

Decoupling theory can evaluate the linkage relationship between environmental stress and economy. Here, we employed the improved Tapio decoupling model [10] to explore the coupling relationship between LCCCE and regional economic development, which was measured by the decoupling elasticity value (DE_n):

$$DE_n = \frac{C_n}{G_n} = \frac{\Delta CO_2}{CO_2} \Big/ \frac{\Delta GDP}{GDP} \tag{4}$$

Where C_n and G_n represent the change rate of LCCCE and GDP in the year of n, respectively. CO_2 and GDP represent LCCCE and GDP in the base year, respectively. And ΔCO_2 and ΔGDP represent the variation of LCCCE and GDP in the year of n compared to the base year, respectively.

Comprehensively considering the decoupling elasticity value, the change rate of LCCCE and GDP, the decoupling states between LCCCE and GDP can be classified into three categories (including eight sub-categories): coupling (expansive coupling and recessive coupling), decoupling (weak decoupling, strong decoupling, and recessive decoupling), and negative decoupling (strong negative decoupling, weak negative decoupling, and expansive negative decoupling) [10].

2.2.3. Sen's Nonparametric Method

Here, Sen's nonparametric method [11] was employed to explore the trend of land cover area and LCCCE. For a set of variables x_i (i=1, 2, 3, ..., n), their long-term trend slope value (represented by Q) can be calculated according to equation (5). And the Mann-Kendall trend test [11] is used to determine whether the trend is significant.

$$Q = Median(\frac{x_k - x_j}{k - j}) \quad (5)$$

Where j and k are the sequence numbers of data value pairs, respectively, and $j<k$.

3. Results and discussion

3.1. Variations of land cover area in Henan Province

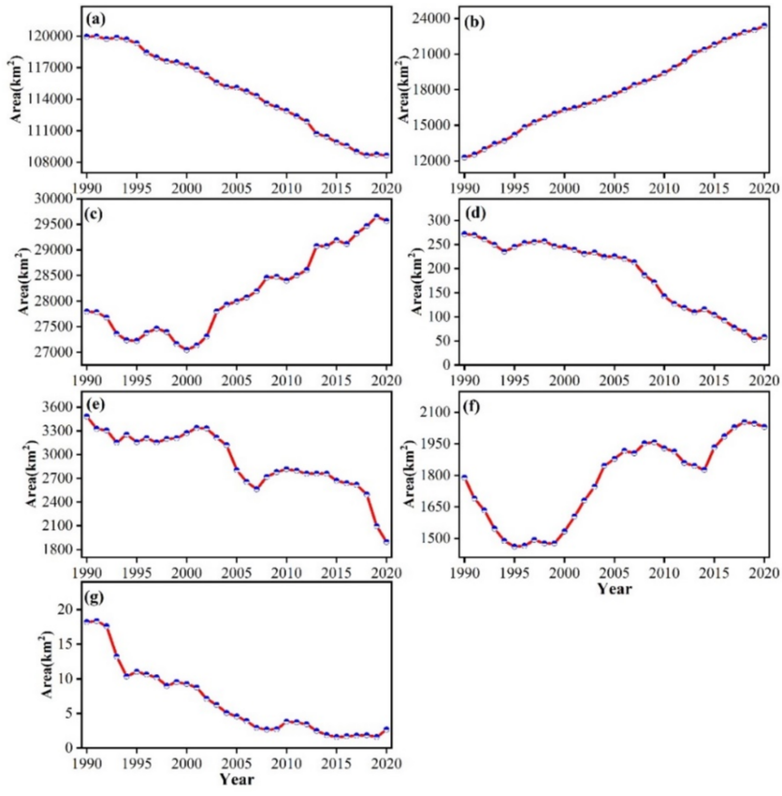

Figure 2. Land cover area change in Henan Province from 1990 to 2020. (a) Cropland, (b) Construction land, (c) Forest, (d) Shrub, (e) Grassland, (f) Water area, and (g) Barren land.

The variation characteristics of different land cover types in Henan Province were significantly different during the period of 1990–2020, which could be divided into five types, as follows: (1) The area changes of cropland (Figure 2a), shrub (Figure 2d) and barren land (Figure 2g) belonged to the type of continuous decline. The area of cropland and shrub significantly decreased at rates of -4260.13 km^2/10a and -74.68 km^2/10a, respectively. Barren land, whose area proportion was very small in Henan Province, showed a trend of "rapid decrease – slow decrease" at rates of -22.63 km^2/10a during 1990–1994 and -3.98 km^2/10a during 1994–2020, respectively. (2) Only the construction land area showed a continuously rising trend with a rate of 3677.61 km^2/10a (Figure 2b) at the 0.001 significance level, which was the result of rapid urbanization in Henan

Province. (3) The forest area in Henan Province mainly decreased first and then increased with a turning point of 2000 (Figure 2c). The increase rate of forest area after 2000 (1204.28 km^2/10a) was about 1.8 times that of the decrease rate before 2000 (-686.82 km^2/10a). The increase in forest area is due to the local government's policy of afforestation to improve the ecological environment. (4) The grassland area in Henan Province showed a change process of "stable – declining – stable – declining" (Figure 2e). The grassland area remained stable during 1990–2001 and 2007–2017, with an average area of 3255.49 km^2 and 2716.84 km^2, respectively. While it decreased at a rate of -1360.17 km^2/10a during 2001–2007 and -2511.02 km^2/10a during 2017–2020, respectively. (5) From 1990 to 2020, the water area of Henan Province fluctuated greatly, showing a fluctuation of decreasing (-672.80 km^2/10a), stabilizing (with an average area of 1475.35 km^2), rising (528.32 km^2/10a), decreasing (-278.80 km^2/10a), and rising (339.40 km^2/10a), with turning years of 1995, 1999, 2009, and 2014, respectively (Figure 2f).

3.2. Variations of LCCCE in Henan Province

The annual average NCE in Henan Province was 14047.11×10^4t during 1990–2020, and the maximum value occurred in 2011 with a value of 25467.16×10^4t (Figure 3a). The interannual change of NCE in Henan Province can be divided into three phases: (1) In the first phase, the NCE of Henan Province increased from 4813.75×10^4t in 1990 to 6346.18×10^4t in 1999, with a growth rate of 2441.94×10^4t/10a. This may be because the economic development and urbanization development of Henan Province were relatively slow in this period, and the high energy consumption economic development mode had also not occupied an important position. (2) During 1999–2011, the NCE in Henan Province increased rapidly at the rate of 16575.21×10^4t/10a, and its amount increased from 6346.18×10^4t in 1999 to 25467.16×10^4t in 2011, with an increase of 301.3%. This could be due to a sharp improvement in urbanization, and a sharp increase of construction land area and energy consumption, resulting in a sharp increase in carbon emissions. (3) In the period of 2011–2020, the NCE in Henan Province showed a rapid decline trend with a rate of -7493.35×10^4t/10a, and it decreased by 28.7%. This may be because Henan Province had paid attention to the adjustment of energy structure and achieved certain results in energy conservation and carbon emissions reduction.

Carbon emissions from cropland and construction land were the two most important carbon sources in Henan Province, accounting for 3.952% and 94.747% of the annual average NCE in Henan Province, respectively. Carbon emissions from cropland continuously decreased at a rate of -21.17×10^4t/10a, and its contribution to NCE decreased from 11.497% in 1990 to 2.910% in 2020 (Figure 3b). Consistent with the change characteristics of NCE, the carbon emissions of construction land showed a trend of slow rise (2454.32×10^4t/10a), rapid rise (16607.05×10^4t/10a), and rapid decline (-7467.67×10^4t/10a) with 1999 and 2011 as turning points (Figure 3c). Its contribution to the NCE of Henan Province increased from 84.917% in 1990 to 96.032% in 2020.

Carbon absorption from forests, grassland, water area, and barren land were the main carbon sinks in Henan Province, among which barren land occupied a very small area proportion and its annual carbon absorption was only about 3.4t. The contribution of grassland carbon absorption to NCE in Henan Province was only 0.004%. Grassland carbon absorption showed an overall downward trend with a rate of -0.06×10^4t/10a during 1990–2020, and reached the minimum value of 3792t in 2020 (Figure 3e). Forest land was the most important land cover type for carbon sink in Henan Province, with a contribution to NCE of 1.266%. There existed two stages for the variation of forest land carbon absorption during 1990–2020 (Figure 3d): the carbon absorption decreased at a rate of -4.54×10^4t/10a in the first stage (1990–2000), and then it increased at a rate of 7.05×10^4t/10a. The carbon absorption of forest land reached the maximum value of 191.31×10^4t in 2019. Carbon absorption from the water area contributed 0.031% to NCE in Henan Province, which was the second largest source of carbon sink after forest land. The fluctuation of water body carbon absorption was similar to that of water area, showing the fluctuation variations of decreasing (-1.70×10^4t/10a), stabilizing (an average amount of 3.73×10^4t), increasing (1.34×10^4t/10a), decreasing (-0.71×10^4t/10a), and increasing (0.86×10^4t/10a), with turning years of 1995, 1999, 2009, and 2014, respectively (Figure 3f).

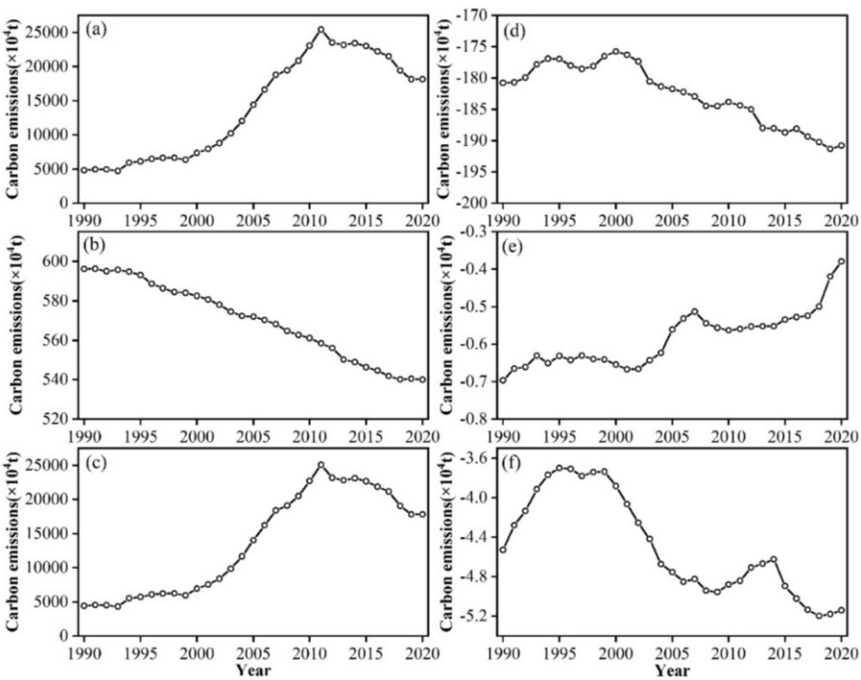

Figure 3. Variations of LCCCE in Henan Province during 1990–2020. (a) Net carbon emissions (NCE), (b) Cropland carbon emissions, (c) Construction land carbon emissions, (d) Forest (including shrub) carbon emissions, (e) Grassland carbon emissions, and (f) Water area carbon emissions.

3.3. Relationship between LCCCE and Economic Development in Henan Province

There existed three main stages for the relationship between economic growth (represented by GDP) and LCCCE in Henan Province from 1990 to 2020, as shown in Figure 4: (1) From 1990 to 1999, the relationship between GDP and LCCCE was dominated by weak decoupling. The GDP growth rate of Henan Province showed a trend of first increasing and then decreasing, and reached the peak value in 1995. Overall, the change rate of GDP was higher than that of carbon emissions during this period. In terms of decoupling elasticity value, we found that GDP and LCCCE were strongly decoupled in 1992–1993 and 1999, but weakly decoupled in other years. Combined with Figure 3, we believed that although energy consumption had promoted economic development in

Henan Province to a certain extent at this stage, economic development mode at the cost of consuming a large amount of energy had not been formed. (2) In the period of 2000–2006, the relationship between GDP and LCCCE was mainly manifested as expansive negative decoupling and expansive coupling. In 2000, the growth rate of LCCCE in Henan Province (16.2%) was much higher than that of economic development (11.8%), and the decoupling elasticity value was as high as 1.36, indicating that GDP and LCCCE presented an expansive negative decoupling state. During 2001–2006, both the growth rate of LCCCE and GDP in Henan Province increased first and then decreased, and reached the peak value in 2005, which was 19.7% and 21.8%, respectively. The average decoupling elasticity value during 2001-2006 was as high as 0.95 (0.84~1.16), which indicated that LCCCE and GDP presented an expansive coupling state. In this stage, the relationship between the two was caused by the extensive economic development mode of Henan Province, which promoted economic development at the cost of massive consumption of fossil energy. (3) From 2007 to 2020, the relationship between GDP and LCCCE was mainly decoupling. Taking 2012 as the boundary, weak decoupling was dominant in the early stage and strong decoupling was dominant in the late stage. It was worth mentioning that due to the impact of the economic crisis in 2008 and the COVID-19 pandemic, the GDP growth rate in 2009 and 2020 was 8.1% and 2.4%, respectively, which was much lower than that of their neighbouring years. As a result, the relationship between GDP and LCCCE showed a state of expansive coupling in 2009 and weak decoupling in 2020. Overall, the relationship between GDP and LCCCE showed a change of “weak decoupling–strong decoupling” at this stage, which benefited from the low-carbon economic development mode, reduction of fossil energy consumption, and optimization of industrial structure vigorously advocated by the government.

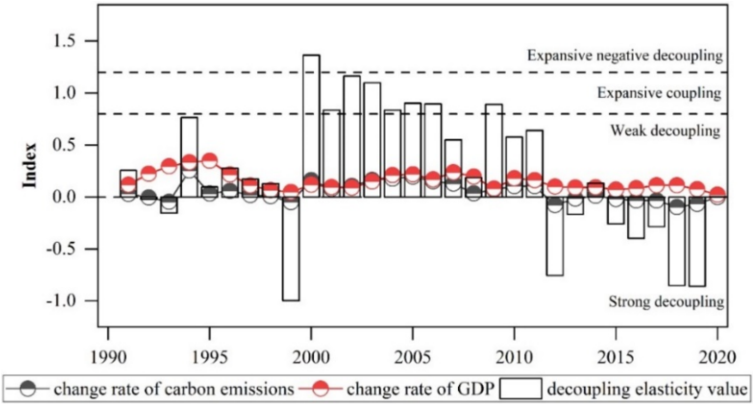

Figure 4. Decoupling relationship between LCCCE and GDP in Henan Province from 1990 to 2020.

4. Conclusions

Based on the multi-source data of land cover, energy consumption, and GDP in Henan Province during 1990–2020, this paper comprehensively used carbon emissions estimation methods, Tapio decoupling model, and Sen’s nonparametric method to analyze the characteristics of land cover area, LCCCE and its relationship with economic development in Henan Province. The conclusions are as follows:

(1) The variation characteristics of different land cover types in Henan Province from 1990 to 2020 can be divided into five categories, as follows: type of continuous decline (cropland, shrub, and barren land), type of continuous rising (construction land), type of "first decreasing and then increasing" (forest land), type of "stable–declining–stable–declining" (grassland), and "declining–stable–rising–declining–rising" type (water area).

(2) The annual average NCE in Henan Province during 1990–2020 were 14047.11×10^4t, and its interannual variation showed a fluctuation of "slow rise–rapid rise–rapid decline" with turning years of 1999 and 2011, respectively. The contribution of different land cover types to NCE in Henan Province was construction land > cropland > forest > water area > grassland > barren land.

(3) With the change of regional economic development mode, the relationship between GDP and LCCCE in Henan Province presented a dynamic change of "weak decoupling–expansive coupling–weak decoupling–strong decoupling", and transition years were 2000, 2007, and 2012, respectively.

Acknowledgments

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