



Investigating the impact of land use management on terrestrial carbon emissions in Nanjing city: past trajectories and multi-scenario simulation prediction

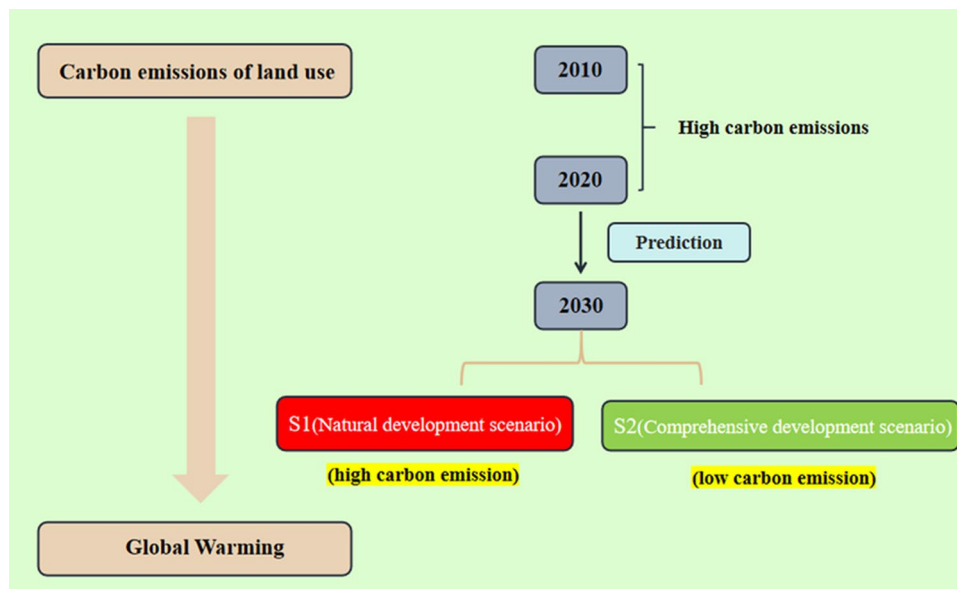
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Abstract

Land-use change is an important factor influencing global climate change and the carbon cycle, and changes in land-use patterns can have a direct impact on global carbon emissions. Therefore, exploring the potential of land use structure optimization and land use management on carbon emission reduction is of great significance in addressing global climate change and achieving carbon emission reduction targets. This paper calculates and analyses the net carbon emissions and evolution characteristics of Nanjing based on the four periods of land use change data in 2010, 2015, 2018 and 2020 using the IPCC carbon emission coefficient method. Then integrates the carbon emissions from land use, land economic and ecological benefits, and establishes a land use structure optimization model under the low-carbon orientation. Finally, the spatial distribution of land use in Nanjing under different scenarios in 2030 is simulated based on the FLUS model.

Graphical abstract



Keywords Land-use change · Carbon emissions · Land-use structure · Linear programming mode · FLUS model

Introduction

Climate warming caused by greenhouse gases such as carbon dioxide is a major problem prevalent in the world today, which has a profound impact on the living environment of human beings and the sustainable development of social economy (Pan et al. 2023). As the world's largest carbon emitter, China has made a commitment to the world to "strive to achieve carbon peaking by 2030 and carbon neutrality by 2060" (Zhu et al. 2021). Currently, land-use change has become the second largest source of greenhouse gas emissions after fossil energy combustion (Xiao and Sun 2023). Therefore, in the context of the "dual-carbon target," China needs to pay attention to the improvement of land-use efficiency and the optimization of the spatial pattern of the national territory, while focusing on strengthening the management of land use (Xia and Chen 2020; Xia et al. 2023).

In recent years, domestic and foreign scholars have also carried out in-depth and systematic research on land use carbon emissions. Early studies mainly focused on the impact of land use changes on carbon emissions (Houghton and Goodale 2004), and later gradually expanded to various elements affecting carbon emissions, such as land use types, management methods, land use modes and so on (Harris et al. 2012). For example, Wang et al. (1999) investigated the impact of the shift between grassland and agricultural land on carbon emissions, and the results showed that the shift from grassland to agricultural land led to a decrease in soil organic carbon content, which in turn contributed to an increase in regional carbon emissions. Wang et al. (2021) adopted the CLU Mondo model to model land use change and carbon emission changes in Fangchenggang City, Guangxi, China, under different policy scenarios for the period 2015–2030, and demonstrated that land use change is an important cause of the rise in annual carbon emissions, and that this phenomenon is more pronounced in highly developed urban agglomerations. Based on this, regarding the content of carbon emissions from land use changes, this paper is more inclined to analyze the change of carbon emissions caused by the change of land use type under different scenarios, so as to reveal the impact of human activities on the carbon cycle.

As one of the core contents of land use planning, the optimization of land use structure is often an important tool in the process of researching the potential impact of land use management on carbon emissions. Chuai et al. (2015b) estimated the carbon emissions and carbon sequestration of various land-use types in the coastal region of Jiangsu by using energy consumption data and land-use data of typical periods, and optimized the land-use structure by using a linear programming model with

the concept of low-carbon development as the guiding principle, and found that the optimized land-use structure effectively reduces carbon emissions. Taking Taixing City, Jiangsu Province as the research object, Yu and Wu (2011) constructed a low-carbon dynamic control land use structure optimization model, and found that this model can effectively meet the needs of maximum efficiency of land resource allocation and sustainable development. Given the enormous pressure on China's share of global carbon emissions (Chuai et al. 2012), it is particularly important and far-reaching to develop plans for optimizing the low-carbon land-use structure for each region of China.

In addition, simulation and analysis of future land use based on quantitative and spatial prediction models has become a research hotspot for carbon emissions in recent years (Lou et al. 2022; Wang et al. 2022a). Some researchers have turned their attention to land use carbon emissions and their spatial distribution over time. Land use distribution and spatial land use patterns are usually combined when modeling and projecting future land use (Li et al. 2022a; Xu et al. 2022a) used the PLUS model to provide an in-depth interpretation and simulation prediction of the expansion behavior of various land use types in Hangzhou, providing a new direction for simulating the city's expansion behavior in the future. Based on the comprehensive application of System Dynamics (SD) model, Patch Generated Land Use Simulation (PLUS) model and InVEST model, Wang et al. (2022b) constructed a dynamic model of land use change and carbon storage quantification in Bortala, China. The study found that by effectively controlling economic growth and population expansion, carbon stocks can be significantly increased. Tang et al. (2020) used both CA-Markov and CLUE-S models to predict the land-use status of Changli County in 2028, and analyzed the spatial and temporal changes and future trends of the habitat quality constrained by land-use, aiming to provide a scientific reference basis for the region's natural environmental protection and land-use planning to provide a scientific reference basis.

In summary, research on the relationship between land use and carbon emissions and the optimization of land use structure under the guidance of the low-carbon concept has achieved certain research results by scholars at home and abroad, but there are still the following areas for further improvement in the current research: firstly, in the optimization of land use structure under the guidance of the low-carbon concept, most of the studies only consider the objective of reducing carbon emissions, while neglecting other benefits of land use. Then, regarding of the optimization of land-use structure, most of the studies only focus on adjusting and optimizing the quantitative structure of land use in the region in the coming period, while the implementation of the optimal scenarios into the regional spatial layout according to the actual regional situation is seldom discussed.

Therefore, this paper will explore the relationship between land use patterns and total carbon emissions based on different land use types, and analyze the impact of land use management on carbon emissions. Land use management refers to a management mode in which the state adopts a series of legal, economic, technical and necessary administrative measures to determine and adjust the structure, layout and mode of land use to ensure the rational use and protection of land resources. Therefore, firstly, land use types were divided into eight categories based on the actual situation of Nanjing and land use carbon budget was calculated according to the land use status of the four periods in 2005, 2015, 2018, and 2020 of the study area. Then, a multi-objective linear programming model of minimizing carbon emission reduction and maximizing economic and ecological benefits of land use is constructed to optimize the quantitative structure of land use in Nanjing. Finally, based on the Geo SOS-FLUS model and combined with national policies, different land use transfer restriction areas are set to simulate the spatial distribution of land use in Nanjing in 2030.

Data and methodology

Representative case

Nanjing is located in the east of China, the southwest of Jiangsu Province, the central affluent area of the lower reaches of the Yangtze River, is a national regional center city, the Yangtze River Delta radiation drive the development of the central and western regions of the country's important gateway city (Fig. 1). The city has 11 districts with a total area of 6587 km². Under the background of the rapid development of the Yangtze River Delta integration, Nanjing has become more and more prominent as a regional central city, and the growing out-migrating population has brought great impetus to the economy, society and urban construction of Nanjing, and at the same time, it has also brought a large amount of carbon emissions to the city. Therefore, this paper selects Nanjing as the study area and explores the potential of land use management on carbon emission from the city scale, which can not only provide

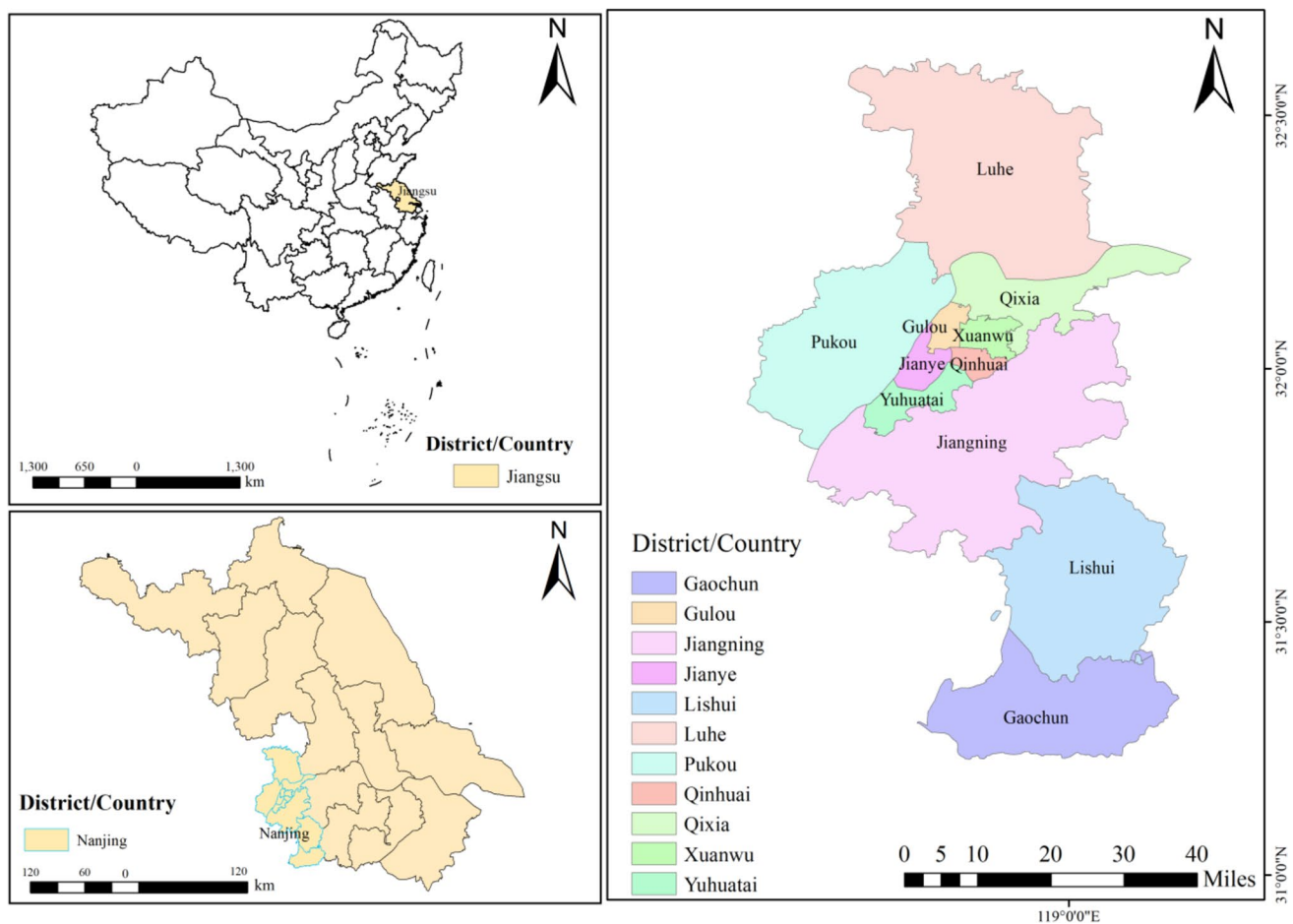


Fig. 1 Location of study area

a theoretical basis for the low-carbon green development policy of Nanjing, but also has a reference significance for other regions of the country.

Data sources

Land-use data: eight land-use types (arable land, woodland, grassland, watershed, urban construction land, rural settlement land, transport and industrial and mining land, and unused land) were established using remote sensing image data with a raster resolution of 30 m × 30 m. Land use types were extracted using ArcGIS, and the remote sensing image data were mainly from the Resource Environment Science and Data Centre (www.resdc.cn).

Basic geographic information data: DEM data (30 m × 30 m) in the study area was obtained from the geo-spatial data cloud website (www.gscloud.cn). The data of national and provincial highways, railway distance, population, and GDP are from the newly released 2020 data from Data Center for Resources and Environmental Sciences (www.resdc.cn) of the Chinese Academy of Sciences, the resolution is 1 km × 1 km. Among them, the slope of the study area, the distance from the study area to the national road, provincial road and railway are calculated by ArcGIS software.

The fossil energy data used in this paper to calculate the carbon emissions from construction land were obtained from the Nanjing Statistical Yearbook (2010–2020).

Calculation of land use carbon emissions

According to the current situation of land use in Nanjing, the carbon emissions of land use in this region mainly come from eight types of land: cultivated land, grassland, forest land, watershed, urban construction land, rural residential land, transportation and industrial and mining land and unused land. Based on the fact that land use has the dual roles of “carbon source” and “carbon sink” at the same time, this paper will use arable land (Shi et al. 2012), urban construction land, rural settlement land, transport and industrial and mining land as carbon sources to calculate carbon emissions and forest land (Li et al. 2022b), grassland (Xu et al. 2022b), watershed (Sun et al. 2015) and unused land (Zhang et al. 2017) as carbon sinks to calculate carbon absorption.

Direct carbon emissions accounting

The carbon emission coefficient method is used to directly account for carbon emissions from arable land, forest land, grassland, watersheds and unused land (it should be noted that arable land has the functions of carbon source and sink at the same time), which are aggregated to obtain the direct

carbon emissions from land use, and the calculation formula is as follows:

$$E_k = \sum e_i = \sum A_i * \partial_i \quad (1)$$

where E_k represents the direct carbon emission; i represents each land use type, which here represents arable land, forest land, grassland, watershed, and unused land; e_i represents the carbon emission absorption of land type i ; A_i represents the area of type i land; ∂_i represents the carbon emission coefficient of land type i . With reference to the research results of relevant scholars (Yang 2021) and combined with the actual situation in Nanjing, the carbon emission coefficient of each land use type is shown in Table 1.

Indirect carbon emissions accounting

Indirect carbon emissions are mainly the carbon emissions generated by human beings in the process of construction land activities (Tian et al. 2021), including fossil energy consumption, electricity consumption and population respiration (Li 2018). The calculation formula is as follows:

$$C_f = \sum n_i * \varepsilon_i * \varphi_i \quad (2)$$

$$C_p = P * \beta \quad (3)$$

$$C_b = C_f + C_p \quad (4)$$

where C_b is the indirect carbon emissions; C_f is the carbon emissions from fossil energy consumption; C_p is the carbon emissions from population respiration; n_i represents the annual consumption of different energy sources; ε_i and φ_i represent different energy conversion factors for standard coal and carbon emissions, respectively; P represents the number of population in Nanjing; β represents the carbon emission's factor of population breathing in Nanjing, based on the results of previous studies, the value is 79 kg/person (Zhou 2011). Due to the fact that it is impossible to accurately count the energy consumed by the three types of land: land for urban construction, land for rural settlements, and land for transport and industry and mines, the indirect carbon emissions are distributed according to the proportion of the area of each land type (51%, 41% and 6.9% of the

Table 1 Carbon emission coefficient of each land use type

Land-use type	Arable land	Woodland	Grassland	Watershed	Unused land
Carbon emission coefficient	0.497	-0.581	-0.021	-0.253	-0.005

Table 2 Carbon emission coefficient of each energy source

Energy type	Raw coal	Coke	Crude oil	Fuel oil	Petrol	Kerosene	Diesel	Natural gas	Electricity
Carbon emission coefficient	0.7559	0.855	0.5857	0.5538	0.5714	0.5921	0.6185	0.4483	0.4040
Standard coal coefficient	0.7143	0.9714	1.4286	1.4286	1.4714	1.4714	1.4571	1.2143	0.7935

weights of the three, respectively). Based on previous studies and current conditions, the following nine major energy sources were selected to calculate such emissions: raw coal, coke, crude oil, fuel oil, petrol, kerosene, diesel, natural gas and electricity (Rong et al. 2022), and the specific coefficients are shown in Table 2.

Total carbon emissions change caused by land use change

Different types of land have different levels of carbon emission intensity, and therefore different levels of carbon emissions (or carbon sequestration) will result from a change in land use type, as calculated by the following formula:

$$C_t = \sum_{ij}^n (V_i - V_j) * S_{ij} \tag{5}$$

where C_t represents the change in total carbon emissions due to changes in land-use types, V_i and V_j represents the carbon emission coefficients for land types i and j , S_{ij} represents the area transferred from land type j to land type i .

Methods

The linear programming model

This paper adopts the multi-objective linear planning method, combined with the actual Nanjing, respectively established the carbon emission target minimization, maximization of economic benefits, minimization of ecological benefits three objective functions, from which to carry out the optimization of land use structure.

$$C(x)_{\min} = \sum_{i=1}^n V_i \times X_i \tag{6}$$

$$E(x)_{\max} = \sum_{i=1}^n b_i \times X_i \tag{7}$$

$$H_x = \left(\sum_{i=1}^n g_i \times X_i \right) / S_L \tag{8}$$

where C is the total carbon emission of Nanjing, E is the total economic output of Nanjing, H is the total green value

Table 3 Coefficient of economic output in 2020

Arable land	Woodland	Grassland	Watershed	Built-up land	Unused land
7.689	3.1597	47.659	2.0001	827.976	0.0001

Table 4 Average green equivalent

Arable land	Woodland	Grassland	Watershed	Built-up land	Unused land
0.5	1	0.49	0.5	0	0.42

of land in Nanjing, V_i represents the carbon emission coefficient of land type i , and is calculated by the carbon emission intensity of each land use type in Nanjing in 2020; b_i represents the economic output per unit of land type i , and is calculated by the unit economic output per unit of land i Nanjing in 2020. The gross product of agriculture, forestry, animal husbandry, fishery and secondary and tertiary industries respectively represents the economic output of cultivated land, woodland, grassland, water area and construction land, and the coefficient of unit economic output value of each land type in 2020 is obtained, as shown in Table 3 for details; g_i represents the average green equivalent of land in category i , as shown in Table 4 (Li 2011). S_L represents the area covered by forest land in Nanjing in 2020 (ha), X_i represents the area of land in category i .

In addition, on the basis of reference to relevant literature (Tao and Zhou 2017; Zhou and Zhao 2018), combined with local land use policies, economic and social development plans, and special planning related to land use in Nanjing (Chuai et al. 2015a), this paper establishes corresponding constraints on 8 variables: the constraints for arable land X_1 , forest land X_2 , grassland X_3 , watershed X_4 , urban construction land X_5 , rural settlement land X_6 , Transport and industrial land X_7 , and unused land X_8 . Here, we define 2020 as the initial year and 2030 as our target projection year.

According to the Nanjing territorial spatial master plan (2021–2035), which will be referred to as the Plan hereafter, the total land area of Nanjing in 2030 will be 658,702 ha, from which the first constraint can be established as:

$$\sum_{i=1}^8 X_i = 658702 \quad X_i > 0 \quad (9)$$

The arable land holding capacity of 1386 km² in the Plan is strictly followed as the lower limit of the arable land area; in addition, the arable land area in the base year (2020) is set as the upper limit. As a result, the arable land area constraints of Nanjing are established:

$$138600 \leq X_1 \leq 335084.77. \quad (10)$$

The protection of forest land is an important measure to improve the ecological environment, so the Plan proposes to focus on strengthening the protection of forest resources and guaranteeing the basic area of forest land, therefore, we take the area covered by forest land in 2020 as the lower limit, and a 10% increase in the area of forest land as the upper limit, to establish the constraints on the area of forest land in Nanjing:

$$66629.34 \leq X_2 \leq 73292.27. \quad (11)$$

Grassland, as a major carbon sink, is of great significance to the construction of a low-carbon green city. According to the requirements of the Plan, the scale of grassland in Nanjing should maintain the status quo. It is calculated that during 2010–2020, the change rate of grassland area is 6.24%, with small fluctuation area. Combined with the actual situation of land management in Nanjing, a change range of 5% is set to establish the constraint conditions of grassland area in Nanjing:

$$5584.18 \leq X_3 \leq 6171.98. \quad (12)$$

According to the requirements of the “Plan,” Nanjing needs to strengthen the construction of ecological protection areas, so it is necessary to strengthen the control of waters with ecological conservation functions to avoid their occupation due to the expansion of construction land. According to the land change in the study area from 2010 to 2020, the change range of Nanjing’s water area is small, only 2.23%, so a change range of 5% is set, thus establishing the constraint of Nanjing’s watershed area:

$$69733.03 \leq X_4 \leq 77073.35. \quad (13)$$

With the development of society and economy, the construction area is bound to expand. According to the growth rate of construction land during 2010–2020, the construction land area in 2030 is predicted to be 201,032.875 ha. From this, the constraints on the total area of construction land in Nanjing are established:

$$175381.28 \leq X_5 + X_6 + X_7 \leq 201032.875. \quad (14)$$

According to the Plan, the urbanization rate of Nanjing will reach 92% in 2030. The size of the entire resident population is 13 million people, and the lower limit of urban construction land is obtained by combining the national urban planning per capital construction land index of 95 m²/person (Xiang and Meng 2013):

$$X_5 \geq 113620. \quad (15)$$

The overall plan of Nanjing’s territorial space requires “actively and steadily promoting the reduction of village construction land, urban low-efficiency industrial land and construction land that affects ecological functions. The average increase and decrease ratio of construction land in 2021–2025 is 1.3:1–1.1:1, and the average increase and decrease ratio of construction land in 2026–2035 is 1.1:1–1:1”. Therefore, the paper predicts that the change range of rural residential land area will be 10% as the lower limit:

$$61599.714 \leq X_6 < 72470.25. \quad (16)$$

In order to ensure the basic transport in the urban area, a 15% change is therefore set as the lower limit to establish the constraints on the area of transport and industrial and mining land in Nanjing:

$$11981.97 \leq X_7 < 13779.27. \quad (17)$$

The average change rate of the unused land area in Nanjing during the three periods of 2010–2015, 2015–2018 and 2018–2020 is about 16%, so the change rate of the unused land area in 2030 is predicted to be 15%:

$$1934.01 \leq X_8 < 2578.68. \quad (18)$$

The Geo SOS-flus model

The Geo SOS-FLUS model consists of artificial neural network (ANN) model and Cellular automaton (CA) model, which is usually used to simulate the land use change pattern in a region (Liu et al. 2017). In reference to related papers, this paper selected three factors of location, nature, and social economic, with a total of seven driving factors (Chen 2020), which are distance to railway, distance to national highway, distance to provincial highway, elevation, slope, population density, and GDP. Then, the neural network algorithm (ANN) is used in the Geo SOS-FLUS model to calculate the probability of each type of land in each pixel in the study area based on the 2010 and 2020 land use grid data and the selected driving force factors, and generate adaptive layers. After that, we use self-adaptive inertia and competition mechanism CA, which comes with the software, to simulate and predict the land use data and spatial distribution in 2020. Here the neighborhood factor

parameters for each land type are 0.6, 0.7, 0.25, 0.65, 0.95, 0.8, 0.6, 0.2 (the scores range from 0–1, and the closer to 1 means that the type of land has a stronger ability to expand); In the simulation, the transfer of construction land to other types of land is restricted, so the corresponding value is set to 0 in the simulation conversion matrix. Then Kappa coefficient test was carried out based on the built-in module of the software, and the result was 0.915 under the above setting conditions, which met the accuracy requirements, indicating that the model could be used to predict the land use status of Nanjing in 2030. In simulating and predicting the land use status in 2030, this thesis sets up two scenarios: natural development scenario and comprehensive development scenario. The natural development scenario, that is, without setting any limiting constraints, is simulated and predicted according to the development trend from 2010 to 2020; the comprehensive development scenario refers to the simulation under the concept of green, low-carbon and recycling economy, and the simulation is carried out by setting up the limiting conversion area according to the basic farmland protection zone and ecological protection red line map given in the Plan.

Results

Changes of carbon emissions

Carbon emissions in typical years

The above formula was used to calculate the carbon emissions of land use in Nanjing in 2010, 2015, 2018 and 2020. During 2010–2020, the carbon emissions of land use in Nanjing showed a general growth trend. From the figure, it can be seen that during the period of 2010–2020, the change trend of land use carbon emissions in Nanjing presents a certain stage, which can be roughly divided into 2 stages: (1) The steady growth stage from 2010 to 2018: under this stage, the land use carbon emissions in Nanjing presents a growth trend, and the carbon emissions increased from 2096.15×10^4 tC in 2010 to 2181.23×10^4 tC in 2018, but

the growth rate is narrowing, and the growth rate also shows a trend of growth followed by a slow decline. (2) The slow decline phase from 2018 to 2020, in which the carbon emission from land use in Nanjing starts to decrease, and the carbon emission decreases from 21.81×10^4 tC in 2018 to 16.59×10^4 tC in 2020, with a large change.

Carbon emissions from different land use types

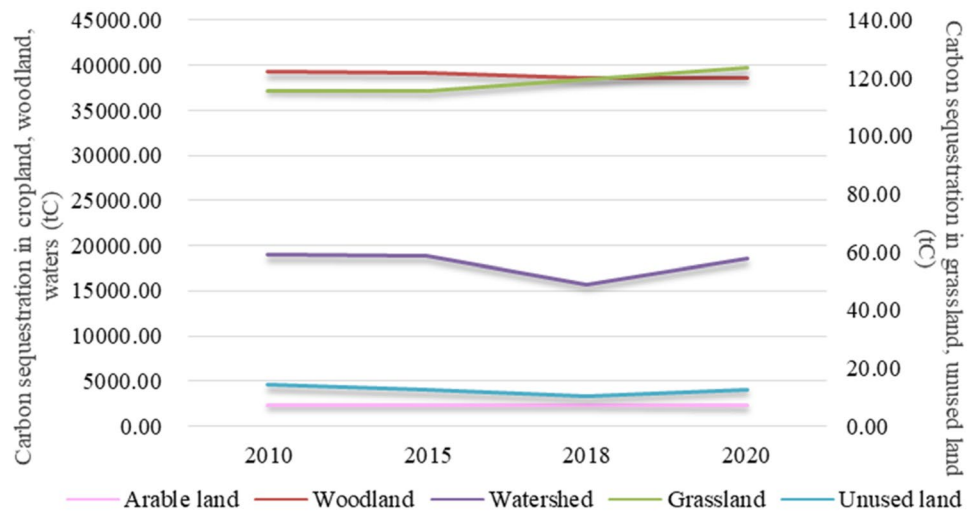
Total carbon emissions from land use are mainly affected by regional carbon emissions and carbon sequestration. According to the actual situation in Nanjing, in these four typical years, arable land, construction land (including urban construction land, rural settlement land, transport and industrial and mining land) are the main sources of carbon, and forest land, grassland, watersheds, and unused land are the main carbon sinks.

From Table 5 and Fig. 2, in terms of carbon sinks, the carbon absorption of land use in Nanjing shows a decreasing trend between 2010 and 2020, with a relatively stable magnitude of change, decreasing from 60,809.19 tC in 2010 to 59,764.58 tC in 2020. From the structure of the land use types, it can be seen that carbon sequestration in woodland decreased from 39,214.21 tC in 2010 to 38,651.15 tC in 2018, with a total decrease of 563.06 tC of carbon sequestration, followed by a small increase to 38,711.65 tC in 2020. Carbon sequestration in watersheds likewise showed a clear downward trend during 2010–2018, with an average annual rate of change of -407.696 tC/a, and then a small increase during 2018–2020. At the same time, during this period, the carbon sequestration of arable land in Nanjing showed a decreasing trend year by year, while the carbon sequestration of grassland showed a slow increasing trend year by year, but the overall changes were not obvious. According to these changes, it can be seen that 2018 was a turning point in the change of carbon emissions in Nanjing, which is mainly due to the rapid economic development of Nanjing during the period of 2010–2018, the continuous improvement of the living standard of the residents, and the urbanization process has entered into the stage of high-speed development, resulting in the frequent occupation of

Table 5 Carbon sequestration by land use types in Nanjing from 2010 to 2020 (tC)

Vintage	Arable land	Woodland	Grassland	Watershed	Unused land	Total
2010	2468.51 4.06%	39,214.21 64.49%	116.19 0.19%	18,996.03 31.24%	14.26 0.02%	60,809.19
2015	2452.20 4.04%	39,173.32 64.55%	115.65 0.19%	18,928.36 31.19%	12.57 0.02%	60,682.10
2018	2450.73 4.30%	38,651.15 67.85%	119.68 0.21%	15,734.46 27.62%	10.66 0.02%	56,966.67
2020	2345.59 3.92%	38,711.65 64.77%	123.44 0.21%	18,571.01 31.07%	12.89 0.02%	59,764.58

Fig. 2 Carbon sequestration by land use types in Nanjing from 2010 to 2020



woodland, watershed, and arable land by construction land. After 2018, with the increasingly tense relationship between land supply and demand, the Nanjing municipal government also paid more attention to the development of low-carbon economy, and released numerous green and low-carbon policies, strictly controlling the scale of construction land, avoiding the damage to the ecological environment caused by the blind expansion of construction land, so that the area of arable land, woodland, watershed, and unused land has risen. This shows that in controlling carbon emissions, government policies and regulations have a great impact on controlling regional carbon emissions, while regions can take the approach of strictly controlling the expansion of construction land and increasing the area of carbon sinks to achieve the purpose of increasing regional carbon absorption and reducing carbon emissions. Meanwhile, during the study period, the carbon absorption of woodland contributes 64.49%, 64.55%, 67.85%, 64.77% to the carbon absorption of Nanjing respectively, which shows that the woodland is the main carbon absorption contributor of Nanjing. Meanwhile, it was found that the carbon sequestration capacity of watershed in Nanjing was also stronger, which was the second largest carbon sink type after forest land. Then, the

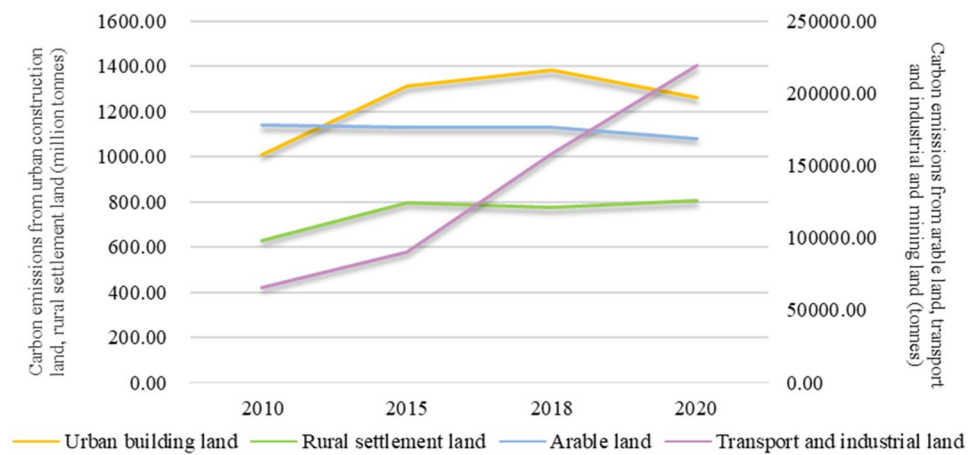
carbon absorption capacity of arable land, grassland and unused land is relatively weak, so their contribution capacity to the carbon absorption of Nanjing is also weak, with the order of contribution being arable land > grassland > unused land.

According to Table 6 and Fig. 3, it can be seen that in terms of carbon sources, the carbon emissions from land use in Nanjing showed an upward trend from 2010 to 2018, increasing from 1664.76×10^4 tC to 2186.93×10^4 tC; it showed a downward trend from 2018 to 2020, but the change was small. During the study period, the carbon emissions from construction land also showed a rising trend followed by a slow decline, but overall it still showed an increasing state, with a total increase of 438.25×10^4 tC, which is 73.3 times of the total carbon absorption in 2020. During the period, the carbon emissions from construction land accounted for 98.93%, 99.17%, 99.19% and 99.2% of the total carbon emissions in Nanjing respectively, of which urban building land was the main carbon source. Meanwhile, arable land mainly shows the function of carbon source during the study period, which also has a certain influence on the carbon emission in Nanjing.

Table 6 Carbon emissions by land use type in Nanjing from 2010 to 2020 (tC)

Vintage	Arable land	Urban building land	Rural settlement land	Transport and industrial land	Total
2010	177,732.41 1.07%	10,098,252.30 60.66%	6,305,365.75 37.88%	66,217.48 0.40%	16,647,567.94
2015	176,558.53 0.83%	13,135,874.97 61.48%	7,962,549.48 37.27%	90,812.54 0.43%	21,365,795.52
2018	176,452.44 0.81%	13,816,078.78 63.18%	7,717,971.54 35.29%	158,778.50 0.73%	21,869,281.26
2020	168,882.72 0.80%	12,619,331.04 60.03%	8,013,905.35 38.12%	219,126.27 1.04%	21,021,245.38

Fig. 3 Carbon emissions by land use type in Nanjing from 2010 to 2020



Carbon emissions variation caused by land use change

The land use type transfer matrix from 2010 to 2020 was established by using the intersection analysis function of ARCGIS software, and the carbon emission change matrix of different land types in the study area was obtained by calculation and sorting in combination with formula 5, as shown in Table 7. It can be seen that during the period of 2010–2020, 25,762.41 hm² of land use types changed, which only accounted for 3.9% of the area of the study area. However, just because of the transformation of this small area of land, the carbon emission of Nanjing will increase by 1,932,188.74 tC per year. The total carbon emission from land use is mainly affected by carbon emission and carbon sequestration. According to Table 7, during the study period, the area of woodland, watershed and unused land as carbon source land decreased, while the area of urban building land, transport and industrial land, rural settlement land as carbon source land increased greatly. This also indicates that with the transformation of each land type in the past 10 years, the carbon sink function of Nanjing has been weakened while the carbon source function has been strengthened at the same time.

Impact of the shift from carbon sink to carbon source on carbon emissions: It was calculated that the carbon loss due to the shift from carbon sink to carbon source during the period from 2010 to 2020 amounted to 231,031.32 tC, of which the transfer of water area caused the most carbon loss, especially the transfer of water area to construction land, which caused a total of 105,194.95 tC and accounted for 45.53% of the total carbon loss. Secondly, although the transfer area of forest land is less than that of water area, as the most dominant type of carbon sink, the transfer of forest land also caused a large amount of carbon loss in the study area during the period.

Impact of the shift from carbon source to carbon sink on carbon emissions: during the study period, a certain scale of

construction land was shifted to land types with stronger carbon sink capacity (e.g., urban construction land was shifted to forest land, urban land was shifted to watersheds, and transport and industrial and mining land was shifted to forests and watersheds, which resulted in the reduction of local carbon emissions by 5703.7 tC, 4229.76 tC, 4171.46 tC, and 7498.12 tC, respectively). To a certain extent, it does enhance the carbon sink capacity of the region, but the reduction of carbon emissions from the transfer of carbon source land category to carbon sink land category is only 22,937.49 tC, which is still unable to offset the amount of carbon loss due to the transfer of carbon sink land category to carbon source land category.

Impact of the internal type shift of carbon source land category on carbon emissions: during the decade of 2010–2020, the construction land showed a continuous expansion trend, and the transfer of arable land was the main source of it, with a total of 191.35 km² of arable land area being converted to the construction land during the period, which was 74.27% of the total transferred area. Through calculation, it can be obtained that the internal type shift of carbon source land category leads to an increase of 172.39×10^4 tC of carbon emissions in Nanjing, among which the urban construction land, rural settlement land, transport and industrial and mining land show a decreasing trend of carbon emissions when they are shifted to arable land, whereas the shift of arable land to reduction land generates a large amount of carbon emissions, about 187.59×10^4 tC.

The effect of type shift within the carbon sink category on carbon emission: during the study period, lands belonging to the carbon sink type also shift to each other, but the calculation results show that the shift within the carbon sink category shows a certain carbon emission effect, the reason is mainly because in this process, more land types with strong carbon sink capacity are shifted to those with weak capacity, which results in a large amount of carbon loss. However, this does not mean that the carbon emission after the transformation is directly related to the scale of the

Table 7 Land use transition matrix and annual emissions change during 2010–2020 in Nanjing

2010	2020								
	Grassland	Arable land	Urban building land	Transport and industrial land	Woodland	Rural settlement land	Watershed	Unused land	Total
Land use transfer (hm ²)									
Grassland	5410.53	7.11	38.43	31.50	1.53	24.57	18.81	0.09	5532.57
Arable land	6.39	332718.31	7395.75	4639.05	271.08	7099.83	501.39	8.46	352640.26
Urban building land	0.27	327.60	82569.42	28.08	40.32	29.34	29.97	0.72	83025.72
Transport and industrial land	0.09	209.16	1.89	6490.62	12.51	5.76	2.43	0.81	6723.27
Woodland	4.05	275.58	279.36	313.74	66220.92	350.73	33.12	16.29	67493.79
Rural settlement land	1.80	859.23	70.92	83.43	37.89	64483.56	68.31	0.81	65605.95
Watershed	454.95	677.25	338.58	358.38	28.71	475.74	72748.35	0.18	75082.14
Unused land	0.00	10.53	234.81	37.17	16.38	0.72	0.81	2551.32	2851.74
Total	5878.08	335084.77	90929.16	11981.97	66629.34	72470.25	73403.19	2578.68	658955.44
Annual carbon emissions transition (t/a)									
Grassland	0.00	3.68	5414.83	448.87	-0.86	2691.25	-4.36	0.00	8553.41
Arable land	-3.31	0.00	1038237.53	63703.43	-292.22	773995.05	-376.04	-4.25	1875260.19
Urban building land	-38.04	-45989.47	0.00	-3556.36	-5703.71	-920.31	-4229.76	-101.44	-60539.08
Transport and industrial land	-1.28	-2872.19	239.37	0.00	-185.27	548.84	-35.19	-11.53	-2317.26
Woodland	2.27	297.08	39518.55	4646.49	0.00	38613.27	10.86	9.38	83097.89
Rural settlement land	-197.16	-93669.82	2224.55	-7949.54	-4171.46	0.00	-7498.12	-88.71	-111350.27
Watershed	105.55	507.94	47784.81	5190.06	-9.42	52220.08	0.00	0.04	105799.06
Unused land	0.00	5.29	33081.21	529.08	-9.43	78.85	-0.20	0.00	33684.79
Total	-131.98	-141717.50	1166500.83	63012.03	-10372.37	867227.03	-12132.81	-196.49	1932188.74

transferred land. According to the calculation, it can be seen that the transferred area of forest land is only 0.53 km², but it can increase the carbon emission by 22.51 tC. Therefore, it can be initially understood that the carbon emission caused by the land use transformation has a greater influence on the carbon sink capacity of the land category where the transformation occurs.

Overall, during the period of 2010–2020, Nanjing showed obvious carbon emission effects due to the shift of land use types, which led to a total increase of 1932.12×10^4 tC of carbon emissions, among which the shift of arable land to construction land made the greatest contribution to the increase in carbon emissions. Secondly, in addition to the obvious carbon emission from the transfer of carbon sink

land use types to carbon source land use types, the transformation within the carbon sink land use types also showed a certain degree of carbon emission during the whole study period, which is related to the carbon sink capacity between the transformed land use types.

Effect of optimized land use structure

In this paper, four scenarios are designed to optimize the land use structure, and LINGO software is used to solve the established objective function and compare it with the land use structure in 2020 (Table 8). Among them, Scenario 1, Scenario 2 and Scenario 3 are the cases that only consider the minimum carbon emissions, the maximum economic

Table 8 Optimization schemes of land use structure in Nanjing city (hm²)

	2020	Option 1	Option 2	Option 3	Option 4
Arable land	335,084.77	312,384.00	313,200.80	320,956.80	306,537.80
Woodland	66,629.34	73,292.27	66,629.34	73,292.27	73,292.27
Grassland	5878.08	6171.98	6171.98	5584.18	6171.98
Watershed	73,403.19	77,073.35	69,733.03	69,733.03	69,700.03
Urban building land	90,929.16	113,620.00	127,451.20	113,620.00	114,783.40
Rural settlement land	72,470.25	61,599.71	61,599.71	61,599.00	72,470.25
Transport and industrial land	11,981.97	11,981.97	11,981.97	11,981.97	13,779.27
Unused land	2578.68	2578.68	1934.01	1934.01	1934.01
Carbon emission (10 ⁴ tC)	2096.15	2289.24	2481.80	2289.84	2428.78
Economic benefit (10 ⁴ Yuan)	148,425,529.91	158,080,305.61	169,502,753.34	158,102,938.23	169,472,541.51
Ecological benefit (green equivalent)	274,836.62	272,128.26	261,932.81	272,185.70	265,247.74

benefits and the maximum ecological benefits, respectively, while Scenario 4 is a comprehensive consideration of the above three cases and is weighted according to the respective degree of importance, and the coefficients of the three objective functions are determined to be 0.5, 0.3, and 0.2, respectively (Song 2017).

Among the carbon emissions from land use, the total amount of Option 2 is the highest at 2481.8×10^4 tC, Option 1 is the lowest at 2289.24×10^4 tC, and Option 4 is ranked the second, which is only 139.54×10^4 tC less than the carbon emissions from Option 1; According to the results of calculating the economic benefits of land use of the various options, it can be seen that Option 2 has the highest economic benefits, and the lowest economic benefits are for Option 1, which are respectively $16,950,275.3 \times 10^4$ yuan and $15,808,030.5 \times 10^4$ yuan, of which Option 4 is second only to Option 2, with $1,139,223.5 \times 10^4$ tC yuan more compared to Option 1; From the analysis of the ecological green equivalent of land use, the green equivalent value is Option 3 > Option 1 > Option 4 > Option 2 in order of magnitude, of which the biggest difference is only $10,252.9 \times 10^4$ yuan. Based on the comprehensive consideration of the carbon,

economic and ecological benefits of land use, Option 4 is more in line with the needs of modern socio-economic construction, and therefore it is selected as the most suitable optimization option.

Comparing the determined optimization scheme with the results of the current land use status quo in 2020, as shown in Table 9, the cultivated land area under the optimization scheme accounts for 46.54% of the total area of the study area, which is $28,546.97 \text{ hm}^2$ less than that of the cultivated land area in 2020, but it also meets the requirement of cultivated land retention in the planning of $138,600 \text{ hm}^2$, which is able to satisfy the local demand for food; the area of woodland and grassland are all This reflects the focus on its carbon sink role in the optimization process, and at the same time, the increase in the area of woodland and grassland can also bring a lot of ecological benefits; for waters and unused land, compared with the status quo in 2020, the waters and unused land under the optimization plan each have an area of 3703.16 hm^2 and 644.67 hm^2 converted to other types of land, which shows that the land utilization rate of Nanjing is also improving; the optimized land use rate is also increasing; the optimized land use rate is also

Table 9 Comparison of land-use structure between the optimized scenario and 2020

Land-use type	Current situation (2020)		Optimization situation(2030)		Variation (%)
	Area (hm ²)	Proportion (%)	Area (hm ²)	Proportion (%)	
Arable land	335,084.77	50.85	306,537.80	46.54	-4.31
Woodland	66,629.34	10.11	73,292.27	11.13	1.02
Grassland	5878.08	0.89	6171.98	0.94	0.05
Watershed	73,403.19	11.14	69,700.03	10.58	-0.56
Urban building land	90,929.16	13.80	114,783.40	17.43	3.63
Rural settlement land	72,470.25	11.00	72,470.25	11.00	0.00
Transport and industrial land	11,981.97	1.82	13,779.27	2.09	0.27
Unused land	2578.68	0.39	1934.01	0.29	-0.10

increasing; the optimized land use rate is also improving; the area of construction land after optimization reaches 201,032.92 hm², account for 30.52% of the total area, an increase of 25,651.54 hm² compared with 2020, which is inevitably related to the rapid development of urbanization in Nanjing.

Low-carbon oriented land use spatial layout optimization simulation

Using Geo SOS-FLUS software, the simulated distribution maps of land use in Nanjing in 2030 under the two scenarios were obtained, as shown in Fig. 4. Compared with 2020, the distribution pattern of land use under the two scenarios changed differently, but the approximate areas of each land type did not change much. Construction land is still mainly distributed in the central and southern areas of Nanjing, with a small portion clustered in the southwest. Cultivated land is

distributed in all areas except the construction land distribution area. Forest land is mostly distributed in the regional boundary zone of Nanjing. Water is mainly distributed in the central part of Nanjing and Gaochun and Lishui districts, with a small amount of water in the western and northwestern parts of the city. Due to the influence of geographic location, grasslands in Nanjing are mainly distributed around water areas. Based on the land use data maps derived from the simulation and extracted using ARCGIS software, the area quantities of each land use type in Nanjing in 2030 under the following two scenarios can be known and compared with the current and optimized land use quantities of Nanjing in 2020, as shown in Table 10.

In the natural development scenario the area of construction land is expanding outward from the original base, and the comparison found that the area of construction land in this scenario is the largest share in all cases, with the area rising by 8 per cent, in which the increase in the area

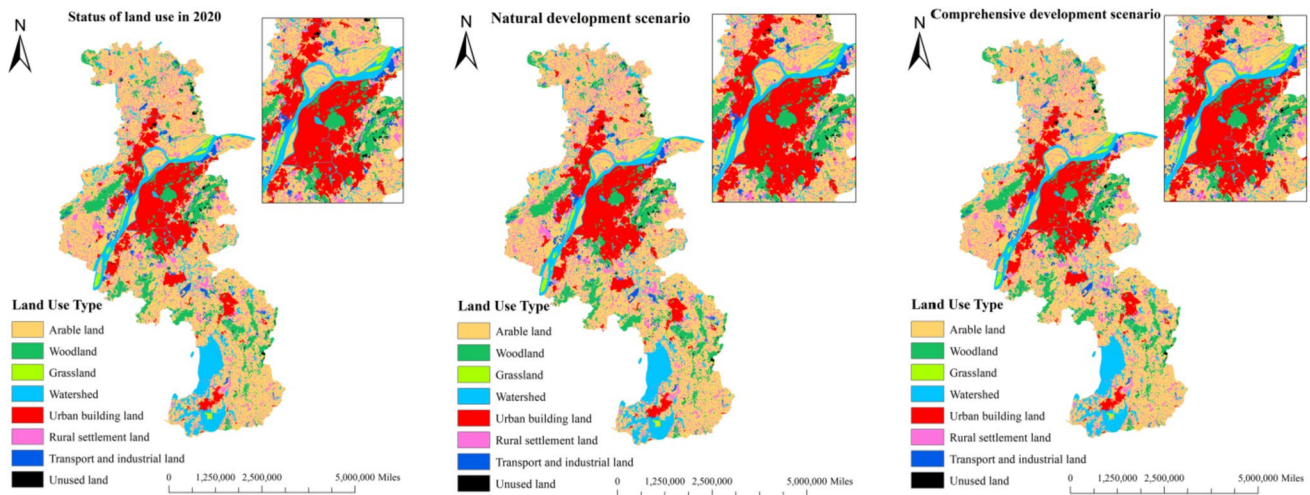


Fig. 4 Simulated spatial distribution of land-use pattern in 2030

Table 10 Comparison of land-use structure in two scenarios with 2020

Land-use type	Land use status in 2020		Natural development scenario		Comprehensive development scenario	
	Area (hm ²)	Proportion (%)	Area (hm ²)	Proportion (%)	Area (hm ²)	Proportion (%)
Arable land	335,084.77	50.85	323,812.35	49.14	333,856.89	50.66
Woodland	66,629.34	10.11	65,767.05	9.98	65,769.84	9.98
Grassland	5878.08	0.89	5837.4	0.89	5642.91	0.86
Watershed	73,403.19	11.14	71,757.36	10.89	71,758.17	10.89
Urban building land	90,929.16	13.80	98,531.37	14.95	93,607.02	14.21
Rural settlement land	72,470.25	11.00	79,047.09	12.00	75,264.03	11.42
Transport and industrial land	11,981.97	1.82	11,843.37	1.80	10,724.76	1.63
Unused land	2578.68	0.39	2359.44	0.36	2331.81	0.35
Carbon emission (tC)	20,961,480.8		22,736,592.54		21,619,380.45	

of urban construction land expands to the northwest as a whole, mainly concentrated in the districts of Xuanwu District, Gulou District, Qixia District, Qinhuai District, Liuhe and other areas. At the same time, it can be seen that compared with 2020, the scenario under the arable land, forest land and water are the main land categories that decrease in area, with a decrease of 11,272.4 hm², 862.29 hm² and 1645.32 hm² respectively, which indicates that the growth of construction land is only formed by the conversion of the above land categories. Therefore, if this trend continues in the future and is not controlled, the area of carbon sinks in Nanjing will be gradually reduced, and the area of land with strong carbon source capacity (e.g., urban construction land, rural settlement land, etc.) will continue to increase, which will lead to a further increase in carbon emissions and bring about great negative impacts.

However, considering other benefits of land, the comprehensive development scenario with restrictions is different. It can be seen that under the integrated development scenario, the land use structure is more rational and there is no significant decline or increase in a particular land type. In particular, the area of land used for construction rises by 2.4%, which is smaller and more concentrated than in the natural development scenario. Among them, the area of urban construction land and the area of rural settlement land are 4924.4 hm² and 3783.1 hm² less than those under the natural development scenario, which indicates that under the comprehensive development scenario, due to the restriction of the transfer of other types of land to the construction land and the addition of the arable land and the ecological restriction transfer area, the trend of the continuous expansion of the construction land due to the socio-economic development is under better control; The area of arable land totals 333,856.89 hm², which is 1227.88 hm² less than that in 2020, but comparing with the amount of arable land under the natural development scenario, it can be found that the transfer out of arable land has been obviously controlled, which makes it possible to coordinate the ecological environment and the economic development of Nanjing; the area of watersheds decreases more in the Lishui and Gaochun districts; and the area of woodlands and meadows has no significant change.

Discussion

Impact of land-use managements on carbon emissions reductions

Land use and change will continuously shape land use patterns and have a profound impact on carbon cycling processes in ecosystems, thus directly causing an increase in carbon emissions. Land-use carbon emissions are closely

related to anthropogenic land management, land-use mode, land-use structure, etc. Therefore, the present study is based on land-use change carbon emissions and covers a wide range of land-use types.

The study shows that with the acceleration of the urbanization and the booming development of social economy, the consumption of all kinds of energy is increasing, and the carbon emission shows a fast-growing trend, which leads to the rapid increase in carbon emission in Nanjing during the period of 2010–2018; and after 2018, the level of urban construction and economy in this period was significantly higher than the previous period, but the carbon emission decreased. The main reason is that, on the one hand, people in that period gradually developed the consciousness of giving equal importance to economic construction and protection of resources and environment, and made more effective use of regional resources under the guiding principle of sustainable development; on the other hand, with the continuous progress of China's science and technology and the emergence of scientific and technological innovations, the application scope of low-carbon technology in our country is more and more extensive. It can be seen that the formulation of relevant policies and the improvement of resource utilization efficiency driven by modern science and technology play a certain role in reducing carbon emissions. With the continuous development of the city, the quantity and structure of different types of energy consumption are also changing, especially in the past ten years, along with the accelerated pace of urban development in Nanjing, the carbon emissions from the construction land in Nanjing have been climbing, with a total increase of 4,382,527.135 tC during the period. Due to the influence of various factors such as land area and carbon sequestration rate, the carbon sink generated by other land types is relatively less significant. The calculation found that the carbon sequestration generated in 2010, 2015, 2018 and 2020 accounted for only 0.365%, 0.284%, 0.26% and 0.284% of the carbon emissions of those years, respectively. Obviously, the carbon sequestration capacity of land type with carbon sink function alone is far from offsetting the impact of rapid expansion of construction land on carbon emissions. Therefore, the future focus of emission reduction in Nanjing should be on maintaining or expanding land types with carbon sinks while strengthening the control of carbon emissions from construction land.

In addition, the 2010–2020 land use transfer matrix shows that land use/cover change is the main factor leading to changes in carbon sources and sinks and thus affecting the regional carbon cycle process (Li et al. 2016). There are some differences in the carbon source/sink capacity of different land types, and the results of the study show that the shift from carbon sink to carbon source land types, the shift from arable land to construction land and the shift within carbon sink land types all contribute to the increase

in carbon emissions in the study area. Among them, the conversion of agricultural land (such as arable land and forest land) to construction land is the main reason for the increase in carbon emissions. During this conversion process, the number of vegetation decreases dramatically, resulting in a significant decrease in the solidification effect of vegetation on atmospheric carbon elements, while vegetation residues release a large amount of carbon and the effect of soil solidification on absorbing organic carbon becomes weak (Johnson 1992). Therefore, the conversion of agricultural land to construction land will lead to a significant increase in carbon emissions. In the process of transformation within the land type with carbon sink, on the one hand, human intervention in farmland tillage will accelerate the decomposition rate of soil organic matter and the above-ground biomass and subsurface biomass of forest are usually more than that of grassland (Qu et al. 2011), so the transformation of forest land to arable land and grassland will produce a large amount of carbon emissions; on the other hand, according to the collation of Table 7, the transformation of arable land to forest land and other land types with carbon sinks can reduce 671.58 tC of carbon emissions per year, which is in line with the finding of many scholars that the conversion of arable land to woodland and grassland will have a positive effect on the increase in organic carbon stock in soil and vegetation, which indicates that in the process of land type conversion with carbon sink effect, the carbon emissions caused by land use conversion have a greater connection with the carbon sink capacity of the transformed land types. Therefore, on the basis of guaranteeing the food security of the population and the red line of basic arable land, the future carbon emission reduction work of Nanjing should strengthen the management from the two aspects of returning arable land to forest and grassland.

At the same time, the shift from carbon source to sink type and the shift within construction land (urban building land, rural settlement land, transport and industrial land) will lead to a reduction in carbon emissions in the study area. Undoubtedly, the shift from land use that emits carbon to land use that absorbs carbon will inevitably lead to the reduction of carbon emission in the region. However, the internal conversion of construction land also resulted in a reduction of 9413.5 tC of carbon emissions per year during the study period. The internal transformation of construction land essentially refers to the transformation of the land that carries the secondary and tertiary industries, which also leads to the adjustment of the industrial structure, the energy consumption and structure of different industries are quite different, and the carbon emissions produced by them are also quite different (Qu et al. 2011). The secondary industry, as the material production sector in China, is the main source of carbon emissions in China, especially the production of heavy industry, while the tertiary industry belongs to

the non-material production sector, which pays more attention to the use of labor resources, and has relatively less energy consumption, and the carbon emissions produced by it are much smaller than those of the secondary industry. From the perspective of energy consumption, to a certain extent, the transformation of Nanjing from the secondary industry to the tertiary industry can achieve the goal of carbon emission reduction. However, the secondary industry, as the main pillar of the national economic development, cannot rely solely on the “retreat from the secondary to the tertiary industry” to achieve the goal of energy saving and emission reduction (Wei and Shen 2008). Therefore, against the background of the “dual-carbon target,” it is necessary for Nanjing to increase its efforts in industrial restructuring in the future, and at the same time pay attention to improving the efficiency of energy utilization in heavy industry.

During the study period, the change of carbon emissions caused by land use change in Nanjing city was obvious, which precisely proves the importance of land use structure optimization for carbon emission reduction. The study shows that the average annual growth rate of carbon emissions caused by land use optimization under the optimal plan is only 0.92%, lower than 2.64% in 2020, which has a huge potential for carbon emission reduction. At the same time, on the basis of quantity structure optimization, this paper also adopts the FLUS model for multi-scenario simulation of the spatial distribution of each land type. According to Table 10, the average annual growth rate is 0.31% after the restricted area is added, which is significantly lower than the current growth rate. This shows that adding human intervention, strengthening land use management, such as limiting the conversion of a certain amount of arable land, and paying attention to the management of forest land and water area can effectively achieve the carbon emission reduction target.

From the perspective of carbon emission, both in the land use structure optimization scheme and in the multi-scenario simulation based on FLUS, with the increase in construction land area, Nanjing’s carbon emissions will also increase, and its carbon emissions will take an increasing proportion in the total net carbon emissions, which also confirms the views of previous studies that the construction land is a key factor influencing the development of the city and the carbon emission reduction (Tayil et al. 2023). Therefore, the government needs to rationally plan the construction land, set up prohibited areas for construction land according to the actual situation, pay attention to the protection of the natural ecological environment in Nanjing, and strictly control the expansion boundary of the construction land (Li et al. 2023). In addition, it can be found that the increase in the area of construction land is mainly derived from the transfer of arable land. In the future, in order to meet the demands of socio-economic development, arable land will certainly continue to show a declining trend. Therefore, on the one hand,

the phenomenon of large-scale occupation of arable land by rural settlements should be reasonably controlled, and on the other hand, with the decrease in arable land, it is necessary to ensure the production of food by actively transforming the medium- and low-yield farmland, innovating science and technology in the field of cultivation, and achieving the goal of high quality and high efficiency.

From the perspective of land use structure, due to the consideration of carbon emission reduction and ecological benefit objectives, a large number of construction land will be transformed into ecological land, such as forest land, grassland and water area, in scenario 1 and scenario 3 after optimization of land use structure. The optimal scheme will be more balanced when considering the economic, ecological benefits and carbon emission reduction targets; under the comprehensive development scenario, after the policy constraints such as basic farmland protection area and ecological protection area are added, the situation of large-scale construction land occupying arable land and forest land has been significantly improved. It can be seen that woodland and grassland are land use types that have a greater impact on carbon sink and have high ecological benefits in the terrestrial ecosystem (Li et al. 2023). To increase the area of woodland and grassland and improve the quality of woodland through reasonable land management and control is an important way to enhance regional carbon sequestration capacity and protect the ecological environment.

Discussion on low-carbon policy

Optimize the land use structure

Based on the results of the land carbon emission accounting in Nanjing, it can be seen that the carbon emissions caused by different land types have large differences, and forest land is the main source of carbon sinks, in the future development strategy, we should make full use of its inherent advantages to maximize its carbon sequestration function; although the carbon sink capacity of grassland and watersheds is relatively weaker, we still cannot be ignored, and in the process of future development, Nanjing should pay more attention to the transformation of this type of land use to give full play to its carbon absorption capacity, thus providing a certain reduction space for land carbon emission reduction. In the process of future development, Nanjing should pay more attention to the transformation of this kind of land use and give full play to its carbon absorption capacity, thus providing certain reduction space for land carbon emission reduction. In other words, in the process of urbanization, the strategy of intensification and land use saving should be implemented within the construction land, and efforts should be made to avoid the phenomenon of blindly expanding the construction land and occupying the carbon

sink land category. After in-depth analyses and summaries of the carbon source and sink land use categories in Nanjing, we believe that other regions can, according to their unique topographical and geomorphological characteristics, explore a land use mode and approach suitable for the region to achieve low-carbon development, and promote the transformation of carbon source land use categories to carbon sink land use categories, so as to better realize multi-purpose land use, multi-objective and dual-carbon objective combinations.

Adjustment of industrial structure and improvement of energy use efficiency

As can be seen from the above, the relatively high share of carbon emissions produced by construction sites in recent years is mainly due to the unbalanced development of the energy industry. Therefore, further optimizing the efficiency of energy use and strengthening energy conservation measures have far-reaching practical significance in addressing resource and environmental constraints, advancing ecological civilization and promoting high quality development. In terms of the overall energy structure of the study area, energy sources with high carbon emission factors such as coal, crude oil and petrol are still the mainstay of energy consumption in Nanjing. Therefore, promoting the development of low-carbon technologies, fostering scientific and technological progress and energy-saving innovations, and improving the efficiency of energy utilization are key ways to reduce carbon emissions. At the same time, the promotion and use of new energy sources, such as wind and water energy, should be actively strengthened, thereby fundamentally reducing energy consumption that leads to increased carbon emissions.

Enhancing low-carbon development policy formulation

Based on the comparison of the four land-use structure scenarios above and the comparison of carbon emissions under the natural development scenario and the integrated development scenario, it can be concluded that the formulation of relevant low-carbon development policies will have a great impact on promoting the transformation of cities to a low-carbon economic development model. Therefore, regions can consider measures such as incorporating green GDP into the government's performance evaluation system to enhance the government's supervision of land use; improving the carbon emission management system for land information; and formulating carbon emission standards for industrial land and creating a carbon trading market, in order to achieve sustainable development of a low-carbon economy.

Conclusion

Under the background of “dual-carbon,” it is necessary to understand the potential of land use adjustment and land use management on carbon emission reduction, so as to realize low-carbon urban development by adjusting land use planning. Therefore, in this study, based on eight different land-use types, carbon emission accounting was conducted for land-use changes in Nanjing in 2010, 2015, 2018 and 2020, and the potential of land-use management in carbon emission reduction was analyzed by simulating with the multi-objective linear planning model and the FLUS model. The main conclusions are as follows:

Through the accounting and analysis of the land use carbon revenue and expenditure in Nanjing, it is found that during the period of 2010–2020, the land use carbon revenue and expenditure of Nanjing City was generally expressed as carbon emission, and the overall trend of growth followed by a slow decline is shown. Among them, forest land and water area are the main carbon sinks in Nanjing, and the contribution rate of construction land as the main carbon source increased from 98.93% in 2010 to 99.2% in 2020, which shows that strictly controlling the scale of construction land and continuously optimizing the land use structure is an effective way to reduce the carbon emissions from land use.

The results of the land use transfer matrix for Nanjing from 2010 to 2020 show that during the study period, the annual carbon emissions in Nanjing increased by 193.29×10^4 tC due to land use changes. Among them, the shift from carbon sink to carbon source, the shift from arable land to construction land, and the shift within carbon sinks all caused the increase in carbon emissions in Nanjing. At the same time, the shift from carbon source land to carbon sink land and the shift within construction land caused a decrease in carbon emissions in Nanjing. Thus, land use changes have a significant impact on carbon emission changes.

Based on the multi-objective linear programming model of carbon emission reduction and economic and ecological benefits of land use, the optimization scheme of land use structure in Nanjing was obtained. The optimal scheme considering the above three cases is the best scheme. Under the optimal scheme, the economic and ecological benefits of land can meet the future development needs of Nanjing, and the average annual growth rate of carbon emission is only 0.92%, which achieves obvious emission reduction effect compared with 2020, reflecting that the optimization of land-use structure has great potential in carbon emission reduction.

The FLUS model simulates the land use distribution under the natural development scenario and the

comprehensive development scenario, and it can be found that: under the unrestricted natural development scenario, the area of construction land will continue to expand outward, occupying a large amount of arable land and carbon sink land. Under the comprehensive development scenario, the land use structure is more balanced and the occupation of arable land is obviously controlled, so that the ecological environment and economic development of Nanjing are coordinated. Meanwhile, the average annual growth rate of carbon emission in the comprehensive development scenario is only 0.31%, which reflects that the growth of carbon emission in Nanjing can be well controlled through the rational management of land use.

Finally, the article obtains some initiatives in terms of carbon emission reduction based on the analysis of carbon emissions from land in Nanjing: first, optimize the land use structure and increase the transformation from carbon source to carbon sink; second, adjustment of industrial structure and improvement of energy use efficiency; third, Enhancing low-carbon development policy formulation.

Overall, this paper provides an in-depth study of the impact of land use management in Nanjing on its carbon emissions, especially from the three dimensions of land use structure, land use change and spatial layout, and provides a reference for other regions of the Yangtze River Economic Belt and those with similar development status to it in achieving the dual-carbon target. At the same time, this study may provide insights for future research in the following ways: due to the many limitations of the FLUS model running in real scenarios, which this study has not yet investigated in-depth. It is suggested that future research could focus more on how to implement the optimized land use quantitative structure into the regional spatial layout.

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Data availability Data are available on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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