Impacts of Human Activities on Carbon Storage in the Irtysh River Basin (Postprint)

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Abstract

Based on land use data from 2000–2020 in the Irtysh River Basin of the Altai Mountains, the InVEST model was employed to simulate and analyze the spatial distribution of carbon storage in the basin across different periods, and to explore the impacts of human activities on the spatial distribution of carbon storage. The results indicate: (1) Grassland and unused land were the dominant land use types within the basin. From 2000 to 2020, the land use pattern underwent significant changes, with cultivated land and urban, industrial, mining, and residential land increasing by 2619.35 km^2 and 186.68 km^2, respectively; grassland and water area increasing by 4725.13 km^2 and 33.47 km^2, respectively; and forest land and unused land decreasing by 2328.88 km^2 and 5237.76 km^2, respectively. (2) During the study period, the spatial distribution patterns of carbon storage within the basin were relatively similar and exhibited a zonal distribution, with high-value areas located in high-altitude regions and low-value areas in low-altitude regions. The total carbon storage in the basin was 641.60 Tg, 645.78 Tg, 646.83 Tg, 650.28 Tg, and 665.91 Tg in 2000, 2005, 2010, 2015, and 2020, respectively, with an annual growth rate of 0.95%, indicating an upward trend. (3) Areas of carbon storage decrease or increase within the basin exhibited a punctate distribution. From 2000 to 2020, the increase in carbon storage exceeded the decrease; therefore, the carbon sequestration capacity of the Irtysh River Basin showed an upward trend.

Full Text

Abstract

Based on land use data from 2000 to 2020 for the Irtysh River Basin in the Altai Mountains, this study employs the InVEST model to simulate and analyze the spatial distribution of carbon storage in the basin across different periods, and explores the influence of human activities on this spatial distribution. The findings indicate that: (1) The primary land use types in the basin are grassland

and unused land. From 2000 to 2020, the land use pattern changed significantly, with cultivated land and urban/industrial/residential land increasing by 2619.35 km^2 and 186.68 km^2, respectively; grassland and water areas increased by 4725.13 km^2 and 33.47 km^2, respectively; while forest land and unused land decreased by 2328.88 km^2 and 5237.76 km^2, respectively. (2) During the study period, the spatial distribution pattern of carbon storage in the basin remained relatively consistent, exhibiting a zonal distribution pattern. High-value areas were located in high-altitude regions, while low-value areas were distributed in low-altitude regions. The total carbon storage in the basin in 2000, 2005, 2010, 2015, and 2020 was 641.60 Tg, 645.78 Tg, 646.83 Tg, 650.28 Tg, and 665.91 Tg, respectively, with an annual growth rate of 0.95%, demonstrating an upward trend. (3) Areas experiencing carbon storage loss or gain were distributed in a point-like pattern. Carbon storage loss primarily resulted from the conversion of forest land and grassland to cultivated land and unused land, whereas carbon storage gain mainly stemmed from the conversion of unused land to cultivated land and grassland. The increase in carbon storage exceeded the decrease during 2000–2020, indicating that the carbon sequestration capacity of the Irtysh River Basin is on an upward trajectory.

Keywords: human activities; carbon storage; InVEST model; Irtysh River Basin

Introduction

To control climate change and achieve sustainable development in China, the Central Economic Work Conference has explicitly identified "achieving carbon peak and carbon neutrality" as a key task for 2021. The carbon sequestration capacity of terrestrial ecosystems directly affects global carbon emissions and climate change processes, and enhancing terrestrial ecosystem carbon storage represents one of the primary pathways for reducing atmospheric CO_2 concentrations. This research focus has attracted widespread attention from governments and scholars worldwide. Human activities alter the carbon sequestration capacity of terrestrial ecosystems by changing land use patterns, becoming a significant factor affecting total carbon storage changes. Existing research demonstrates that at different scales, human activities influence global terrestrial ecosystem carbon cycles in various ways. At the global scale, large-scale deforestation is the main cause of declining global carbon storage. At national and regional scales, the conversion of cultivated land to construction land reduces total carbon storage, while programs such as returning farmland to forests and grasslands and afforestation increase total carbon storage. These two land use transition pathways are key factors affecting total carbon storage changes.

Currently, numerous scholars have conducted extensive research on the carbon sequestration functions of terrestrial ecosystems, and carbon storage estimation methods have become well-established. Methods for estimating soil and vegetation biomass carbon storage primarily include field surveys, remote sensing estimation, and model simulation. Due to the substantial workload involved in surveying soil and vegetation carbon storage and the inability to intuitively reflect the impacts of climate change and land use change on carbon storage across long time series and spatial scales, field surveys are only suitable for small-scale regions or limited sample plots. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, based on land use data, can quantify the spatial distribution of terrestrial ecosystem carbon storage and its influencing factors under different objectives and scenarios, and has been widely applied by numerous scholars. The IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report's Special Report on Climate Change and Land indicates that land use-related carbon emissions account for 23% of anthropogenic greenhouse gas emissions, demonstrating that human activities directly affect land use change, which in turn influences global terrestrial ecosystem carbon cycles. Therefore, managing terrestrial ecosystems is of great significance for identifying optimal land use approaches to enhance ecosystem carbon storage.

In recent years, watershed ecosystem services have received considerable scholarly attention. As a composite system with diverse natural resources and ecosystem elements, estimating different ecosystem services at the watershed scale helps address ecological and environmental issues within the basin. Consequently, this study focuses on the watershed scale, combining temporal and spatial scales to estimate and analyze the impacts of different land use types on terrestrial ecosystem carbon storage. This research contributes to the sustainable development of the watershed environment and promotes optimal land use allocation.

Cold region carbon pools constitute an important component of global carbon reserves, primarily distributed in Arctic, subarctic, and boreal regions, as well as in mid- to low-latitude alpine and plateau areas sensitive to climate change. The Irtysh River Basin, located in the arid and cold region of northwestern China, features rich vegetation types and substantial carbon storage in both vegetation and soil. Due to low mean annual temperatures and slow decomposition rates of soil organic matter, this region represents one of China's areas with high carbon density, highlighting the importance of carbon sequestration in cold regions. The basin represents a typical mountain-desert composite ecosystem with complex terrain, significant regional differences, fragile ecological environments, and extremely important ecosystem service functions. This composite ecosystem provides diverse ecosystem services including water conservation, soil retention, windbreak and sand fixation, water purification, biodiversity, and carbon storage.

1 Study Area Overview

The Irtysh River originates on the southern slopes of the Altai Mountains (Fig. 1) and is the largest river in northern Xinjiang, the second largest river in Xinjiang, and the only international river in China that flows into the Arctic Ocean. The basin is located between 85°30 –90°30 E and 46°55 –49°10 N, with elevations ranging from 300 to 4000 m. The basin is divided into eastern and western sections. The western geomorphological features can be summarized as "two mountains flanking one valley," with the Altai Mountains and Sawur Mountains enclosing the Irtysh River valley. The eastern terrain consists primarily of mountains and plains. The entire basin exhibits a topography that is higher in the north and west, and lower in the south and east.

The Irtysh River Basin lies at the southern boundary of the latitudinal permafrost zone, with a mean annual temperature of approximately 4°C. Mean annual precipitation in mountainous areas can reach about 500 mm, while plains receive approximately 150 mm. The main soil types are brown calcic soil and chestnut soil. The basin encompasses six land use types: cultivated land, forest land, grassland, water area, urban/industrial/residential land, and unused land. Forest vegetation consists primarily of coniferous and broadleaf forests, with main species including Siberian larch (*Larix sibirica*), Siberian spruce (*Picea obovata*), and Siberian fir (*Abies sibirica*). Human activities in the basin are mainly distributed in low-altitude areas and around water systems and lakes.

2 Methods

2.1.1 Land Use Transfer Matrix

The land use transfer matrix reflects transitions between different land use types, showing not only the transfer changes of various land use types within the Irtysh River Basin during different periods but also the sources of each land use type at the end of each period. Its mathematical form is expressed as:

$$S = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{pmatrix}$$

where S is the land use transfer matrix; i and j $(i, j = 1, 2, \cdots, n)$ represent the land use types before and after transfer, respectively; n is the number of land use types before and after transfer; and S_{ij} represents the area converted from land use type i before transfer to land use type j after transfer.

2.1.2 Carbon Storage

The carbon storage module of the InVEST model divides terrestrial ecosystem carbon storage into four carbon pools: aboveground biomass carbon (all living plant materials above soil such as bark, trunks, branches, and leaves), belowground biomass carbon (carbon in living plant root systems), soil carbon (organic carbon in mineral and organic soils), and dead organic matter carbon (litter, downed or standing dead trees). For the purposes of this carbon storage model, extremely unstable carbon in aboveground pools, such as short-cycle annual crops, is temporarily excluded because such carbon pools are relatively small, very stable, or rapidly renewed compared to terrestrial ecosystem carbon pools.

Since the Irtysh River Basin covers a wide area, carbon densities for different land types cannot be surveyed individually. According to the InVEST model user manual, the carbon storage module assumes that the carbon density of the same land use type is constant and does not vary interannually. Therefore, carbon density data for aboveground biomass, belowground biomass, soil, and dead organic matter carbon pools were obtained from model manuals and literature on the Altai Mountains, Ili Valley, and western arid regions. Based on the land use classification of the Irtysh River Basin, average carbon densities for the four carbon pools of different land use types were calculated and statistically analyzed. The total carbon density for each land use type was then multiplied by its area and summed to obtain the total carbon storage in the basin. The calculation formula is as follows:

$$C_i = C_{i,above} + C_{i,below} + C_{i,soil} + C_{i,dead}$$

$$C_{total} = \sum_{i=1}^{n} C_i \times S_i$$

where i represents the i-th land use type; C_i is the total carbon density of the four carbon pools for land use type i ($\mathrm{t \cdot hm^{-2}}$); $C_{i,above}$ is the carbon density stored in aboveground biomass for land use type i ($\mathrm{t \cdot hm^{-2}}$); $C_{i,below}$ is the carbon density stored in belowground biomass for land use type i ($\mathrm{t \cdot hm^{-2}}$); $C_{i,soil}$ is the carbon density stored in soil for land use type i ($\mathrm{t \cdot hm^{-2}}$); $C_{i,dead}$ is the carbon density stored in dead organic matter for land use type i ($\mathrm{t \cdot hm^{-2}}$); S_i is the total area of land use type i ($\mathrm{hm^2}$); C_{total} is the total carbon storage (Tg); and n is the number of land use types.

2.2 Data Sources

Land use data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) with a spatial resolution of 1 km × 1 km. The data were clipped to the study area to obtain land use types, which were classified into cultivated land, forest land, grassland, water area, urban/industrial/residential land, and unused land. Administrative boundary and river data were obtained from the National Earth System Science Data Center (http://www.geodata.cn) to extract vector data for the study area.

2.3 Carbon Density Data

Based on the land use classification of the Irtysh River Basin, carbon density data for the four carbon pools of different land use types were compiled from model manuals and relevant literature [23, 25-27] (Table 1).

Table 1 Four types of carbon densities of different land use types in Irtysh River Basin ($t \cdot hm^{-2}$)

Land use type	C_{above}	C_{below}	C_{soil}	C_{dead}
Cultivated land	5.56	2.23	55.46	1.00
Forest land	35.64	8.91	98.54	3.00
Grassland	3.24	8.10	48.65	1.00
Water area	0.00	0.00	0.00	0.00
Urban/industrial/residential land	0.00	0.00	0.00	0.00
Unused land	0.56	0.14	21.36	0.50

Note: C_{above} is aboveground biomass carbon density; C_{below} is belowground biomass carbon density; C_{soil} is soil carbon density; C_{dead} is dead organic matter carbon density.

3 Results and Analysis

3.1 Land Use Changes from 2000 to 2020

As shown in Fig. 2, grassland is the dominant land use type in the Irtysh River Basin, with an average annual proportion of 49.30%, followed by unused land at 34.37%. Land use types exhibited different temporal trends from 2000 to 2020. Cultivated land area expanded continuously, increasing from 5185.87 km^2 to 7954.56 km^2 (an increase of 2768.69 km^2, or 53.39%). Forest land area showed a decreasing trend, declining from 5625.68 km^2 to 38962.74 km^2, which will impact the ecological environment of the study area. Grassland area first decreased then increased, rising from 43687.87 km^2 to 1845.80 km^2. Water area first expanded then contracted, changing from 1879.27 km^2 to 107.47 km^2. Urban/industrial/residential land area expanded, increasing from 24093.02 km^2 to 29328.78 km^2 (an increase of 294.16 km^2, or 1.22%). Unused land area decreased from 29328.78 km^2 to 24093.02 km^2 (a decrease of 5235.76 km^2, or 17.85%).

Figure 2 [Figure 2: see original paper] Area proportion of land use types from 2000 to 2020

The land use transfer matrix (Table 2) reveals that from 2000 to 2005, the total transferred area accounted for 1.32% of the basin area. Cultivated land increased by 676.22 km^2, primarily from grassland and unused land. Water area decreased by 15.08 km^2, mainly converting to unused land. Urban/industrial/residential land increased by 0.73 km^2. Forest land and grassland decreased by 7.21 km^2 and 547.50 km^2, respectively, mainly converting to cultivated land.

From 2005 to 2010, the total transferred area accounted for 1.61% of the basin area. Cultivated land increased by 815.14 km^2. Urban/industrial/residential land increased by 12.98 km^2. Unused land area decreased by 3.05 km^2, mainly converting to cultivated land. Forest land decreased by 684.93 km^2, while grassland decreased by 6.72 km^2.

From 2010 to 2015, the total transferred area accounted for 2.98% of the basin area. Cultivated land increased by 1505.64 km^2, mainly from grassland and unused land. Water area increased by 97.14 km^2, primarily from unused land and grassland. Urban/industrial/residential land increased by 91.89 km^2, sourced from cultivated land, forest land, grassland, and unused land. Unused land decreased by 1398.28 km^2, mainly converting to cultivated land. Forest land and grassland decreased by 25.64 km^2 and 272.56 km^2, respectively.

From 2015 to 2020, the total transferred area accounted for 32.02% of the basin area. Cultivated land increased by 2619.35 km^2, mainly from grassland and unused land. Water area increased by 33.47 km^2. Urban/industrial/residential land increased by 186.68 km^2, sourced from cultivated land, forest land, grassland, and unused land. Unused land decreased by 5237.76 km^2, mainly converting to cultivated land and grassland. Forest land decreased by 2328.88 km^2, mainly converting to grassland. Grassland increased by 4725.13 km^2, sourced from forest land and unused land.

3.2 Spatial Changes in Carbon Storage from 2000 to 2020

The spatial distribution maps (Fig. 3) show that the carbon storage distribution pattern in the Irtysh River Basin remained relatively consistent from 2000 to 2020, all exhibiting zonal distribution without significant spatial changes. However, in 2020, obvious changes occurred in the spatial distribution of carbon storage, primarily in the western, northern, and southeastern parts of the basin. Areas with higher carbon storage were mainly located in high-altitude regions where land use types are predominantly forest land and grassland, and where human activities decrease with increasing altitude, resulting in less vegetation disturbance and higher carbon storage. Areas with lower carbon storage were mainly distributed in low-altitude regions dominated by unused land, where frequent human activities lead to relatively lower soil and vegetation carbon content.

The total carbon storage in the basin in 2000, 2005, 2010, 2015, and 2020 was 641.60 Tg, 645.78 Tg, 646.83 Tg, 650.28 Tg, and 665.91 Tg, respectively, with an annual growth rate of 0.95%, demonstrating an upward trend.

To visually reflect the spatial changes in carbon storage in the Irtysh River Basin, the spatial change values from 2000 to 2020 were classified into three categories: decrease, no change, and increase. Fig. 4 shows that most areas of the basin experienced no change in carbon storage from 2000 to 2020, with only small areas showing changes that were distributed in a point-like pattern, primarily in low-altitude regions.

In summary, during the conversion of different land use types from 2000 to

2020, most conversions were from unused land to cultivated land, accounting for 54.91% of the total transferred area. The area where carbon storage increased was 1574.91 km^2, accounting for 0.49% of the total basin area. The area where carbon storage decreased was 736.43 km^2, accounting for 0.41% of the total basin area.

Figure 3 [Figure 3: see original paper] Spatial distribution of carbon storage from 2000 to 2020

Figure 4 [Figure 4: see original paper] Spatial distribution of carbon storage change from 2000 to 2020

3.3 Impact of Land Use Change on Carbon Storage

Table 3 shows the changes in carbon storage resulting from land use changes. From 2000 to 2005, carbon storage in the basin increased by 4.18 Tg. In terms of transfer area, the conversion was mainly from grassland and unused land to cultivated land. Grassland conversion to cultivated land decreased carbon storage by 0.49 Tg, while unused land conversion to cultivated land increased carbon storage by 4.10 Tg.

From 2005 to 2010, carbon storage increased by 8.68 Tg. The conversion was mainly from grassland and unused land to cultivated land. Grassland conversion to cultivated land decreased carbon storage by 0.56 Tg, while unused land conversion to cultivated land increased carbon storage by 0.49 Tg.

From 2010 to 2015, carbon storage increased by 9.41 Tg. The conversion was mainly from forest land to grassland and from unused land to grassland. Forest land conversion to grassland decreased carbon storage by 1.29 Tg, while unused land conversion to grassland increased carbon storage by 0.53 Tg.

From 2015 to 2020, carbon storage increased by 0.49 Tg. The conversion was mainly from grassland and unused land to cultivated land. Grassland conversion to cultivated land decreased carbon storage by 0.56 Tg, while unused land conversion to cultivated land increased carbon storage by 0.91 Tg.

Overall, from 2000 to 2020, carbon storage loss was mainly due to the conversion of grassland to unused land and cultivated land, with an average annual loss of 58.81 Tg, indicating that grassland reclamation and desertification are the main causes of carbon storage reduction. Carbon storage gain was primarily due to the conversion of unused land to cultivated land and grassland, with an average annual increase of 64.82 Tg. During this period, the source of cultivated land was mainly from reclaiming unused land, continuously expanding planting areas to increase carbon storage in the basin. The net carbon sequestration exceeded the net release in all periods, indicating that the overall carbon sequestration capacity of the Irtysh River Basin is increasing.

Table 3 Changes of converted area and carbon storage of different land use types from 2000 to 2020

4 Discussion

This study reveals that from 2000 to 2020, the spatial distribution pattern of carbon storage in the Irtysh River Basin remained relatively consistent, while the spatial distribution in 2020 changed significantly compared to other years. The reason lies in the "13th Five-Year Plan for National Economic and Social Development of Altay Region," which concluded in 2020. During this period, the development of characteristic planting industries was encouraged, tourism developed rapidly, urbanization intensified, and the geographical advantages of the basin were fully utilized. Additionally, projects such as returning grazing land to grassland, returning farmland to forests and grasslands, and returning farmland to wetlands were implemented, while protection of Populus euphratica forests, desert shrub forests, and valley forests was strengthened. These measures led to significant changes in land use patterns in 2020 compared to other years, resulting in substantial changes in carbon storage.

Land use change significantly affects terrestrial ecosystem carbon storage in the basin. On the one hand, mutual transfers between different land use types alter the carbon storage of each type. On the other hand, when land use types with low carbon density convert to those with high carbon density, total carbon storage in the basin increases; conversely, it decreases. Grassland, as the most important land use type in the Irtysh River Basin with extensive distribution, represents a huge carbon pool in the study area. Therefore, preventing grassland shrinkage is essential to avoid carbon storage loss. Forest land also significantly impacts carbon storage in the basin, as its soil and vegetation carbon storage is the highest among all land types. Consequently, conversion of forest land to grassland or cultivated land leads to carbon storage loss, representing a carbon release process. In summary, land use change, vegetation types, climate change, and grazing all affect watershed ecosystem carbon storage. Therefore, policies such as returning farmland to forests and grasslands, returning grazing land to grassland, artificial afforestation, and closing hillsides for forest growth should continue to be implemented to effectively increase carbon sink levels.

However, the expansion of cultivated land also introduces uncertainties in water resource supply. Large-scale reclamation of unused land to cultivated land continuously increases planting areas to enhance carbon storage, while simultaneously facing increased agricultural water consumption that depletes water resources. From 2000 to 2020, cultivated land area in the basin continued to expand, and large-scale crop planting affected the readjustment of agricultural water demand. The increase in water demand not only intensifies water scarcity in other sectors but also triggers ecological and environmental problems in the basin. Crop growth requires continuous irrigation and heavy fertilization, leading to soil and water pollution as excess nitrogen, phosphorus, and other elements are washed into soils or groundwater by irrigation water and precipitation. Although the Irtysh River Basin has abundant unused land near water systems, excessive reclamation should be avoided to prevent exacerbating water resource distribution imbalances. The complex relationship between cultivated land and water resources affects the availability of water and soil resources, subsequently impacting the sustainability of agricultural production and the agricultural economy in the basin. As mentioned earlier, reclaiming unused land for cultivated land has both advantages and disadvantages: while it increases total carbon storage, it also consumes more water resources, causing water shortages. Therefore, when expanding cultivated land area, the coupling relationship and matching level between water and soil resources in the basin must be fully considered. Blind exploitation should be prevented to avoid creating new ecological and environmental problems. Coordinated and rational planning of water and soil resources in the basin should be implemented to maximize water resource utilization efficiency and achieve rational use of cultivated land and water resources, ultimately realizing sustainable economic development in the Irtysh River Basin.

This study assesses carbon storage and its changes in the basin from 2000 to 2020 based on the InVEST model. In the model calculations, carbon density is assumed to have no interannual variation, and the carbon density of each component of the ecosystem in the Irtysh River Basin is assumed to remain constant over time. Therefore, changes in ecosystem carbon storage in the basin are mainly due to mutual transfers between different land use types. However, as trees, shrubs, and herbaceous vegetation grow, carbon densities of various components in the basin may continuously increase. Additionally, the InVEST model does not consider carbon density changes in the four carbon pools (aboveground, belowground, soil, and dead organic matter) before and after crop harvest, which may affect the carbon sequestration potential of terrestrial ecosystems. The model only considers carbon density differences among land use types without accounting for spatial heterogeneity within the same land use type, so assessment results only change with land use type transitions. Furthermore, the special environmental conditions of cold regions may exacerbate uncertainties in these estimates. Therefore, future research should strengthen continuous monitoring of carbon density through field plot establishment in the Irtysh River Basin.

5 Conclusions

Using the InVEST model to simulate the spatial distribution of carbon storage and the impact of land use change on carbon storage in different periods, this study reaches the following main conclusions:

1. From 2000 to 2020, the land use types in the Irtysh River Basin were dominated by forest land, grassland, and unused land. The land use pattern changed significantly, with continuous expansion of cultivated land, water area, and urban/industrial/residential land. Grassland area first decreased then expanded, while forest land and unused land areas continued to shrink.
2. The spatial distribution pattern of carbon storage in the basin from 2000 to 2020 remained relatively consistent, while the changed areas in 2020

were mainly located in the western, northern, and southeastern parts of the basin. All periods exhibited zonal distribution patterns, with high carbon storage values distributed in high-altitude areas where forest land and grassland were concentrated, and low values mainly distributed in low-altitude areas where unused land was concentrated.

3. The total carbon storage in the basin in 2000, 2005, 2010, 2015, and 2020 was 641.60 Tg, 645.78 Tg, 646.83 Tg, 650.28 Tg, and 665.91 Tg, respectively, with an annual growth rate of 0.95%, showing an upward trend.
4. Areas where carbon storage decreased or increased in the basin were distributed in point-like and zonal patterns. Carbon storage loss mainly resulted from the conversion of grassland to unused land and cultivated land, with an average annual loss of 58.81 Tg. Carbon storage gain primarily stemmed from the conversion of unused land to cultivated land and grassland, with an average annual increase of 64.82 Tg. The net carbon sequestration exceeded the net release in all periods, indicating that the carbon sequestration capacity of the Irtysh River Basin is on an upward trajectory.

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