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Land Use Carbon Emission Estimation and Simulation of Carbon-Neutral Scenarios Based on System Dynamics in Coastal City: A Case Study of Nantong, China

Qingyun Xu [1] and Kongqing Li [2,*]

[1] College of Public Administration, Nanjing Agricultural University, Nanjing 210095, China; 9212010105@stu.njau.edu.cn
[2] College of Humanities & Social Development, Nanjing Agricultural University, Nanjing 210095, China
* Correspondence: likq@njau.edu.cn; Tel.: +86-138-1542-5968

Abstract: Land use directly affects the carbon emissions and carbon stock of the ecosystem, and indirectly affects the carbon emissions from anthropogenic activities, which occur more frequently in coastal regions. Taking Nantong City as an example, detailed carbon emission projects were classified and calculated for different land use types by combining land use images of five typical years. Based on the complex relationship between land use carbon emissions and socio-economic factors, the system dynamics model (SD) was used to simulate the land use carbon emissions from 2005 to 2060, and to construct carbon-neutral policy scenarios. Compared with inlands, carbon emissions from land use in Nantong are more pronounced than inland areas, and unique land use types, such as shallows, play an important role as carbon sinks. Total land use carbon emissions show an upward trend from 2005 to 2020 and carbon emissions from construction land dominate. Under the natural development condition, the total net carbon emissions of Nantong are about 4,298,250 tons in 2060, failing to achieve carbon neutrality. The scenario with all four policies adjusted (LO, IO, TP, and PC) has the best emission reductions, peaking at 10,949,010 tons of net carbon emissions in 2029 and reducing them to 1,370,202 tons in 2060, which is the scenario closest to the carbon-neutral target. Overall, this study provides a meaningful conclusion for the study of land use carbon emission characteristics and low-carbon pathways in coastal cities, which can guide the formation of government policies.

Keywords: coastal city; land use; carbon emissions; carbon neutrality; system dynamics; policy scenario simulation

Citation: Xu, Q.; Li, K. Land Use Carbon Emission Estimation and Simulation of Carbon-Neutral Scenarios Based on System Dynamics in Coastal City: A Case Study of Nantong, China. *Land* **2024**, *13*, 1083. https://doi.org/10.3390/land13071083

Academic Editor: Nir Krakauer

Received: 23 May 2024
Revised: 14 July 2024
Accepted: 15 July 2024
Published: 18 July 2024

1. Introduction

The problem of global warming has intensified in recent years, exacerbating environmental changes and posing numerous challenges to the sustainable growth of human society [1,2]. As a result of accelerated industrialization and urbanization, carbon emissions in developing nations continue to rise, exacerbating climate change [3,4]. Aware of the stark truth that its carbon emissions have been the highest globally for consecutive years, China has proactively accepted its global obligations by setting the "double carbon target" in motion: achieving "carbon peaking" by 2030 and "carbon neutrality" by 2060 [5]. To achieve thorough decarbonization in the future, China must make efforts including technological innovation, industrial restructuring, land allocation, and spatial planning.

Land use is one prominent human activity that significantly contributes to the release of greenhouse gases [6]. In 2016, the Global Carbon Project (GCP) statistics showed that of the cumulative global carbon emissions from 1870 to 2015, land use change cumulatively emitted 531 $GtCO_2$, accounting for 26.1% of the total [7]. On the one hand, land use change has a significant impact on the soil carbon pool of terrestrial ecosystems by altering the amount of organic matter in the soil and its structural nature [8]. On the other hand, land-based socio-economic activities lead to massive carbon emissions, and human-caused carbon emissions are invariably mirrored in the degree of land expansion within built-up regions [9]. In addition, land use-induced carbon emissions as a "cost" of improving the level of intensive land use, with negative externalities [10], can guide the land use mode in a low-carbonization direction of transformation. In light of this, China is determined to further implement the National Outline of Territorial Spatial Planning (2021–2035) during the Fourteenth Five-Year Plan period, enhance the carbon sink capacity of ecosystems through territorial spatial optimization, and develop a land use structure and spatial pattern system that is focused on creating a low-carbon economy. There exists a highly interconnected correlation between land utilization, sustainable economic progress, and carbon emissions [11]. Therefore, using land use carbon emissions as a starting point to conduct pertinent research and explore the path and mode of low-carbon land use progress will make a substantial contribution to the "carbon neutrality" objective.

In recent years, scholars have conducted extensive research on carbon emissions associated with land use, with a particular emphasis on the carbon effect of land use change [3,12], the measurement of carbon emissions from human activities across various industries and regional levels [13–15], the efficiency and intensity of carbon emissions from land use [16–18], and the mechanism by which land use carbon emissions impact the environment [19,20]. Some scholars have directed their attention toward decreasing carbon emissions by modifying the land use structure, mostly using Gray Linear Programming and Multi-objective Linear Programming methods. Zhao et al. [21] used Multi-objective Linear Programming to propose a land use structure optimization scheme for Nanjing based on three major objectives. Chuai et al. [22] calculated the total carbon emissions in the coastal areas of Jiangsu Province and used a Linear Programming Model to optimize the land use structure. Huang et al. [23] recommended an optimized land use pattern that is low in carbon emissions, based on a predictive planning model and the principles of urban development. Nevertheless, this kind of static model fails to consider that socio-economic factors, carbon emissions, and land use changes are complex and mutually constraining systematic factors, and lacks an in-depth analysis of the feedback mechanism and causality between the factors.

System dynamics (SD), proposed by Forrester, has significant advantages in understanding non-linear, multivariate, and dynamic carbon emission processes [24]. The method has been implemented extensively in the prediction of regional low-carbon economic development models and the prediction of land resource demand under low-carbon requirements. Zeng et al. [25] developed an SD model for reductions in carbon emissions and pollution, and investigated the effects of different policy combinations on regional pollution reduction and carbon reduction in four scenarios. Wang et al. [26] utilized the published scenes for climate change of CMIP6, coupled with the SD model, and the PLUS model to simulate the land use and carbon stock changes in Bortala. Tang et al. [27] used a combination of shared socio-economic pathways and representationally concentrated pathways for three future scenarios, the SD model, and the PLUS model to simulate the land use patterns. However, at present, the application of the SD model in the simulation of municipal land use carbon emissions is still relatively limited.

Climate change-induced sea level rise may make living on the coast a high-risk option. The IPCC's Sixth Assessment Report states that sea level will likely rise by 28–101 cm by 2100. The China Sea Level Bulletin states that the rate of sea level rise along the coasts of China from 1980 to 2021 was 3.4 mm/a, higher than the global level in the same period. Flooding, coastal erosion, shoreline migration, or seawater intrusion may not only severely affect the economic and social development of human communities; they may also have serious impacts on coastal environments and ecosystems. As the center of economic development shifted to coastal areas, the population density and urbanization levels in coastal areas were considerably more than those in non-coastal areas, which was accompanied by a surge in land development intensity and carbon emissions [28,29]. From 2005 to 2019, the coastal region accounted for 45–50% of China's total carbon emissions [30]. In 2021, the "Jiangsu Coastal Area Development Plan (2021–2025)" was issued, putting forth an effort to advance ecological and low-carbon development in Jiangsu's coastal area and helping the Yangtze River Delta region to achieve its dual-carbon goal on schedule. In the context of industrialization and coastal development, the imbalance between demand and supply for land in coastal cities of Jiangsu Province has intensified dramatically, and how to effectively utilize and allocate land and reduce carbon emissions is now an urgent issue that requires a solution. Furthermore, alterations in carbon emissions resulting from modifications in land use and cover along coastlines will be more conspicuous in comparison to those occurring inland and may exhibit distinct coastal attributes [22]. However, research regarding the characterization of carbon emissions resulting from land use and the investigation of low-carbon pathways in coastal cities is limited.

In summary, scholars have undertaken methodical investigations into carbon emissions resulting from land use, which provide a lot of references for this study. However, there are some shortcomings. First, there are fewer studies specifically focusing on the effects of land use alterations in coastal cities on carbon emissions, and only a few studies have considered the carbon emission characteristics of particular land use types in coastal areas, and have not yet established an inventory of municipal land use carbon emission measurements with coastal characteristics. Second, although existing studies have focused on carbon emission reduction scenarios from a land use perspective, most of them only measured the time of the carbon peak, and very few studies measured the carbon neutralization target. Third, for the exploration of emission reduction paths, few studies analyze low-carbon regulation under the integrated policy combination tools, and there is a lack of a carbon emission reduction framework centered on land use regulation and combining socio-economic factors.

To address the aforementioned research deficiencies, this article takes Nantong, a coastal city in Jiangsu Province, as an example, and the main research objectives are as follows: (1) to construct an inventory of land use carbon emissions in line with the coastal characteristics of Nantong and measure the carbon emissions in five typical years; (2) to analyze the spatial and temporal distribution pattern of land use carbon emissions in Nantong by using the land use transfer matrix and the explicit carbon flow model; (3) to use the SD model, construct a land use carbon emission system in Nantong, study the complex relationship between land, economy, environment, energy, and carbon emissions, predict the trend of land use carbon emissions in Nantong from 2021 to 2060, and explore whether Nantong can attain carbon neutrality by 2060 at the level of natural development. Then, we simulate the changes in carbon emissions under different policy combination scenarios to provide practical evidence for the government to scientifically regulate the land use carbon emissions in Nantong, and to inspire other coastal cities to find a carbon-neutral development path.

2. Materials and Methods

2.1. Theoretical Framework

The research design of this study consists of four main steps (Figure 1). First is the allocation of carbon emission projects based on the four major carbon emission sectors identified by the IPCC carbon emission inventory and the major land use types identified in this study. Second, the geographic data and statistical data are used to measure the carbon emissions from land use in Nantong for five typical years. Third, the land use transfer matrix is combined with the explicit carbon flow model to analyze the direction of land use carbon flow during the four periods in the study area, and to reveal the spatial and temporal patterns of land use carbon emissions. Fourthly, an SD model of land use carbon emission is constructed, which includes five subsystems: land, economy, energy, environment, and carbon emission, to predict the net carbon emissions from land use in Nantong from 2005 to 2060, and simulate the carbon emissions under various policy combination scenarios.

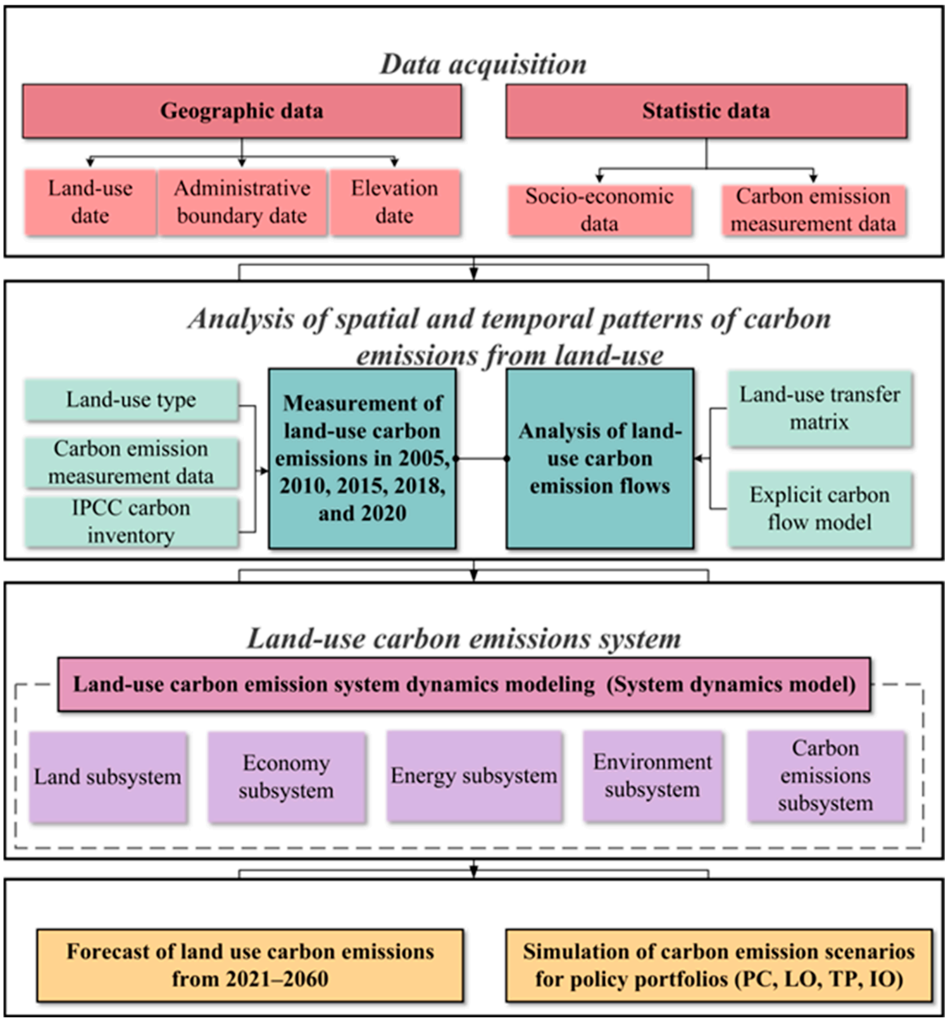

Figure 1. Research framework diagram for this study.

2.2. Study Area

Nantong City is located in the east of Jiangsu Province, at 31°41′06″–32°42′44″ N and 120°11′47″–121°54′33″ E (Figure 2). It has a total administrative area of 18,329.19 km^2, with a land area of 9380 km^2 and a sea area of 8949.19 km^2. Combined with the marine characteristics of land use in Nantong City, this study reclassified the land use types into cropland, forest land, grassland, waters, shallows, construction land, and unutilized land (Figure 3). The Modern Ocean Cities Research Report (2021), released in June 2022, selected 40 representative ocean cities around the world, and Nantong was among them. Located at the intersection of the "T" structure of the coastal economic belt and the Yangtze River economic belt, it has a superior geographic position. As one of the most important coastal industrial cities in Jiangsu Province, its GDP exceeded CNY 1 trillion by 2020, making it the fourth prefecture-level city in Jiangsu to achieve this goal, and the most economically developed of the three coastal cities in the Jiangsu coastal area. Rapid industrialization and urbanization have brought a series of problems to Nantong, such as the massive expansion of construction land, resulting in the extensive use of land resources and excessive energy consumption.

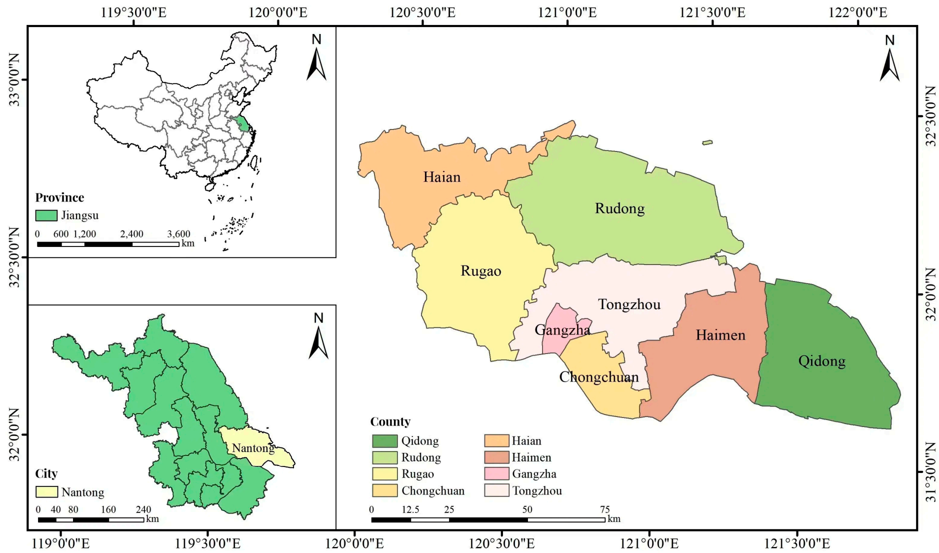

Figure 2. The location of Nantong.

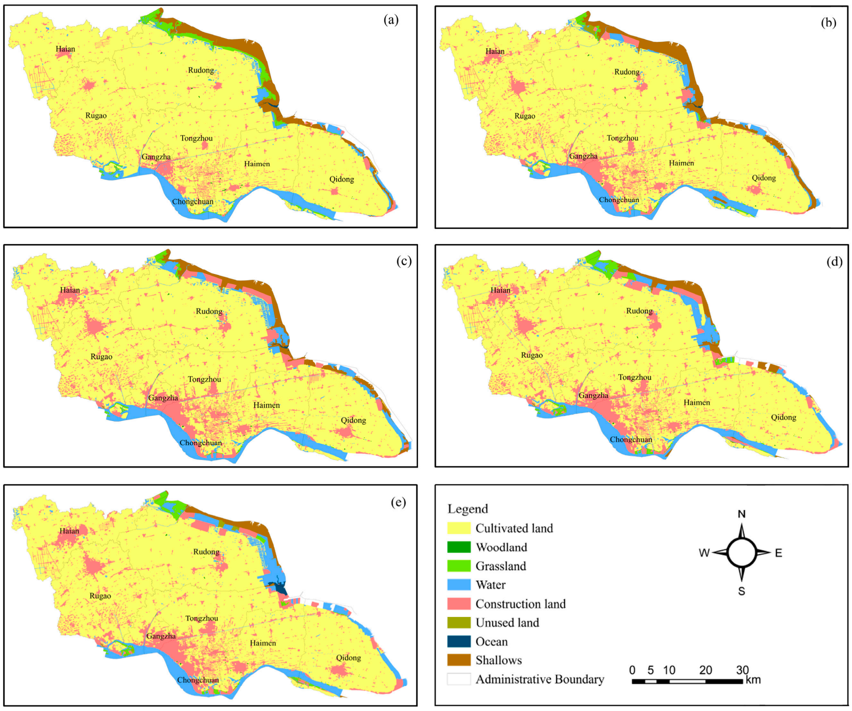

Figure 3. Land use spatial distribution in Nantong: (**a**) 2005; (**b**) 2010; (**c**) 2015; (**d**) 2018; (**e**) 2020.

2.3. Data Acquisition

(1) Raster data: Nantong's 5-period land use data (30 m) for 2005, 2010, 2015, 2018, and 2020 were obtained from the Resource and Environment Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 14 April 2024).

(2) Vector data: The vector data of the administrative boundary of Jiangsu Province and Nantong City were obtained from the Geographical information Monitoring Cloud by Platform (https://www.resdc.cn/, accessed on 17 April 2024).

(3) Statistical data: Socio-economic data such as GDP, fixed-asset investment, investment in science and technology innovation, and population, as well as carbon emission accounting data such as energy consumption, fertilizer use, pesticide use, agricultural film use, animal stock, crop production, and industrial product production were all

derived from the Nantong Statistical Yearbook (2006–2021) and the Jiangsu Provincial Statistical Yearbook (2006–2021).

2.4. Allocation of Carbon Emissions to Different Land Use Types

The IPCC identifies four sectors that contribute to carbon emissions: (1) Energy, (2) Industrial Processes and Product Use, (3) Agriculture, Forestry, and Other Land Use, and (4) Waste, which all require land as a spatial carrier. Based on the regional development features of Nantong, we established a correlation between land use categories and carbon emission projects (Table 1). The construction land discussed in this paper mainly includes urban and rural residential land, industrial, mining, and warehousing land, and transportation land. According to the actual situation of rural farming in Nantong, animal husbandry activities are mainly carried out in rural settlements, so this paper categorizes the carbon emissions related to animal husbandry into construction land. In addition, waste mainly comes from industry and households, exists in the form of wastewater and solid waste, and is carried by urban and rural residential land and industrial land, so we also categorize its carbon emissions into construction land. Carbon emissions from unutilized land were not measured in this study due to its limited scope and lack of data information.

Table 1. Correspondence between land use types and carbon emission items.

Land Use Type	Energy Consumption	Industrial Processes and Product Use	Agriculture, Forestry and Other Land Use	Waste
Cropland	Agricultural energy	—	Rice methane, agricultural activities and crop carbon absorption	—
Woodland	—	—	Carbon absorption	—
Grassland	—	—	Carbon absorption	—
Water	—	—	Carbon absorption	—
Construction land	Industry, construction, wholesale and retail trade and food services, transportation, storage, post and telecommunications	Industrial production	Livestock farming in rural settlements	Wastewater and waste treatment from industry, urban households and rural settlements
Shallows	—	—	Carbon absorption	—

2.5. Calculation of Land Use Carbon Emissions

2.5.1. Calculation of Net Carbon Emissions from Cropland

Cropland functions as both a carbon absorber and a source, and carbon emissions originating from cropland are predominantly attributed to carbon discharges occurring during agricultural production processes. Hence, following the approach proposed by Zhao et al. [31] and Zhai [32], the formula for quantifying carbon emissions on cropland is as follows:

$$C_T = S_r \cdot A \cdot 12/16 + S_i \cdot B + G_f \cdot C + U_p \cdot D + S_m \cdot E + P_m \cdot F \quad (1)$$

where C_T represents the total carbon emission from cropland utilization, S_r is the sown area of rice, S_i is the irrigated area, G_f represents the discounted amount of fertilizer application, U_p represents the amount of agricultural film used, S_m represents the planted area of crops, and P_m represents the total power of agricultural machinery. A is the emission coefficient of methane for rice, and it is taken as the emission coefficient of the single-season rice area of the Jiangsu region, which is 0.365 t/hm^2; B, C, D, E, F are the coefficients of carbon emissions, which were taken as 0.26648 t/hm^2, 0.8956 t/t, 5.180 t/t, 0.01647 t/hm^2, 0.00018 t/hm^2, respectively, and 12/16 is the carbon conversion factor.

Plants take up carbon dioxide through photosynthesis while they are growing and developing. In this study, seven major crops in Nantong were selected for carbon sink estimation. According to the research results of Sun et al. [33] and Zhao et al. [31], the economic coefficients, root–crown ratios, carbon contents, and moisture coefficients of the crops are shown in Table 2. The specific calculating formula is as follows:

$$C_A = \sum_i [C_i \cdot W_i \cdot (1 - H_i) \cdot (1 + R_i)] / M_i \tag{2}$$

where C_A stands for cropland carbon uptake, i is the ith crop type, n is the number of crop species, C_i is the carbon content rate of the ith crop, W_i is the crop yield of the ith crop, H_i is the moisture coefficient of crop i, R_i is the root–crown ratio of crop i, and M_i is the economic coefficient of crop i.

Table 2. Estimation coefficients of carbon sequestration of major crops in Nantong.

Crop	Paddy	Wheat	Corn	Soybean	Cotton	Rapeseed	Peanut
C	0.41	0.48	0.47	0.45	0.45	0.45	0.45
M	0.45	0.40	0.40	0.35	0.10	0.25	0.43
R	0.60	0.39	0.16	0.13	0.12	0.04	0.72
H	0.12	0.12	0.13	0.13	0.08	0.10	0.10

Net carbon emissions from cropland land use can be obtained by subtracting carbon sequestration from carbon emissions.

2.5.2. Calculation of Carbon Emissions from Construction Land

Construction land includes residential, industrial, mining, warehousing, and transportation land. Its carbon emissions mainly come from various production and living activities carried out by human beings on the construction land.

1. Carbon emissions from livestock farming

The primary livestock grown in Nantong include cattle, pigs, sheep, donkeys, and poultry. Enteric fermentation in ruminant livestock (cattle and sheep) encompasses over 80% of the overall gastrointestinal CH_4 emissions of all livestock [34]. Enteric fermentation in non-ruminant livestock (donkeys), monogastric livestock (pigs), and poultry produces a very small amount of CH_4 and can be disregarded. According to the results of Chuai et al. [22] and Yao et al. [34], the measurement formula is as follows:

$$C_F = N_i \cdot (V_i + E_i + F_i) \tag{3}$$

where C_F represents carbon emissions from livestock farming, N_i represents the number of animals, and the carbon emission coefficients of respiration, enteric fermentation, and animal feces are denoted as V_i, E_i, and F_i, respectively (Table 3).

Table 3. Estimation coefficients of carbon emissions of major animals (t/a).

Animal Type	Cow	Pig	Sheep	Donkey	Poultry
V	0.796	0.082	0.0042	0.037	0.013
E	40.75	—	3.75	—	—
F	1.34	0.57	0.11	0.45	0.01

2. Carbon emissions from energy consumption

Compared with other types of land, construction land has the highest energy-related carbon emissions. According to the characteristics of energy consumption in Nantong and based on the calculation method of IPCC and Zhai [32], the formula is as follows:

$$C_E = \sum_i (Q_i \cdot \alpha_i \cdot \gamma_i) \tag{4}$$

where C_E is the carbon emission from energy consumption, i is the ith energy type, Q_i is the energy consumption of i, γ is the factor of standard coal discount for i, α_i is the carbon emission factor of standard coal per unit of category i energy (Table 4).

Table 4. Carbon emissions of coefficients of various energy types.

Energy Type	Standard Coal Factor (kg Standard Coal/kg)	Carbon Emission Factor (kg/kg Standard Coal)
Raw Coal	0.7143	0.7559
Finely washed coal	0.9000	0.7559
Coke	0.9714	0.8550
Coke Oven Gas	0.5714	0.3548
Other Coal Products	0.6000	0.7669
Gasoline	1.4714	0.5538
Kerosene	1.4714	0.5714
Diesel oil	1.4571	0.5921
Fuel oil	1.4286	0.6185
Liquefied Petroleum Gas	1.7143	0.5042
Natural Gas	1.3300	0.4483
Liquefied Natural Gas	1.2140	0.5042
Other Petroleum Products	1.2000	0.5857

3. Carbon emissions from industrial process and product use

Industrial activities produce industrial products and release carbon emissions through the chemical or physical transformation of materials. Their carbon emissions can be determined by multiplying the number of products by a production-based emission factor. This paper mainly adopts the results of Chuai et al. [22] for parameter estimation. According to the characteristics of industrial production in Nantong, this paper mainly collects the carbon emissions of five products, and their calculation formula is as follows:

$$C_I = Q_i \cdot K_i \tag{5}$$

where C_I is the amount of carbon emissions from industrial production i, Q_i is the quantities of production i, and K_i is the emission factor in the process of product i (Table 5).

Table 5. Carbon emission factors for major industrial processes (t/t).

Industrial Product	Steel	Cement	Fiberglass	Synthetic Ammonia	Aluminum
Carbon Emission Factor	0.289	0.037	0.057	0.893	0.436

4. Carbon emissions from waste.

Currently, China commonly employs three waste treatment methods: landfilling, incineration, and composting. The initial two are the primary contributors to carbon emissions from waste treatment, releasing CH_4 and CO_2, respectively [35]. Furthermore, the process of treating wastewater also has a role in the release of methane and carbon dioxide gases. According to Zhao et al. [36], the formula is as follows:

$$C_W = Q_B \cdot V_B \cdot T_B + Q_L \cdot V_L \cdot W_L + Q_C \cdot V_C \cdot 12/16 \tag{6}$$

where C_W represents the carbon emissions from waste; Q_B, Q_L, and Q_C represent the amount of waste incineration, landfill, and the chemical oxygen demand (COD) of wastewater, respectively; V_B, V_L, and V_C represent the CO_2 emission coefficient, the CH_4 emission factor, and the wastewater methane emission parameter, which are taken as 0.99945, 0.167, and 0.25 kg/kg COD, respectively; T_B and W_L are the carbon content of the waste and the carbon content of water, which are taken as 45% and 28%. T_B and W_L are the carbon content of waste and water, respectively, which were taken as 45% and 28.5%.

In conclusion, total carbon emissions from construction land can be expressed as:

$$C_B = C_F + C_E + C_I + C_W \quad (7)$$

2.5.3. Calculation of Carbon Sequestration from Other Land Use Types

Grasslands, waters, and woodlands are commonly acknowledged as carbon sinks. Furthermore, the carbon sequestration function of the community vegetation dispersed throughout the shallows along the coast of Nantong is significant; thus, the shallows are acknowledged as carbon sinks in this study. Based on the carbon emission factors derived from Zhao [36] and Fan [37] (Table 6), the following carbon sequestration was computed:

$$A_i = S_i \cdot \beta_i \quad (8)$$

where A_i is the carbon sequestration rate of type i land, S_i is the area of type i land, and β_i is the carbon emission factor of type i land.

Table 6. Carbon emission factors for carbon sink land types (t/hm^2).

Land Use Type	Woodland	Grassland	Water	Shallows
Carbon Emission Factor	0.289	0.037	0.057	0.893

2.6. Analysis of Carbon Flow for Different Land Use Types

2.6.1. Land Use Transfer Matrix

The land use migration matrix is a tool that can accurately depict the extent of reciprocal transformation among different land use categories in a certain location over a given period.

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1n} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \dots & S_{nn} \end{bmatrix} (i, j = 1, 2, 3 \dots n) \quad (9)$$

where i and j are the two types before and after transfer, S_{ij} represents the area transferred from i to j, S_{11}, $S_{22} \dots S_{nn}$ represents the area where there is no change in land use type.

2.6.2. Explicit Carbon Flow Model

The explicit carbon flow model [23] facilitates the visualization of the carbon transfer law between various land use types, which is introduced in this paper to assess the carbon emission impact of different land use types with greater precision.

$$\begin{gathered} f_{ij} = \Delta W \cdot \Delta S \\ \Delta W = W_j - W_i = \frac{V_j}{S_j} - \frac{V_i}{S_i} \end{gathered} \quad (10)$$

where f_{ij} represents the "carbon flow" from land type j to i, ΔW is the density of carbon metabolism from land type j to land type i, ΔS represents the area of land use type conversion, W_j and W_i represent the density of carbon flow from land type j and i, respectively. V_j and V_i represent the carbon emissions of land type j and land type i. If $\Delta W > 0$, it means that the "carbon sink" increases, which is a positive "carbon flow"; if $\Delta W < 0$, it means that the "carbon sink" decreases or the carbon emission increases.

2.7. Simulation and Modeling of Land Use Carbon Emission System

2.7.1. System Dynamic Model

The distinguishing characteristic of system dynamics is its ability to capture the interactions between the structure, function, and dynamic behavior of complex systems [24]. In this study, the model is delineated by its spatial boundary as Nantong City, its temporal boundary spanning from 2005 to 2060, the simulated base year being 2005, the primary historical data period comprising 2005 to 2020, and the simulated forecast period extending from 2021 to 2060. The principal trends of land use carbon emissions in Nantong from 2021 to 2060 are simulated using the Vensim PLE 10.1.3 software. Subsequently, scenario simulation is conducted by manipulating the controllable parameters to assess the extent of variation in land use carbon emissions across various simulation scenarios. The land use carbon emission system is determined by the interaction between five subsystems: land subsystem, energy subsystem, environmental subsystem, economic system, and carbon emission subsystem.

The five subsystems contain a variety of complex causal relationships. For example, there is a causal relationship between the economic subsystem and the energy subsystem. The growth of industrial energy consumption drives the growth of the economy, while the growth of the industrial economy also drives industrial energy consumption, and there is a positive promotional relationship between them. There is also a causal relationship between the land subsystem and the environmental subsystem, in the process of land development, and utilization of carbon emissions will lead to changes in the climate environment, and environmental pollution will be through the environmental policy and other behaviors to counteract the development and utilization of land resources, thereby reducing carbon emissions. In addition to the causal relationships mentioned above, there are also various causal relationships between and within other subsystems, and this study realizes the model simulation by exploring the interaction of these causal relationships. The causality of the model is shown in Figure 4.

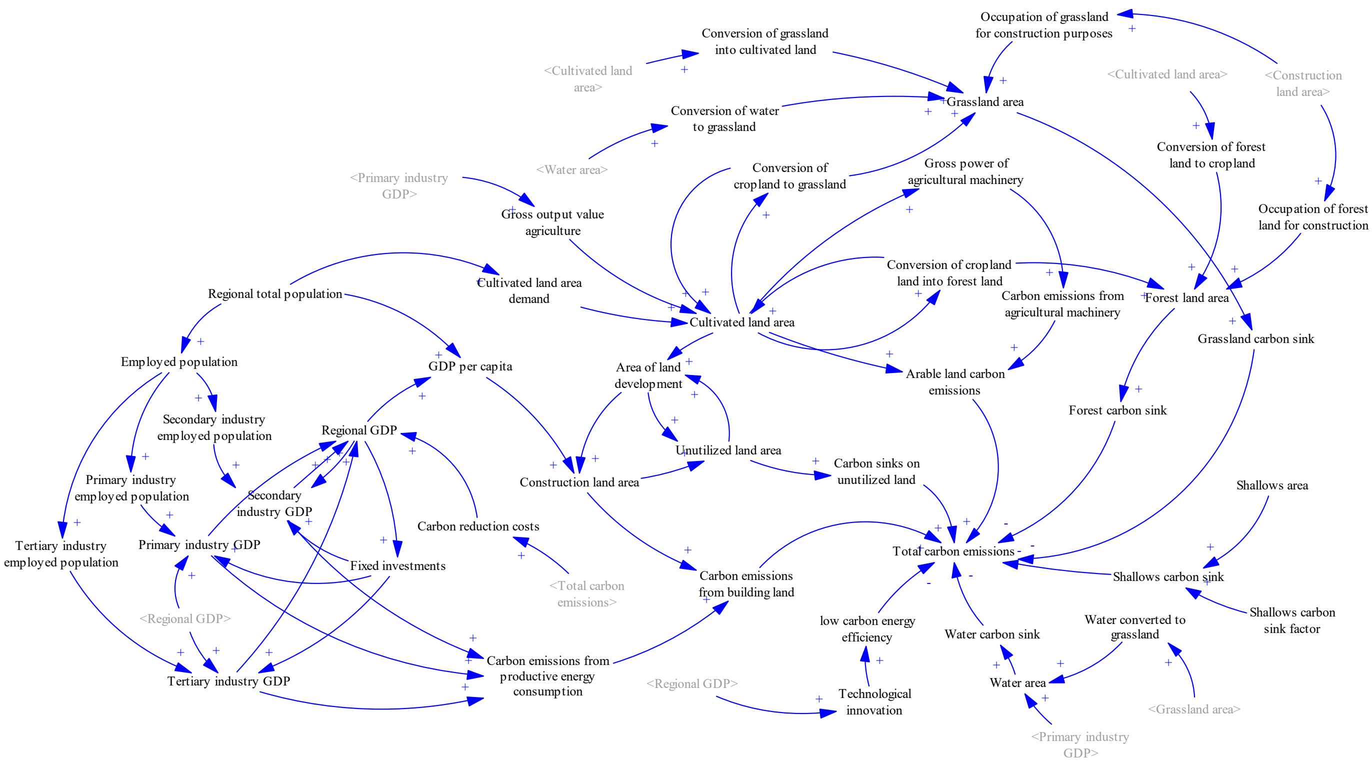

Figure 4. Causality in land use carbon emission system.

Based on the causal feedback relationship analysis of the land use carbon emission system in Nantong City, the variables and parameters of each subsystem are further clarified and set to construct the stock flow diagram of the land use carbon emission system. Among them, the land subsystem includes 22 variables, including the area of various land use types, the amount of change of various land use types, and the rate of change of various land use types; the economy subsystem involves 26 variables, including the regional GDP, GDP of the three industries, investment in social fixed assets, the total population, and the mortality rate and birth rate of the population; the energy subsystem includes 10 variables, including the total amount of consumption of various energy sources, and the amount of energy consumption per unit of GDP; the environmental subsystem involves 15 variables, such as the total amount of garbage, changes in financial investment in science, technology, and innovation, and the amount of harmless garbage treatment; and the carbon emission subsystem includes 67 variables, such as the carbon emissions of each project, the carbon emission coefficient, the amount of carbon absorbed, etc. Then, the corresponding equations of the land use carbon emission system were established, and the initial values of the horizontal variables in the model were adopted from the statistical data of 2005, while the other parameters were mainly determined by the methods of table function, empirical formula, and linear regression. In Vensim PLE 10.1.3 software, the SD model of land use carbon emissions was constantly adjusted and modified, so that each subsystem in the SD model and the internal factors of the subsystems were combined, and the stocks and flows of the model shown in Figure 5 were drawn.

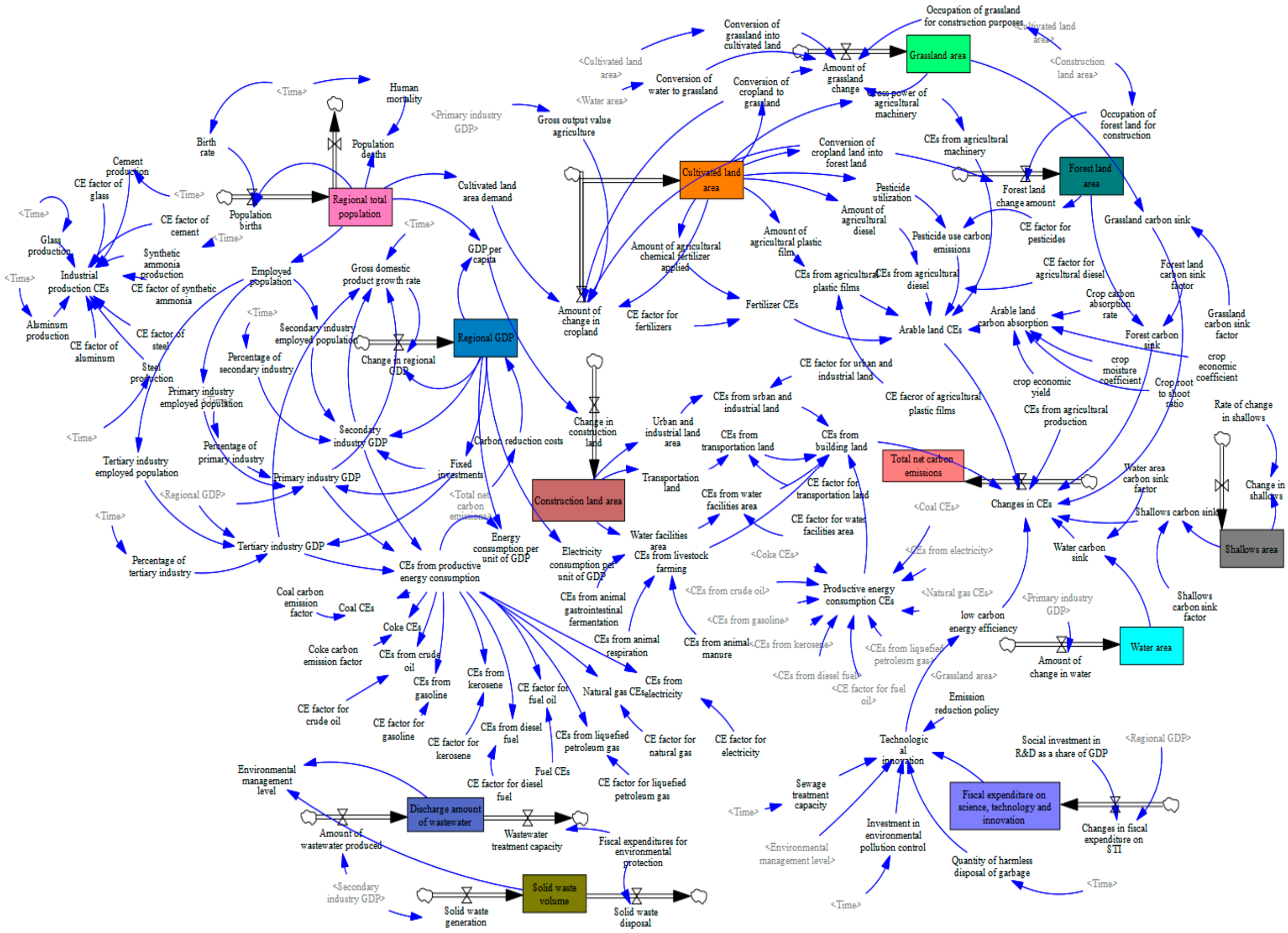

Figure 5. Stocks and flows in the land use carbon emission system (The boxes with cloudy graphs at either end of the figure refer to inventory, which is something in the real world that can accumulate

or decrease over time, and it indicates the state of an environmental variable at a given point in time. No boxes indicate flows, which represent the rate of change of inventory over time. Gray indicates shaded variables (i.e., variables that have appeared and reappeared in the model). Two variables are connected by arrows to indicate that the two variables are causally related, with each arrow containing a functional relationship).

2.7.2. Policy Simulation

Policy simulation is the process of changing the parameters of one or more influencing factors under certain conditions and performing numerical simulations using Vensim software, comparing them with the set objectives, and finally comparing the extent to which each factor exerts influence according to the set environmental conditions, to provide valuable recommendations. Using policy simulation, we can explore pathways for lowering land carbon emissions in Nantong. This study adjusts the parameters of four policies in the model (Table 7), namely population size control, land use structure optimization, advances in science and technology, and industrial structure optimization, and differentiates the combinations to investigate potential carbon emission reduction strategies for Nantong's future development.

Table 7. Parameter adjustments.

Program	Specific Planning Objectives
Optimization of industrial structure (IO)	Fixed investment in the primary sector remains unchanged, fixed asset investment in the secondary sector declines by 20%, and fixed asset investment in the tertiary sector rises by 20%.
Progress in science and technology (TP)	Increase financial investment in science, technology, and innovation by 20%.
Optimization of land use structure (LO)	Reduce the area of construction land by 15%, increase the area of cultivated land by 5%, and increase the area of woodland by 10%.
Population size control (PC)	The average annual net population growth rate is set at 0.4‰ before 2030 and −1‰ after 2030.

To achieve the "dual-carbon" goal, China needs to transform into an economic development model and industrial structure with high energy efficiency, low energy consumption, and low emissions. Fixed asset investment is the primary factor influencing the industrial structure in the model. Therefore, this study determines the adjustment parameters for industrial fixed asset investment based on Wu [38]. Science, technology, and innovation (STI) perform a crucial function in improving the efficiency of carbon emissions and advancing the modernization and ecological transformation of industries. Therefore, the financial investment in STI is increased by 20% to simulate the impact of scientific and technological progress. As the population grows, energy consumption increases, resulting in a subsequent rise in carbon emissions. The average annual net population growth rate is set to be 0.4‰ until 2030. After 2030, the rate is projected to decline to −1‰ due to population aging and negative population growth. The Outline of the 14th Five-Year Plan for the National Economic and Social Development of Nantong City proposes controlling the upper limit of the aggregate quantity of construction land and actively revitalizing the stock of construction land. Moreover, the amount of arable land influences food security, and this emphasizes resolutely curbing the 'non-agriculturalization' of arable land and strictly controlling the 'non-foodization' of cropland. Forest carbon sinks are a significant part of natural carbon sinks, so Nantong's afforestation rate needs to maintain a high growth rate and increase forestry carbon sinks. On this basis, according to Yang et al. [39], this study set planning objectives for optimizing the spatial structure of the national territory.

3. Results

3.1. Spatial and Temporal Patterns of Land Use in Nantong

According to the land use images of Nantong from 2005 to 2020 (Figure 3), land use transfers over the four periods of 2005–2010, 2010–2015, 2015–2018, and 2018–2020 were obtained by using ArcGIS 10.3 software and OriginPro 2024 software (Figure 6), respectively, and this paper concentrates on changes in area and the magnitude of changes of six land use types, excluding the unutilized land due to its negligible area.

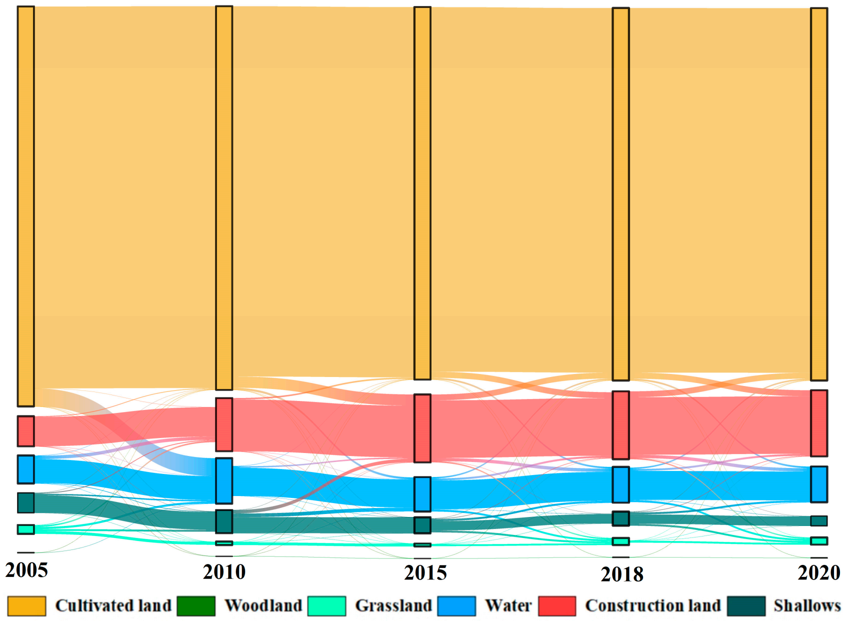

Figure 6. Sankey map of land use transfers from 2005 to 2020.

According to Figure 6 and Table 8, between 2005 and 2020, the principal use of land in Nantong was cropland, followed by construction land and water. Influenced by the implementation of Jiangsu's coastal development strategy in 2009, the land use type had the most drastic changes in area increase and decrease in 2005–2010 and 2010–2015. These two phases were periods of rapid expansion of construction land. The rate of decline in cultivated land area remained relatively constant, with more than 90% of new construction land coming from the transfer of cultivated land. The area of woodland in Nantong is relatively modest, and unchanged in the other stages, except for a reduction rate of 22% from 2005 to 2010. The fluctuating change in the area of grassland is very obvious; it has been decreasing until 2015 but increased sharply in 2015–2018 by 95.37 km^2. The increase in its area is mainly from the outflow of construction land, water, and shallows. Nantong is relatively rich in sea and shallow resources, and shallows, as a large amount of land reserve resources, are extremely favorable for agriculture and ecological environment construction in the region. Since 2010, the area of mudflats has been decreasing, and their outflow has mainly gone to construction land and waters, followed by cultivated land and grassland.

Table 8. Area changes for different land use types from 2005 to 2020.

Land Use Type	2005–2010		2010–2015		2015–2018		2018–2020	
	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)
Cultivated land	−351.5	−0.05	−211.06	−0.03	−0.79	0.00	−74.83	−0.01
Woodland	−0.87	−0.22	0.00	0.00	−0.01	0.00	0.00	0.00
Grassland	−114.84	−0.64	−13.08	−0.12	95.37	2.33	−12.86	−0.10

Table 8. *Cont.*

Land Use Type	2005–2010		2010–2015		2015–2018		2018–2020	
	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)	Area of Change (km^2)	Rate (%)
Construction land	439.85	0.76	282.35	0.36	−34.61	−0.05	93.41	0.13
Water	23.92	0.03	77.22	0.08	25.6	0.02	34.16	0.03
Shallows	3.44	0.07	−135.43	−3.46	−85.56	−1.53	−39.88	−1.39

3.2. Land Use Carbon Emissions in Typical Years

According to Table 9, from 2005 to 2020, the net carbon emissions resulting from land use in Nantong exhibited a consistent upward trajectory, escalating from 4,799,792 tons in 2005 to 12,966,694 tons in 2020 at an average annual rate of 4.20%. Construction land is the primary source of carbon emissions, with a fluctuating upward trend from 7,815,152 tons in 2005 to 15,729,060 tons in 2020, representing a 2.01-fold increase over the study period. The period from 2010 to 2015 exhibited the most rapid growth of construction land use carbon emissions, nearly doubling. It is the consequence of this period's accelerated expansion of construction land. Carbon emissions from cultivated land ranked second, with a smaller increase between 2005 and 2020, and a significant decrease of 60,341 tons in 2020 compared to 2018. This decline can be attributed to the ecological preservation efforts focused on cultivated land in Jiangsu Province and the implementation of the double-reduction policy, which entails a reduction in both chemical fertilizers and pesticides. In addition, except for forest land, whose carbon uptake has remained unchanged, the other three types of carbon sink land have experienced fluctuations and decreases in carbon uptake due to land transfers, which undoubtedly hinders Nantong's progress towards carbon neutrality.

Table 9. Amount of carbon emissions on different land use types from 2005 to 2020 (10^4 t).

Land Use Type	Cultivated Land	Woodland	Grassland	Water	Construction Land	Shallows	Carbon Source	Carbon Sink	Total Net Carbon Emissions
2005	49.9422	−2.3381	−3.796	−335.4326	781.5152	−9.9115	831.4574	−351.4782	479.9792
2010	51.9668	−1.8225	−0.0113	−364.9096	1028.1398	−8.4044	1080.1066	−375.1478	704.9588
2015	50.4888	−1.8225	−0.8595	−338.8154	1410.9746	−12.0551	1461.4634	−353.5525	1107.9109
2018	60.4708	−1.8166	−2.7086	−330.4846	1370.9570	−6.1490	1431.4278	−341.1588	1090.2690
2020	54.4367	−1.8166	−2.3560	−319.4594	1572.9060	−7.0413	1627.3427	−330.6733	1296.6694

3.3. "Carbon Flow" of Land Use in Nantong

The explicit carbon flow model was used to determine the carbon transfer pattern in Nantong from 2005 to 2020 (Table 10, Figure 7). Positive carbon flows in the land transfer process mainly come from the conversion of construction land to other land types and the carbon sinks formed by the change of cropland to waters, while negative carbon flows mainly come from the carbon emissions generated in the conversion of other land use types to construction land. Except for the initial period, the remaining three periods exhibit negative carbon fluxes. This trend is not conducive to Nantong achieving its carbon reduction targets on schedule. The substantial rise in the overall positive carbon flow from 2015 to 2018 can be attributed to the increased transfer of construction land to other land types, resulting in a substantial increase in the carbon stock of vegetation. Furthermore, it exemplifies the efficacy of initiatives undertaken by Nantong to encourage the establishment of urban forests and to safeguard the environment. From 2018 to 2020, the intensity of carbon emissions from construction land was regulated, and the negative carbon flow level decreased steadily as a result of industrial structure optimization, as well as the intensification of green energy substitution measures. Overall, over the 2005–2020 period, negative carbon flows generally exceed positive carbon flows, although they are trending downward. This suggests that the issue of uncontrolled expansion of construction land persists, and the rising trend in anthropogenic carbon emissions, which hinders carbon sequestration, is exacerbated by the rapid transformation of ecological land into construction land. Combined with what was previously analyzed, carbon sequestration in waters, grasslands, and mudflats demonstrates a declining trajectory due to land transfer, and it is necessary to take measures to correct the imbalance of regional carbon metabolism.

Table 10. Carbon flow from 2005 to 2020 ($tC \cdot a^{-1}$).

The Direction of Carbon Flow	2005–2010	2010–2015	2015–2018	2018–2020
Positive carbon flow	2,089,415.21	690,039.29	2,288,285.99	1,372,545.60
Negative carbon flow	−2,042,913.42	−3,677,932.96	−2,358,382.37	−2,296,215.12

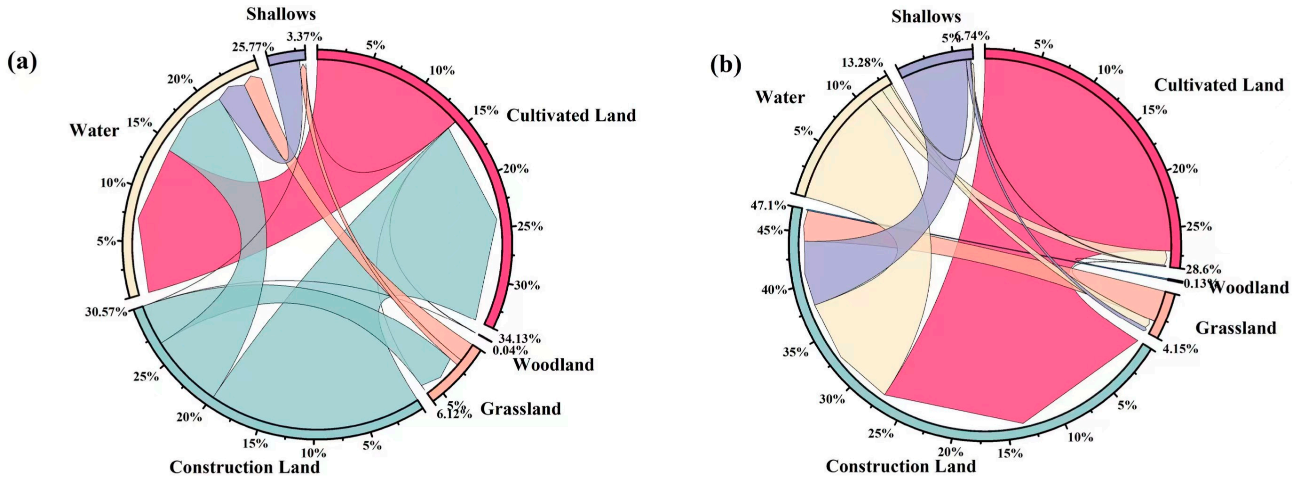

Figure 7. Land use carbon flow: (**a**) positive carbon flow; (**b**) negative carbon flow.

3.4. Simulation of Land Use Carbon Emission System Dynamics

3.4.1. Model Validity Test

The model rationality was assessed using the equation test and magnitude test features provided by the Vensim software. The test findings indicate that the equation on both sides of the scale is coherent, and the trial run of the model did not yield any abnormal outcomes. Hence, the carbon emission simulation model for land use in Nantong developed in this study is deemed to be rational.

A historical test evaluates the correctness of a model by comparing its predicted values with historical data values. It estimates the relative error between the two, where a smaller absolute number indicates higher accuracy and greater effectiveness of the model. This paper selects the historical data of five important indicators in Nantong from 2005 to 2020. These data are used as test variables and inputted into the model for analysis. The findings of the examination are displayed in Table 11. The simulation findings demonstrate that the relative error rates of all ten indicators are below 5%, suggesting a strong alignment between the values observed and the results of the system simulation. The study successfully developed a model for carbon emission from land use in Nantong.

Table 11. Relative errors of simulation (%).

Year	GDP	Primary Industry Fixed Asset Investment	Secondary Industry Fixed Asset Investment	Tertiary Industry Fixed Asset Investment	Scientific and Technological Innovation Input
2005	0.73	4.78	2.37	0.82	1.73
2006	1.22	1.15	0.58	1.11	4.75
2007	1.91	0.02	0.93	3.94	3.96

Table 11. *Cont.*

Year	GDP	Primary Industry Fixed Asset Investment	Secondary Industry Fixed Asset Investment	Tertiary Industry Fixed Asset Investment	Scientific and Technological Innovation Input
2008	3.32	4.82	2.99	1.93	3.31
2009	4.11	0.68	1.64	2.34	0.93
2010	1.29	1.35	1.49	1.13	1.88
2011	3.33	3.54	2.29	3.01	2.76
2012	4.25	0.03	2.71	0.47	2.04
2013	3.75	0.55	0.74	0.51	4.86
2014	2.63	2.88	1.97	0.90	0.29
2015	4.52	2.15	2.55	0.66	2.95
2016	3.26	1.45	3.87	4.09	1.23
2017	0.53	2.91	0.21	3.92	0.81
2018	1.01	0.75	4.98	4.98	4.13
2019	0.62	3.57	4.57	0.25	4.78
2020	2.12	0.45	1.70	0.14	4.30

3.4.2. Multi-Scenario Simulation of Carbon Emissions from Land Use

As the land use carbon emission system is a holistic system in which its components influence and interact with one another, regulating a single variable may have certain limitations. Combined application of various carbon emission reduction policies is a common occurrence in the actual development process. This study employs a composite dynamic simulation of the system to distinguish between the combinations of various policies and investigates the carbon reduction potential of diverse comprehensive scenarios. In light of the practicability of implementing the program, the following specific scenarios have been established (Table 12).

Table 12. Comprehensive adjustment scenario simulation.

Scenario	Population Control	Optimization of Land Use Structure	Advances in Science and Technology	Optimization of Industrial Structure
Original Scenario	Natural development	Natural development	Natural development	Natural development
PC	√	Natural development	Natural development	Natural development
LO	Natural development	√	Natural development	Natural development
TP	Natural development	Natural development	√	Natural development
IO	Natural development	Natural development	Natural development	√
Scenario 1	√	Natural development	√	√
Scenario 2	√	√	√	Natural development
Scenario 3	Natural development	√	√	√
Scenario 4	√	√	√	√

"√" means that this parameter is adjusted.

Figure 8 shows the changes in total carbon emissions in Nantong from 2005 to 2060 under the natural development scenario. The data show that under the original scenario, the net carbon emissions in Nantong peak in 2032, totaling 16,390,941 tons. Thereafter, the carbon emissions gradually decrease. However, under the natural development condition, the total net carbon emissions of Nantong are about 4,298,250 tons in 2060, failing to achieve carbon neutrality. In the scenarios of population control (PC), optimization of land use structure (LO), optimization of industrial structure (IO), and technology and science progress (TP), the net carbon emissions from land use in 2060 are reduced by 448,184 tons, 1,534,917 tons, 1,121,203 tons, and 850,346 tons, respectively, compared with the original scenario, and the emission reduction potentials of the scenarios in 2060 are as follows: LO > IO > TP > PC. Although the net carbon emissions under the population control scenario are decreasing year by year, it is always higher than the other three scenarios, indicating that the effect of controlling the population size on the carbon emissions from land use is relatively weak, and needs to be implemented in synergy with other carbon emission reduction policies.

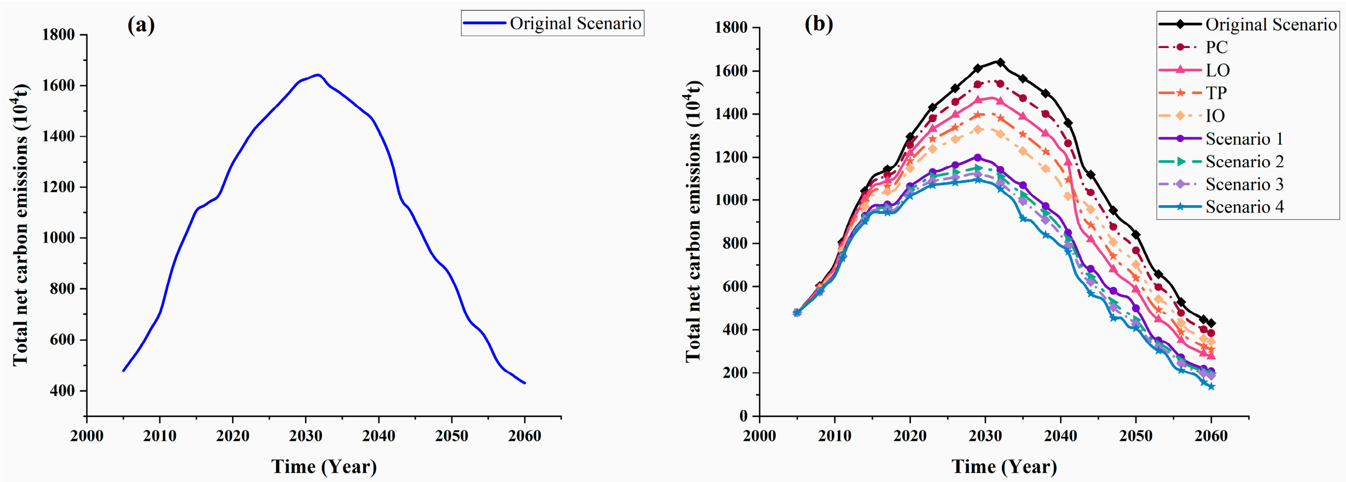

Figure 8. Projections of net carbon emissions: (**a**) original scenario; (**b**) policy combination scenarios.

Analysis of the four policy combination scenarios reveals that Scenario 4, in which all four policies are adjusted, has the greatest emission reduction and the best effect, reaching a peak net carbon emission of 10,949,010 tons in 2029 and a net carbon emission of 1,370,202 tons in 2060, and it is the scenario that is closest to the goal of carbon neutrality. Scenario 1 adjusts the parameters of the three policies of population growth rate, scientific and technological progress, and industrial structure optimization to reach the peak of net carbon emissions of 11,988,872 tons in 2029, and the net carbon emissions of 2,092,834 tons in 2060. Scenario 2 reaches the peak of net carbon emissions in the same year as Scenario 1, and the net carbon emissions are 1,979,348 tons in 2060, which is 113,486 tons less than Scenario 1. Scenario 3 reaches the peak of 11,218,750 tons in 2028, and is 1,074 tons less than Scenario 2 in 2060. Comparing the four single-policy regulation scenarios of IO, TP, LO, and PC with the four policy combination scenarios and the original scenario, all eight regulation scenarios help to reduce the land use-induced carbon emissions in Nantong. The carbon emission reduction potential of the four scenarios under comprehensive regulation is much higher than that of single-scenario regulation, specifying that the coordinated control of multiple policies is more helpful in realizing low-carbon development.

4. Discussion

4.1. Analysis of Land Use Carbon Emissions and Low-Carbon Scenarios

The study found that land use carbon emissions in Nantong showed an upward trend from 2005 to 2020. The possible explanation is that, as the Jiangsu Coastal Area Development Plan has been formally elevated to the status of a national strategy, coastal development is gradually affecting the changes in the coastal land use structure of Nantong, and construction land is occupying a large amount of ecological land, which is generating a series of ecological and environmental problems, and is causing an increasing contradiction between the implementation of the coastal development strategy and environmental protection [40,41]. Similar to the results of previous studies, among all land use types, the increase in carbon emissions from construction land is the main source of total carbon emissions in the study area [42,43]. In addition to controlling the expansion of construction land, it is particularly important to regulate the internal structure of construction land and the industrial, energy, transportation, and municipal activities it carries [44]. Therefore, in the future, the scale, structure, layout, and intensity of construction land should be integrated to further optimize the spatial pattern of construction land under the carbon emission constraint. Agricultural production activities are an important source of anthropogenic GHG emissions, with about 1/5 of the global GHGs originating from agricultural production activities, and their impact on global climate change is second only to GHG emissions from industrial processes [45,46]. Unlike the results of other studies [32,47], carbon emissions from cropland in Nantong decreased rather than increased in the context of economic development, and the carbon emissions from cropland in 2020 were significantly reduced by 60,341 tons compared to 2018, while the area of cropland is the same in these two years. This study attributes this decrease to the ecological protection work focusing on cropland, the improvement of farming techniques, and the implementation of the policy of double reduction of chemical fertilizers and pesticides in Jiangsu Province. For example, intermittent irrigation can effectively reduce carbon emissions during crop growth compared with flood irrigation; rotary plowing and tilling of land after straw return can improve the physical structure of the soil while realizing emission reduction in rice paddies [48,49].

The domain of carbon emissions includes a multitude of elements, including economic, social, resource, environmental, energy, and political factors. By employing the system dynamics approach, one can examine the methodical correlation between land use development and urban economic progress, which in turn influences carbon emissions. This paper finds that if no other measures are imposed, Nantong will still have 4,298,250 tons of carbon emissions in 2060, and the carbon neutrality goal of net-zero emissions cannot be achieved. Therefore, this paper simulates four single policy adjustment scenarios consisting of land use structure optimization (LO), industrial structure optimization (IO), scientific and technological progress (TP), population control (PC), and four comprehensive policy adjustment scenarios, and the results are conducive to reducing carbon emissions. Among them, for the single policy adjustment scenario, from 2042 to 2060, the carbon emission reduction potential of the LO scenario shows a gradual increase, while the carbon emission reduction effect brought by the IO scenario gradually decreases. The possible reason for this is that, as China's comprehensive national power jumps significantly to reach the level of middle-developed countries in 2035, the industrial structure will be optimized and remain relatively stable for a longer period, and thus the adjustment of land use structure, which is mainly aimed at increasing carbon sinks, will have a particularly significant impact on emission reduction. Adjusting the land use structure not only helps to guide the rational allocation of industrial space and weaken the demand for construction land for economic development, but at the same time, it also helps to reduce the encroachment of land for carbon sinks in the development of urbanization and protect the land for carbon sinks, which effectively suppresses the carbon emissions from land use and at the same time increases ecological carbon sinks. For the comprehensive policy adjustment scenario, similar to the results of previous studies, the emission reduction effect of the interplay of different policies is more significant [32,39,47], providing certain theoretical references for exploring the low-carbon land use model in Nantong City, and at the same time providing certain policy guidance for the development of targeted low-carbon spatial planning for coastal cities.

4.2. Policy Enlightenment towards Low-Carbon Development

High-carbon energy supply structure and low energy utilization efficiency form a high-carbon industrial structure, and the significant concentration of high-carbon industries determines the spatial pattern of land carbon emissions in coastal areas. Nantong, with its favorable geographic location, has great potential for developing renewable energy sources such as photovoltaic, wind, hydropower, ocean energy, and geothermal energy. Through eliminating high-energy-consumption, low-output, high-pollution, and other industries, and vigorously developing tertiary industry, high-tech industry, and other measures to implement the development strategy of energy conservation and emission reduction, we can continuously improve energy use technology, optimize the energy structure, and increase the proportion of renewable energy use.

The coastal development strategy has given rise to a certain degree of blind and disorderly land development. On the one hand, it is necessary to reduce construction land use-induced carbon emissions, optimize the land use structure, and ensure comprehensive social, economic, and ecological benefits to enhance the intensive utilization of land, maximize the benefits of land use on limited land resources, promote industrial upgrading and agglomeration, and achieve high-quality development of the region. On the other hand, the coastal mudflats in Jiangsu Province are still growing at a rate of no less than 2% per year [50], which is an important reserve resource of arable land with huge potential for utilization and will become a new growth point for economic development. It is necessary to coordinate the reclamation project of coastal mudflat resources, determine the nature of the use after reclamation, strengthen the management after reclamation, ensure the proportion of construction land, cropland, and ecological land, and avoid blind development. In addition, studies should be conducted on the establishment of ecological functional zones for blue carbon sinks, giving full attention to the carbon sequestration in mudflats and wetlands, and expanding the area of forests, to enhance the capacity of ecosystems as carbon sinks.

At present, the R&D of low-carbon technology in Nantong City is in the early exploration stage, and the pace of forward-looking industrial technology innovation projects should be accelerated. Firstly, Nantong should increase the investment of scientific research funds and increase the investment and subsidies for R&D. Secondly, Nantong should support researchers to focus on exploring key technologies such as carbon capture, utilization, and storage (CCUS), new energy storage technologies, clean energy recycling, and other key technologies, break down technical barriers, overcome bottlenecks, and improve the whole process system of carbon reduction, zero-carbon, and carbon-negative technologies. Once again, Nantong should encourage high-carbon enterprises with the conditions to adopt low-carbon innovative processes, the orderly phase-out of the high-carbon operation mode of existing equipment and processes, and adopt new processes, new equipment, and new technologies to carry out high-efficiency energy conservation and emission reduction.

Population growth will increase carbon emissions from respiration, energy consumption, and land development. Despite the comparatively minor impact of population regulation on carbon emissions in comparison to other determinants like land use structure optimization and industrial structure optimization, the significance of population size in carbon emissions cannot be disregarded. Population growth will persist as a result of Nantong's economic development; therefore, the government should reasonably regulate population growth. Carbon emission reduction is inextricably linked to the active engagement of local inhabitants. It is the responsibility of the government to enhance the dissemination of information regarding low-carbon environmental protection, foster a societal consciousness regarding low-carbon emissions, and direct citizens towards adopting green consumption practices, low-carbon behaviors, and low-carbon travel.

4.3. Limitations and Future Directions

Overall, this study initially constructs a carbon emission inventory adapted to the land use characteristics of coastal cities and fills the gap in the literature on the study of carbon neutrality in coastal cities from the perspective of an integrated system of land use and socio-economic factors, which provides a reference to achieve the dual-carbon goal in coastal cities in other regions. Meanwhile, this study may inspire future research in the following aspects:

(1) Strengthen the research on the carbon emission effect of coastal mudflat utilization. As a special type of land use in coastal areas, a scarcity of studies exists regarding the carbon effects of the development and utilization of mudflats. In future research, we should strengthen this part of the study through experimental means to monitor the effect of different beach reclamation methods on soil carbon storage, to increase carbon uptake and decrease carbon emissions.

(2) Research on the carbon balance of offshore ecosystems. This thesis has only studied the carbon effect of terrestrial ecosystems in coastal areas, while the blue carbon sinks formed by marine ecosystem organisms through a series of oceanic activities of fixing and storing need to be further studied.

(3) As a result of the constraints associated with data acquisition, a comprehensive categorization of various land use types within the secondary land use category was not possible for this study. However, future research may aim to further refine the carbon emission accounting items about these distinct land use types.

5. Conclusions

This study constructed an accounting inventory of carbon emissions from land use in Nantong and adopted an explicit carbon flow model to analyze the temporal and spatial changes in carbon emissions from land use in Nantong. We constructed a dynamic coupling system of land, economy, energy, environment, and carbon emissions, predicted whether Nantong can achieve carbon neutrality in 2060, and set up different policy combination scenarios to simulate the changes in carbon emissions in Nantong under different options.

From 2005 to 2020, the land use structure of Nantong City has undergone significant changes. On the whole, the area of construction land continues to grow, with more than 90% of new construction land coming from the transfer of cultivated land. And the area of cultivated land and shallows continues to decrease. The grassland area and water area show a trend of decreasing first and then increasing. The net carbon emissions from land use in Nantong exhibited a consistent upward trajectory from 2005 to 2020, with an average annual growth rate of 5.22%. Specifically, these emissions rose from 4,799,792 tons in 2005 to 12,966,694 tons in 2020. Land use-induced carbon metabolism in Nantong was significantly out of balance during the period of study. Positive carbon flows are primarily attributable to the carbon sinks created by the transition of construction land to other land uses and cultivated land to water. Negative carbon flows are primarily attributable to the carbon emissions produced when other land uses are converted to construction land. Within the framework of natural development, Nantong might face obstacles in achieving its dual-carbon objectives; therefore, urgent implementation of a combination of policies is required. A complex, multi-factor, multi-feedback, cyclic urban land carbon emission system is comprised of subsystems whose modifications have interdependent effects on the carbon emission activities of other systems. When analyzing low-carbon development strategies for coastal cities, policymakers must therefore comprehend the interdependencies between multiple subsystems, including energy, land, environment, economy, and carbon emissions. For the single policy regulation scenario simulation, the magnitude of the potential for emission reduction of each scenario in 2060 is in the following order: LO > IO > TP > PC. In contrast to the scenario of natural development, the other eight scenarios all help to reduce carbon emissions from land use in Nantong. The carbon emission reduction potential of the four scenarios under integrated regulation is much higher than that of single-scenario regulation, indicating that coordinated control of multiple policies is more helpful in realizing low-carbon development.

Author Contributions: Conceptualization, Q.X.; methodology, Q.X.; software, Q.X.; validation, Q.X.; formal analysis, Q.X.; investigation, K.L.; resources, K.L.; data curation, Q.X.; writing—original draft preparation, Q.X.; writing—review and editing, Q.X.; visualization, Q.X.; supervision, K.L.; project administration, K.L.; funding acquisition, K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by General Project of National Social Science Foundation of China (Grant No. 22BGL192).

Data Availability Statement: Data are available on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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