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# Regulation and Mechanisms of Carbon Effects by Land Use Change

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**Abstract:** Land use change is one of the most direct and significant impacts of human activities on the Earth system. It not only changes the physical characteristics of the land surface, but also affects the energy, water, and material cycles of the Earth, and thus affects the global and regional climate change and ecosystem services. Among them, the impact of land use change on the carbon cycle is particularly important, because the carbon cycle is one of the most basic and critical cycles in the Earth system. It determines the greenhouse effect and climate sensitivity of the Earth, and also affects the biodiversity and productivity. This paper systematically analyzes the impact and mechanism of the carbon effects of land use change on different ecosystem types, different geographic regions, different climate conditions, different land use modes and management measures from different angles and levels, using various methods and models, evaluates the factors such as the size, direction, persistence, and sustainability of the carbon effects of land use change, proposes some evaluation and promotion of management techniques and measures, as well as policy suggestions and institutional designs for the carbon effects, and provides scientific basis and reference suggestions for the optimization and control of the carbon effects of land use change.

**Keywords:** Land use change; carbon effects; evaluation methods; management measures; institutional design.

## 1. Introduction

Land use change is one of the most direct and significant impacts of human activities on the Earth system. It not only changes the physical characteristics of the land surface[1], but also affects the energy, water, and material cycles of the Earth, and thus affects the global and regional climate change and ecosystem services[2-4](Figure 1). Among them, the impact of land use change on the carbon cycle is particularly important, because the carbon cycle is one of the most basic and critical cycles in the Earth system. It determines the greenhouse effect and climate sensitivity of the Earth, and also affects the biodiversity and productivity. Land use change affects the carbon input and output, as well as the carbon storage and sink capacity of terrestrial ecosystems, by changing the distribution, structure, and function of vegetation, and the physical, chemical, and biological characteristics of soil, thereby affecting the global and regional carbon balance and budget. However, the impact of land use change on carbon effects is not a simple linear relationship, but is regulated and influenced by various land environmental factors, such as ecosystem type, geographic region, climate condition, land use mode, and management measure[5-7]. These factors have complex interactions and feedback mechanisms, resulting in significant differences, complexities, and uncertainties in the impact of land use change on carbon effects. Therefore, revealing the regulation and mechanism of land use change on carbon effects of different land environmental factors is an important and frontier research topic in land ecology. It has important theoretical and practical values for understanding and predicting the impact of land use change on the carbon cycle, and for formulating and implementing effective carbon management and low-carbon development strategies[8]. This paper takes the regulation and mechanism of land use change on carbon effects of different land environmental factors as the research theme, aiming to comprehensively analyze and evaluate the impact and mechanism of land use change on carbon effects of different ecosystem types, geographic regions, climate conditions, land use modes, and management measures, to explore the comparison and optimization of the evaluation methods and models of land use change on carbon effects, and the uncertainty analysis of carbon effects, to assess the evaluation and promotion of the management technologies and measures of land use change on carbon effects, and the policy suggestions and institutional design of carbon effects, to point out the shortcomings and challenges in this field, and to look forward to the future research directions and focuses.

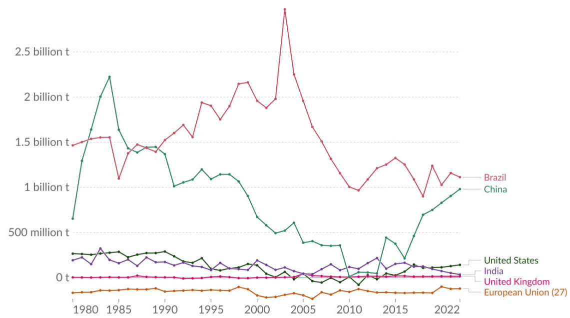


**Figure 1.** Annual $CO_2$ emissions from land-use change, 1980 to 2022
Data source: Global Carbon Budget (2023)

## 2. Carbon Effects in Different Ecosystem Types

### 2.1. Forest Ecosystems

Forest ecosystems are one of the most important carbon pools in terrestrial ecosystems. They absorb carbon dioxide from the atmosphere through photosynthesis, and store carbon in plant biomass and soil, forming carbon sinks(Figure 2). However, land use change, especially deforestation, conversion, and degradation, can reduce the carbon storage, increase the carbon emission, and lower the carbon sink capacity of forest ecosystems, thereby affecting the global and regional carbon balance and budget. According to estimates, since the 1980s, China's forest area has increased by $1.2\times10^6$ $km^2$, and its forest carbon storage has increased by 1.8 PgC, of which vegetation carbon storage has increased by 1.2 PgC, and soil carbon storage has increased by 0.6 PgC[9]. This is mainly attributed to a series of forest protection and restoration projects implemented by the Chinese government, such as the Natural Forest Protection Project, the Grain for Green Project, and the Three-North Shelter Forest Project. These projects not only increased the area and quality of forests, but also improved the structure and function of forests, enhanced the productivity and stability of forests, and strengthened the ability of forests to resist disturbance and adapt to change.

However, China's forest carbon storage is still lower than the global average, and there are significant regional differences. The forest carbon storage in the eastern region is higher than that in the western region, the forest carbon storage in the southern region is higher than that in the northern region, and the forest carbon storage in the low-altitude region is higher than that in the high-altitude region. This is mainly related to the factors such as climate condition, soil type, vegetation type, and human activity. In addition, due to the influence of various natural and anthropogenic factors on the carbon cycle process of forest ecosystems, such as temperature, precipitation, light, atmospheric carbon dioxide concentration, nitrogen deposition, fire, pest and disease, and forestry management, the carbon emission and absorption of forest ecosystems have large interannual and seasonal variations, and high uncertainties.

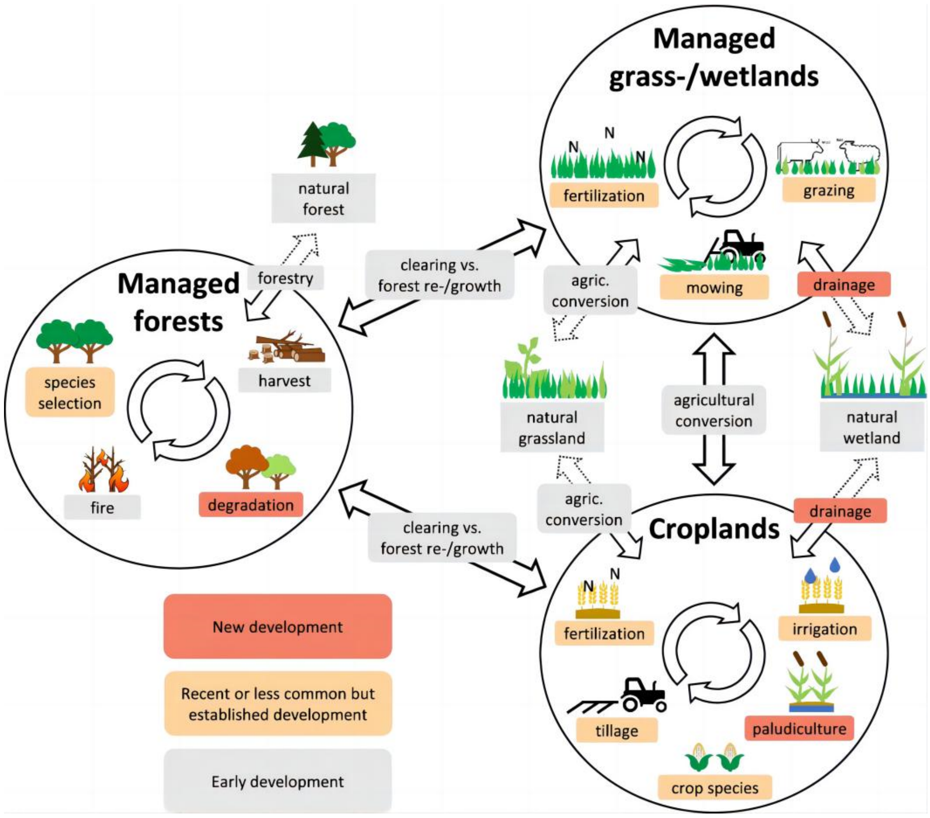


**Figure 2.** Land Use Effects on Climate: Current State, Recent Progress[10]

## 2.2. Grassland Ecosystems

Grassland ecosystems are one of the most widely distributed types of terrestrial ecosystems. They occupy more than 40% of the global land area, and store about 20% of the global terrestrial ecosystem carbon storage. The carbon cycle of grassland ecosystems mainly consists of two parts: plants and soil. Plants absorb carbon dioxide from the atmosphere through photosynthesis, and store carbon in aboveground and belowground biomass. Soil releases carbon dioxide to the atmosphere through microbial decomposition, forming carbon balance. However, land use change, especially grassland degradation, conversion, and management, can reduce the carbon storage, increase the carbon emission, and lower the carbon sink capacity of grassland ecosystems, thereby affecting the global and regional carbon balance and budget.

Since the 1980s, China's grassland area has decreased by $0.4\times10^6$ $km^2$, and its grassland carbon storage has decreased by 0.2 PgC, of which vegetation carbon storage has decreased by 0.1 PgC, and soil carbon storage has decreased by 0.1 PgC[9]. This is mainly related to China's grassland degradation phenomenon, which refers to the process of grassland productivity, stability, and diversity decline, and grassland function and service value reduction. The causes of grassland degradation include natural factors and human factors. Natural factors include climate change, fire, pest and disease, etc. Human factors include overgrazing, cultivation, construction, development, etc. Grassland degradation leads to the decline of indicators such as vegetation coverage, biomass, species diversity, etc., and the decline of indicators such as soil organic matter, moisture, nutrient, etc., thus affecting the carbon input and output of grassland, and reducing the carbon storage and sink capacity of grassland.

However, China's grassland carbon storage also has obvious regional differences. The grassland carbon storage in the western region is higher than that in the eastern region, the grassland carbon storage in the northern region is higher than that in the southern region, and the grassland carbon storage in the high-altitude region is higher than that in the low-altitude region[11]. This is mainly related to the factors such as climate condition, soil type, vegetation type, and human activity. In addition, due to the influence of various natural and anthropogenic factors on the carbon cycle process of grassland ecosystems, such as temperature, precipitation, light, atmospheric carbon dioxide concentration, nitrogen deposition, fire, pest and disease, and grassland management, the carbon emission and absorption of grassland ecosystems have large interannual and seasonal variations, and high uncertainties.

# 3. The Differences and Causes of Carbon Effects

## 3.1. The differences of geographic regions

Geographic region is an important factor that affects the carbon effects of land use change. Different geographic regions have different natural conditions, population distribution, economic development level, land use structure and mode, which lead to different spatial distribution and scale transformation of carbon emission and absorption[12]. China's total carbon emission from land use change showed a trend of gradually increasing from the southeast coast to the northwest inland from 2001 to 2019, among which, the land use carbon emission of North China, Northeast China, Northwest China and Southwest China accounted for 28.2%, 18.6%, 17.8% and 16.8% of the national total, respectively, while the land use carbon emission of East China, Central China and South China accounted for 8.4%, 6.2% and 4.0% of the national total, respectively[13]. This is mainly related to the land use types and intensities of different geographic regions, for example, the land use in North China is mainly agriculture, with a high proportion of cultivated land, high land use intensity, high soil organic carbon loss, and high carbon emission; while the land use in East China is mainly urbanization, with a high proportion of construction land, low land use intensity, high soil organic carbon increase, and low carbon emission. In addition, the climate condition, vegetation type, soil type and other factors of different geographic regions also affect the differences of carbon effects of land use change, for example, the arid and semi-arid climate, desert grassland vegetation, and alkaline soil in Northwest China, all reduce the sensitivity of land use change to carbon emission; while the humid subtropical climate, forest vegetation, and acidic soil in Southwest China, all increase the sensitivity of land use change to carbon emission.

## 3.2. The differences of climate conditions

Climate condition is another important factor that affects the carbon effects of land use change. Different climate conditions affect the process and result of land use change, as well as the impact of land use change on the carbon cycle. China's total carbon emission from land use change showed a trend of gradually increasing from warm and humid to cold and dry from 2001 to 2019, among which, the land use carbon emission of temperate humid zone, subtropical humid zone and tropical humid zone accounted for 9.8%, 8.7% and 3.9% of the national total, respectively, while the land use carbon emission of temperate semi-arid zone, temperate arid zone and cold arid zone accounted for 24.1%, 23.3% and 19.6% of the national total, respectively. This is mainly related to the driving and response of different climate conditions to land use change, for example, the warm and humid climate condition is conducive to vegetation growth and soil organic carbon accumulation, the land use change has a greater promoting effect on carbon absorption than inhibiting effect on carbon emission, and the carbon emission is low; while the cold and dry climate condition is unfavorable to vegetation growth and soil organic carbon accumulation, the land use change has a greater inhibiting effect on carbon emission than promoting effect on carbon absorption, and the carbon emission is high. In addition, the changes of different climate conditions also affect the differences of carbon effects of land use change, for example, global warming will increase the sensitivity of land use change to carbon emission in high-latitude regions, while precipitation change will increase the sensitivity of land use change to carbon emission in arid and semi-arid regions.

## 3.3. The differences of land use modes and management measures

Land use mode and management measure are another important factor that affects the carbon effects of land use change. Different land use modes and management measures affect the type and intensity of land use change, as well as the impact of land use change on the carbon cycle. China's total carbon emission from land use change showed a trend of gradually decreasing from traditional agriculture to modern agriculture, and from extensive type to intensive type from 2001 to 2019, among which, the land use carbon emission of traditional agricultural zone, modern agricultural zone and non-agricultural zone accounted for 46.7%, 28.5% and 24.8% of the national total, respectively, while the land use carbon emission of extensive zone, intensive zone and non-agricultural zone accounted for 41.2%, 34.0% and 24.8% of the national total, respectively[13]. This is mainly related to the impact of different land use modes and management measures on land use change, for example, the land use mode in traditional agricultural zone is mainly planting food crops, with high land use intensity, high soil organic carbon loss, and high carbon emission; while the land use mode in modern agricultural zone is mainly planting economic crops, with low land use intensity, high soil organic carbon increase, and low carbon emission. In addition, the selection and implementation of different land use modes and management measures also affect the differences of carbon effects of land use change, for example, using organic fertilizer, straw returning, conservation tillage and other measures, can increase soil organic carbon content, reduce carbon emission; while using water-saving irrigation, precision fertilization, green prevention and control and other measures, can increase crop productivity, increase carbon absorption.

# 4. Comparison of Evaluation Methods and Models of Carbon Effects

## 4.1. Comparison of evaluation methods and models

### 4.1.1. Carbon emission coefficient method

This method is a simple calculation method based on statistical data, by multiplying the carbon emission coefficients of different land use types, to obtain the carbon emission from land use change. The advantage of this method is that it is easy to calculate, low data requirement, suitable for large-scale carbon emission assessment; the disadvantage is that it ignores the dynamic process and spatial heterogeneity of land use change, the determination of carbon emission coefficients has large uncertainty, and it is difficult to reflect the complexity and diversity of carbon effects of land use change.

#### 4.1.2. Ecosystem type method

This method is a comprehensive calculation method based on ecosystem types, by determining the carbon storage and carbon density of different ecosystem types, to obtain the carbon storage change from land use change. The advantage of this method is that it considers the spatial distribution and difference of land use change and ecosystem types, and can reflect the structure and function of carbon effects of land use change; the disadvantage is that it requires a large amount of sample survey and experimental data, data acquisition is difficult, calculation process is complex, suitable for medium and small-scale carbon storage assessment.

#### 4.1.3. Life cycle analysis method

This method is a whole-process calculation method based on life cycle, by analyzing the carbon emission and absorption of land use change in the pre-stage, mid-stage and post-stage, to obtain the carbon balance and carbon footprint of land use change. The advantage of this method is that it fully considers the time scale and dynamics of land use change and carbon cycle, and can reflect the process and result of carbon effects of land use change; the disadvantage is that it requires the integration of multiple data sources and models, data processing is difficult, calculation accuracy is low, suitable for specific scenarios of carbon balance assessment.

#### 4.1.4. Process simulation method

This method is a dynamic simulation method based on process models, by establishing mathematical models of land use change and carbon cycle, to simulate the process and mechanism of carbon emission and absorption of land use change. The advantage of this method is that it can reveal the intrinsic laws and influencing factors of carbon effects of land use change, and can carry out multi-scenario carbon effects prediction and optimization; the disadvantage is that it requires a large number of parameters and input data, model validation and verification are difficult, model applicability and reliability need to be improved.

### 4.2. Optimization of evaluation methods and models

#### 4.2.1. Data optimization

Using remote sensing and geographic information system and other technologies, to obtain higher resolution and longer time series of land use change data and carbon emission data, to improve the quality and availability of data; using big data and cloud computing and other technologies, to integrate multi-source and multi-type data, to improve the compatibility and sharing of data; using artificial intelligence and machine learning and other technologies, to mine the potential information and value of data, to improve the intelligence and flexibility of data.

#### 4.2.2. Model optimization

Using cellular automata, system dynamics, multi-agent system and other technologies, to construct more complex and refined mathematical models of land use change and carbon cycle, to improve the realism and sensitivity of models; using niche theory, ecological network analysis, ecological footprint and other technologies, to construct more comprehensive and in-depth evaluation indicator system of land use change and carbon effects, to improve the scientificity and objectivity of evaluation; using multi-criteria decision analysis, cost-benefit analysis, ecological compensation mechanism and other technologies, to construct more optimized and sustainable management schemes of land use change and carbon effects, to improve the feasibility and effectiveness of management.

#### 4.2.3. Uncertainty Analysis Optimization

Employ techniques such as Monte Carlo simulation, grey theory, and fuzzy theory to analyze the sources and impacts of uncertainty in land use change and carbon effect assessments, improving the credibility and robustness of evaluations. Utilize sensitivity analysis, variability analysis, and risk analysis techniques to assess the impact of uncertainty on evaluation results, improving the sensitivity and risk assessment of evaluations. Use uncertainty propagation, uncertainty reduction, and uncertainty control techniques to analyze the propagation and variation of uncertainty in land use change and carbon effect assessments, improving the accuracy and controllability of evaluations.

## 5. Evaluation and Promotion of Measures

### 5.1. Evaluation and promotion of management techniques and measures

Management techniques and measures are important means to optimize and control the carbon effects of land use change. Different management techniques and measures will have different impacts on the carbon emission and absorption of land use change[5]. Therefore, it is necessary to evaluate and promote the carbon effects of management techniques and measures, to improve the carbon efficiency and benefit of land use change.

#### 5.1.1. Land use planning and layout adjustment

By rationally planning and optimizing the structure and mode of land use, reducing the carbon emission and increasing the carbon absorption of land use change, such as increasing the proportion of carbon sink land such as forest, grassland, wetland, reducing the proportion of carbon source land such as cultivated land, construction land, improving the spatial agglomeration and functional coordination of land use, etc(Figure 3).

#### 5.1.2. Improvement of land use modes and management measures

By improving the modes and management measures of land use, increasing the carbon storage and sink capacity of land use, reducing the carbon loss and emission intensity of land use, such as using organic fertilizer, straw returning, conservation tillage and other measures, increasing soil organic carbon content, reducing carbon emission; using water-saving irrigation, precision fertilization, green prevention and control and other measures, increasing crop productivity, increasing carbon absorption, etc.

#### 5.1.3. Land use ecological compensation and incentive mechanism

By establishing land use ecological compensation and incentive mechanism, mobilizing the enthusiasm and initiative of all parties to participate in land use change carbon effect management, promoting land use change carbon emission reduction and carbon sink increase, such as establishing carbon emission right trading system, realizing the internalization and marketization of carbon emission, promoting the reduction and low price of carbon emission; establishing carbon sink service payment system, realizing the externalization and monetization of carbon absorption, promoting the increase and high price of carbon absorption, etc.

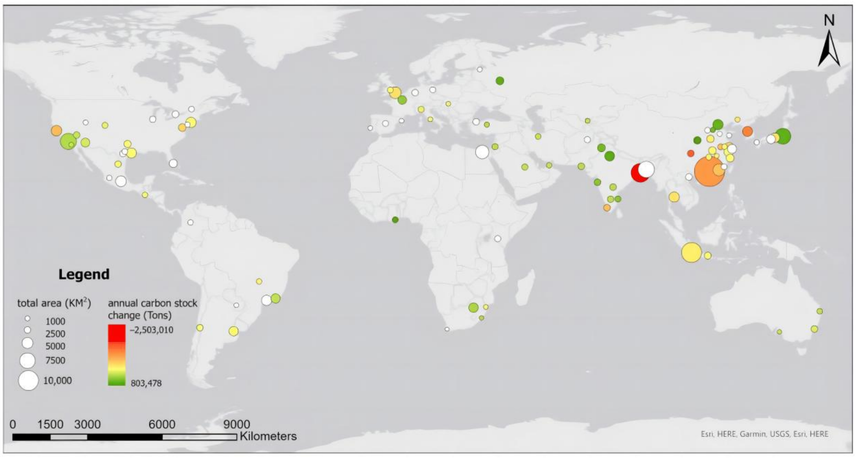


**Figure 3.** Average annual change of land carbon stock in the selected 100 cities from 2013 to 2022[14].

## 5.2. Institutional design

Institutional design is an important way to realize the standardization and guarantee of the carbon effects of land use change. Different policy suggestions and institutional designs will have different guidance and constraint effects on the carbon effects of land use change[9]. Therefore, according to the evaluation results and management objectives of the carbon effects of land use change, reasonable policy suggestions and institutional designs should be put forward, to promote the optimization and control of the carbon effects of land use change. Institutional design can be divided into the following categories:

### 5.2.1. Carbon emission control and reduction target

By formulating and implementing carbon emission control and reduction target, clarifying the limitation and requirement of the total amount and intensity of carbon emission from land use change, promoting the reduction and decrease of carbon emission from land use change, such as formulating and implementing national and regional carbon emission control and reduction target, establishing and improving carbon emission accounting and monitoring system, implementing carbon emission responsibility system and assessment system, etc.

### 5.2.2. Carbon absorption increase and sink target

By formulating and implementing carbon absorption increase and sink target, clarifying the improvement and enhancement of the scale and efficiency of carbon absorption from land use change, promoting the increase and enhancement of carbon absorption from land use change[15], such as formulating and implementing national and regional carbon absorption increase and sink target, establishing and improving carbon absorption accounting and monitoring system, implementing carbon absorption reward system and incentive system, etc.

### 5.2.3. Legal regulations and standards for carbon effect management

By formulating and implementing legal regulations and standards for carbon effect management, clarifying the principles and rules of carbon effect management of land use change, promoting the standardization and guarantee of carbon effect management of land use change, such as formulating and implementing legal regulations for carbon effect management of land use change, establishing and improving standards and norms for carbon effect management of land use change, implementing supervision and law enforcement system for carbon effect management of land use change, etc.

# 6. Conclusion

This study systematically analyzes the impact and mechanism of the carbon effects of land use change on different ecosystem types, different geographic regions, different climate conditions, different land use modes and management measures from different angles and levels, using various methods and models, evaluates the factors such as the size, direction, persistence, and sustainability of the carbon effects of land use change, proposes some evaluation and promotion of management techniques and measures, as well as policy suggestions and institutional designs for the carbon effects, and provides scientific basis and reference suggestions for the optimization and control of the carbon effects of land use change. The main findings and conclusions of this study are as follows:

Land use change is an important factor affecting the global and regional carbon balance and budget. Different land use changes will lead to different carbon emission and absorption, thus affecting the size and direction of carbon effects.

The carbon effects of land use change are affected by various natural and human factors. Different ecosystem types, geographic regions, climate conditions, land use modes and management measures will lead to different differences and heterogeneity of carbon effects.

The evaluation and management of the carbon effects of land use change is a complex system engineering, which requires the comprehensive use of various methods and models, from different angles and levels of analysis and calculation, to improve the accuracy and effectiveness of evaluation, and the feasibility and effectiveness of management

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