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Enhancing natural carbon sinks: Simulation of land use change under different carbon market scenarios by developing an ANN-ABM model

Ruimin Lin [a], Ru Guo [a,b,c,*], Yunyang Li [a], Guanghui Shao [a], Yuhao Zhang [a], Kaiming Peng [a,b,c], Xiangfeng Huang [a,b]

[a] College of Environmental Science and Engineering, Tongji University, Shanghai, 200092, PR China
[b] Institute of Carbon Neutrality, Tongji University, Shanghai, 200092, PR China
[c] Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, PR China

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ABSTRACT

The carbon market mechanism presents an innovative approach to achieving carbon neutrality, however, its impact on regional carbon sink enhancement remains uncertain. This paper proposes an analysis framework based on an Artificial Neural Network-Agent-Based Model (ANN-ABM) to simulate the potential contribution of carbon market mechanism in enhancing carbon sinks. Taking the case of Chongming, China, the results demonstrate significant economic potential with forest land expansion from 2010 to 2020, equivalent to 30.69 % of eco-compensation. Under scenarios introducing a carbon market, there is an increased probability of converting land to high carbon sink types. Compared to the baseline scenario, carbon prices at 1.34 US$/t and 6.27 US$/t result in additional funds of 8.94 % and 41.46 %, respectively, and increase the carbon sink by 12.52 % and 30.28 %. The findings contribute to an understanding of how the value of carbon sinks can be realized through market mechanism and offer guidance for innovative eco-compensation approaches.

1. Introduction

Climate change stands as one of the foremost global challenges, exerting long-term and widespread impacts on China and the world (IPCC, 2021; Jia et al., 2023). That compelling countries worldwide to propose carbon-neutral targets. In the pursuit of carbon neutrality, natural carbon sinks play an important role (Ruehr et al., 2023). Optimizing land use management and land cover pattern are important ways to increase carbon sinks (Wang et al., 2022a), among which afforestation and efforts to avoid deforestation have significant carbon reduction potential (Griscom et al., 2017). However, many regions around the world, especially developing countries, are confronted with the need for economic development and poverty reduction. The conservation of natural resources is frequently perceived as a barrier to economic growth. To balance carbon reduction with development, it is essential to assign economic value to enhancing carbon sinks.

Compensatory conservation has been widely recognized as an effective approach to protecting natural carbon sinks and ecosystems. The mechanism internalizes negative environmental externalities and has been frequently employed worldwide (May et al., 2017). The earliest conservation incentives were in the United States and the European Union, which began in the 1970s and 1980s, and mainly compensated agricultural projects (Schomers & Matzdorf, 2013). In China, the most popular mechanism is 'eco-compensation', providing environment protectors compensation in the form of funding, projects, or technologies (Shang et al., 2018). China's eco-compensation commenced in 1998 with the establishment of the forestry compensation fund. According to incomplete statistics, China's total eco-compensation fund in 2011 was about $14.6 billion (Wu et al., 2019). With gradual improvement, it is approximately $26 billion in 2020 (Kou, 2021), encompassing a spectrum of ecosystem components. The government-led compensation mechanism faces some challenges, such as single-source funding, weak incentive effect, and high supervision costs (Shang et al., 2018; Liu & Dou, 2022).

The carbon market mechanism provides an option for the diversification of compensation funds. In the carbon market mechanism, a cap on carbon emissions is set and carbon emission rights trading is allowed to establish a price for carbon emissions. Enterprises can buy or sell carbon emission rights to meet their emission needs. Compared to administrative orders or carbon taxes, this approach's advantage lies in

* Corresponding author.
E-mail address: ruguo@tongji.edu.cn (R. Guo).

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its comprehensiveness and flexibility. Enterprises can choose the most cost-effective method to comply with the emission limit. Through market transactions to optimize the allocation of carbon emission rights, the social can achieve the greatest carbon reduction effect at the lowest cost, enhancing emission reduction efficiency and complementing other mechanisms (Bi et al., 2019). The market mechanism can be subdivided into quota-based trading and Voluntary Carbon Market (VCM) (Zhou & Li, 2019). VCM is an alternative market instrument that rewards greenhouse gas (GHG) offsets and is used to increase participation and investment in climate action (Miltenberger et al., 2021). China Certified Emission Reduction (CCER) mechanism is a type of VCM and is an important component of China's carbon emissions trading. It focuses on projects such as forest carbon sequestration and clean energy. The voluntary emission reductions of GHG from these projects can be traded in the carbon market. This complements the carbon allowance market and helps promote industry-wide cooperation in reaching carbon targets (Liu et al., 2022). Due to the low investment and high carbon sink of forestry, some regions have generated additional revenue from forestry projects (He et al., 2017). However, the development of the CCER market is still in the early stage, and it needs more in-depth research to study the effective mechanism, to support the diversification of eco-compensation.

Effectiveness assessments of eco-compensation revolve around ecological, economic, and social outcomes. Methodologies include the input-output method (Miao et al., 2019), econometric modeling (Laukkanen & Nauges, 2012), questionnaire surveys (Rensburg et al., 2009; Petheram & Campbell, 2010; Le & Leshan, 2020), and others. Among these approaches, the land use and land cover change (LUCC) models stand out for its integrated economic-ecological assessments (Laukkanen & Nauges, 2012). LUCC models mainly consisted of nonspatial models, spatial models, and comprehensive models (He et al., 2022). Nonspatial models quantify the mechanism and trend of LUCC from the time dimension, such as Markov and system dynamics (SD) models (Muller & Middleton, 1994; Portela & Rademacher, 2001). The spatial model describes the spatial pattern characteristics of LUCC. Some spatial models, such as the Cellular Automata (CA) model, reflect the suitability and constraints of the environment in the land units (Yang et al., 2015). Comprehensive models have the characteristics of the first two models, such as the CLUE-S model, which confirms the characteristics of land use on a macro level and assigns them to individual land units. Some studies optimize the model effect by coupling different types of models, such as SD-CA model (Qin et al.,2009) and Markov-Logistics-CA model (Han & Jia, 2017). However, the majority of current models emphasize top-down land management mechanisms and prioritize macro-level impacts. They pay less attention to human choices and other socio-institutional factors within the land use process. However, ecological conservation requires a bottom-up approach (Liu et al., 2022). The existing research on beneficiaries mainly focuses on perception, willingness, and agent behavior. For example, researchers employ investigation and conditional valuation methods to scrutinize the factors that influence the willingness of individuals to receive compensation (Martín-López et al., 2007). Some other researchers utilize evolutionary game models or structural equation models to investigate the behavioral traits of relevant agents (Lalika et al., 2016). Regrettably, few studies have combined agent decision behavior with spatial pattern evolution. A comprehensive understanding of the intricate relationship between eco-compensation and ecological conservation outcomes remains elusive.

Agent-based modeling (ABM) offers a novel method for bottom-up land use research, enabling the emulation of agent behavior, decisions, interactions, and environments (Moglia et al., 2010). It has robust computational capabilities and spatiotemporal dynamics. For LUCC studies, the bottom-up dynamic evolution of ABM overcomes the limitations encountered by traditional analysis methods, which often face challenges in quantifying individual behavioral influences (Batty, 2005). Particularly, ABM demonstrates significant applicability in modeling structural shifts within the agricultural system (Parker et al., 2003; Matthews et al., 2007). Nonetheless, the ABM model has limited ability to simulate the influence of natural drivers (Bartkowski et al., 2020). To address this limitation, recent studies have incorporated specialized indices into ABM (Brady et al., 2009), constructed natural driver sub-models (Cássio and Célia, 2022), or integrated ABM with other models (Robinson et al., 2013; Kumar et al., 2021; Hashemi Aslani et al., 2022) to simulate natural ecological factors as drivers of land change.

In summary, considering the requirement for social development, it is crucial to increase carbon sinks while protecting the economic benefits of local people. This pressure for sustainable development is particularly acute in developing countries like China. If market trading of carbon sinks is introduced, the current compensatory protection mechanism can be enriched. It is imperative to simulate the evolution of regional carbon sinks following the implementation of a carbon market to quantify the effectiveness of this mechanism. In specific, within the current research on compensation mechanisms, there remains a gap in how the decision-making behaviors of micro-level agents contribute to the macro-level ecological spatial patterns. To bridge this gap, a suitable model and fine-grained simulations are requisite to evaluate the mechanism and quantify the compensation effect. In this study, we proposed the Artificial Neural Network-Agent-Based Model (ANN-ABM) methodology, grounded in bottom-up agent-based simulations, with the intent of unraveling the influence mechanism of market mechanisms on land use change decisions. This could provide a theoretical basis and an operational model for carbon trading policies, particularly the emerging CCER mechanism.

In the following, an exposition of the research methodology will be presented in Section 2, spotlighting the design of the ANN-ABM model. The research findings will be given in Section 3, showcasing insights acquired through historical carbon accounting and simulation outcomes. the practical effectiveness of the model and its implications will be explored in Section 4. A conclusive statement will be made in the final Section 5.

2. Methodology

2.1. Conceptual framework

To investigate regional carbon sinks, ABM can model the attributes and behaviors of microscopic agents, and thus simulate the system dynamics at the macro level. It is acknowledged that land use patterns are shaped by a complex interplay between socio-economic and natural factors (Hersperger et al., 2010). The model needs to consider natural factors, as well as socio-economic factors such as subsidies, as inputs to the decision-making of the subject.

The theoretical framework and the research flowchart of the study are shown in Figs. 1 and 2. The study proposes an ANN-ABM land evolution model. The model was applied to simulate land evolution at small-scale regions in the study. The ANN combined with logistic regression was used to simulate the complex nonlinear relationships between multiple natural factors and land change, and the agent-based model (ABM) was used to construct the differential land decisions of agents under changes in socio-economic factors. ABM simulated changes in each subunit to form the overall land evolution. The InVEST model was used to calculate carbon sinks. This study assumed that carbon sink trading can provide local farmers with additional economic incentives. Based on this hypothesis, we selected three eco-compensation scenarios to compare the effects of different levels of carbon trading.

2.1.1. ANN-ABM land evolution model

The ANN-ABM model simulates the dynamics of land under the influence of external conditions. The model proposes that both natural and economic factors have joint effects on non-natural land types. These factors act on agents, and the agent attributes shape the land use

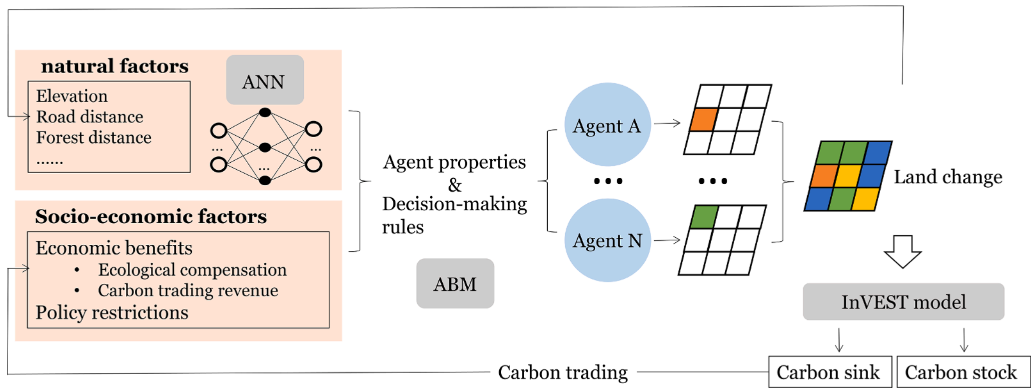

Fig. 1. Conceptual diagram of the proposed ANN-ABM method.

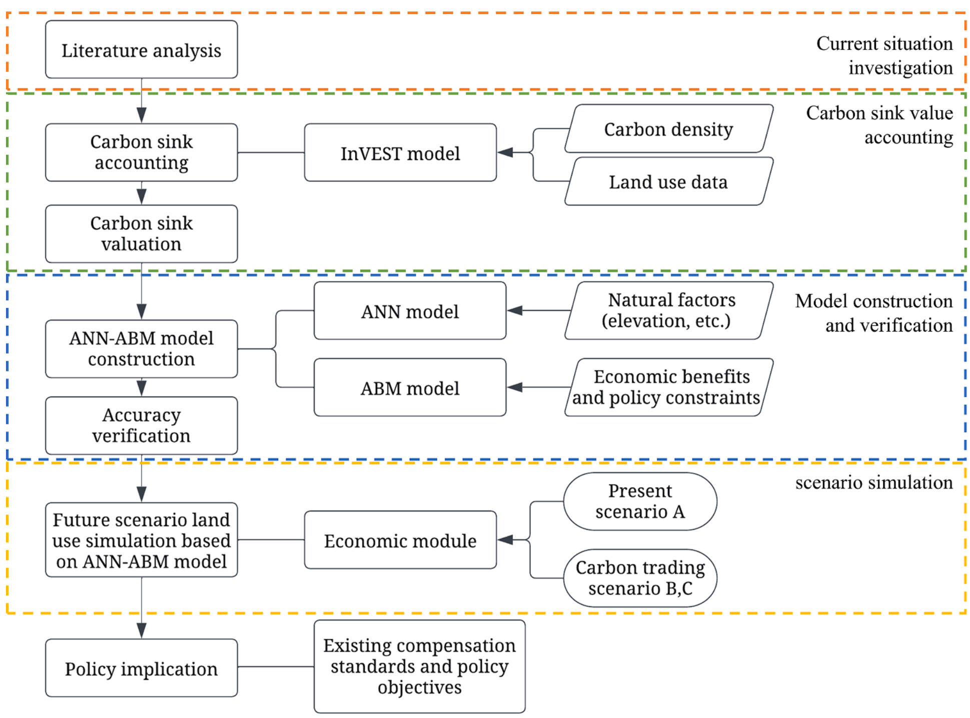

Fig. 2. Research flowchart.

decision-making behavior. Considering that the study area predominantly comprises cropland, where farmers play a pivotal role in land transfer decisions, these farmers can be regarded as the most important "agents" corresponding to the cropland pixels. The essence of the model lies in the attributes and decision-making rules of agents, which are designed based on local data and existing research.

The model is developed and implemented using the Python programming language and TensorFlow framework. To integrate the artificial neural network with the agent-based model, a three-stage approach is employed (Appendix A.1). Initially, the ANN model is trained for analyzing the influence of natural factors on land use change. Concurrently, agent-related rules are established based on research and local conditions. Finally, an integration rule combines the outputs of the two models and incorporates them into a specific decision-making process to calculate the final predicted land class.

ANN is used to simulate the natural drivers of land change. As a machine learning model, it fits nonlinear relationships through iteration, enabling the model to replicate the complex driving forces (Li et al., 2002). Before constructing the ANN, binary logistic regression was performed. Historical land data from 2010-2015 were analyzed for correlations between natural factors and land evolution. The model selected factors with significant correlation as input (Appendix A.2), which included land type in the previous period, DEM, distance to main roads, distance to nearest cropland, distance to nearest forest land, distance to nearest grassland, distance to nearest rivers, distance to nearest lakes, distance to nearest wetlands and distance to nearest construction land. The ANN model outputs the natural conversion probability $P_{c\to i,1}$ (i denotes the land type, $i = 1, 2, 3, 4, 5, 6$). This represents the tendency of land use conversion under selected natural elements.

ABM model is used to simulate the process of socio-economic factors acting on land change. The farmers who make decisions in the context of eco-compensation are the main agents in this study. Research in Shanghai, China shows that farmers' support for eco-compensation is mainly related to their basic characteristics (age, education level, etc.), farmers' economic characteristics (proportion of agricultural income, annual income, etc.), and farmers' perceptions (Komarek et al.,2014; Li & Cai, 2014). Eq. (1) concerning the studies of West et al. (2018) and Yuan et al. (2016).

$$P_{c\rightarrow i,2} = \left(\frac{I_1}{I_2 * \alpha}\right) \tag{1}$$

Where $P_{c\rightarrow i,2}$ is the agent conversion probability for converting the plot from cropland to land class *i*. I_1 is the eco-compensation standard; $I_2*\alpha$ is the agent's agricultural income, I_2 is the disposable income per capita, and α is the proportion of agricultural income of the agent (Appendix A.3). The parameters were determined by statistical data (Guo et al., 2020). The age and the proportion of agricultural income of the agents were assigned randomly during the initialization of the model (Appendix A.4). There is no relevant standard for the eco-compensation of the conversion of cropland to water area, grassland, and wetland, which is regarded as no compensation.

Integrated rules evaluate whether each pixel is allowed to change land use type under the policy, and couple the two sub-models with corresponding $P_{c\rightarrow i,1}$ and $P_{c\rightarrow i,2}$ to determine the final land type. In the operation, if the input type is forest land, grassland, water area, or wetland, the predicted type is determined by the maximum value in the natural conversion probability $P_{c\rightarrow i,1}$. When the corresponding land type is construction land, it is regarded that land type does not change. When the input type is cropland, the initial determination involves assessing whether the plot is subject to policy restrictions as an immutable cropland. If yes, it remains unchanged; if no, calculate the integrated probability $P_{c\rightarrow i}$ according to Eq. (2).

$$P_{c\rightarrow i} = kP_{c\rightarrow i,1} + (1-k)P_{c\rightarrow i,2} \tag{2}$$

Where k=0.5. The land type corresponding to the maximum $P_{c\rightarrow i}$ is the predicted type. If the max($P_{c\rightarrow i}$) corresponds to cropland, it should be compared with decision threshold a additionally. After hyperparameter optimization, a_1 for labor forces and a_2 for non-labor forces are 0.3 and 0.55, respectively (refer to Appendix A.5 for labor classification rules). When $P_{c\rightarrow i}$ does not exceed a, it is converted to the land type with the second largest $P_{c\rightarrow i}$.

The model assumes the age structure distribution of agents aligning with demographic trends in the study area. The model time step is 5 years, and for each run, the age attribute of each agent changes to the present value +5. Considering the case of newborn and dead, when the changed age is greater than 86, the age is set to the changed age -86. The agent's age alteration is utilized for labor classification reassessment.

After training the model using the real data from 2010 and 2015, the model was validated by data from 2015 and 2020. The quantitative evaluation was conducted using the spatial global fit method, which is widely employed in land evolution models (Jantz et al., 2004), as described by Eq. (3).

$$D_i = 1 - \Sigma\frac{S_{m,i}\cup S_{0,i} - S_{m,i}\cap S_{0,i}}{S_{m,i}\cup S_{0,i}} \tag{3}$$

Where D_i is the spatial global fit of land type *i*, $S_{m,i}$ is the distribution of land type *i* from simulation, and $S_{0,i}$ is the actual distribution of land type *i*.

2.1.2. Carbon sink accounting

In this study, the carbon storage and sequestration module of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is adopted for accounting. The carbon storage capacity of land use types is determined by four carbon pools: above-ground organisms, subsurface organisms, soils, and dead organic matter. For croplands, the InVEST model considers the short growth cycle of crops and the unstable carbon storage, the carbon emissions from agricultural production are not included. In addition, the choice of boundaries significantly impacts the calculation of carbon sequestration by crops (Shan et al., 2020). Therefore, only the carbon sequestered by soils was taken into account for croplands.

The carbon sink is calculated as in Eq. (4).

$$Q_{tCO_2} = S_{i\rightarrow j} \times \left(C_{total,j} - C_{total,i}\right) \tag{4}$$

Where Q_{tCO_2} is the total carbon sink of the land type conversion, $S_{i\rightarrow j}$ represents the total area converted from land type *i* to *j*. $C_{total,i}$ is the total carbon density value of land class *i* (Appendix A.6, Dun et al., 2019; Hu et al., 2021; Jiang, 2019; Liu and Zhu, 2020; Mei and Zhang, 2008; Shi et al., 2010; Wang, 2021; Xu, 2013; Zhou, 2023).

2.1.3. Calculation of the economic potential of carbon sinks

This study employs the market value method to calculate the economic potential of carbon sink, as outlined in the "Technical Guide to Accounting for GEP" (September 2020 version), in Eq. (5).

$$V_{cf} = Q_{CO_2} \times C_c \tag{5}$$

Where V_{cf} is the economic value potential of carbon sink ($), Q_{CO_2} is the amount of carbon sink (t C), and C_c is the carbon market price ($/t C), using the average price.

2.1.4. Scenario setting

In this section, we present three scenarios for determining future eco-compensation standards, each with varying degrees of involvement in the carbon market.

(1) Scenario A (Baseline): This scenario assumes no participation in carbon trading, maintaining the current eco-compensation standard at 266,595 US$/(km^2·a).
(2) Scenario B (Low Carbon Price): In this scenario, we assume that afforestation participates in carbon trading. The average allowance price of the Chinese national carbon market is 6.27 US$/t, through March 31, 2022. For the CCER operating period, the historical average ratio of CCER to carbon allowance price is 0.21. Multiply this ratio by allowance price, we assume C_c is 1.34 US$/t. By calculating the potential annual carbon sink value of forest land and adding it to the compensation standard, the carbon sink trading compensation is 290,445 US$/(km^2·a).
(3) Scenario C (High Carbon Price): In this scenario, we assume that CCER prices will align with carbon allowance prices. Using a similar calculation as Scenario B, the carbon sink trading compensation is estimated to be 377,145 US$/(km^2·a).

The assumptions for Scenarios B and C include the successful realization of carbon sink economic value through the carbon market, with zero trading costs. Note that this study tends to use historical prices as the basis for designing scenarios. In the future, with increased emission reduction efforts, there may be higher CCER trading prices.

2.2. Study area

The Chongming Island is located on the eastern coast of China, and at the estuary of the Yangtze River in the western Pacific Ocean (Fig. 3). As of the end of 2021, the land area of Chongming District amounted to 1413 km^2, with a population of 0.67 million. As an urban fringe area, Chongming occupies a significant portion of forests and farmland. It plays a crucial role in promoting ecological protection due to its abundant natural resources. Since 2009, local governments have implemented eco-compensation mechanisms, encompassing Chongming within a significant compensation area. The compensation fund relies mainly on municipal transfer payments, which account for nearly 70 % of the region's fiscal revenue in 2020. In addition, to ensure food supply and the construction of low-carbon demonstration zones, the planning of cropland and construction land is restricted.

2.3. Data source

The data used mainly include land use, administrative divisions, roads,

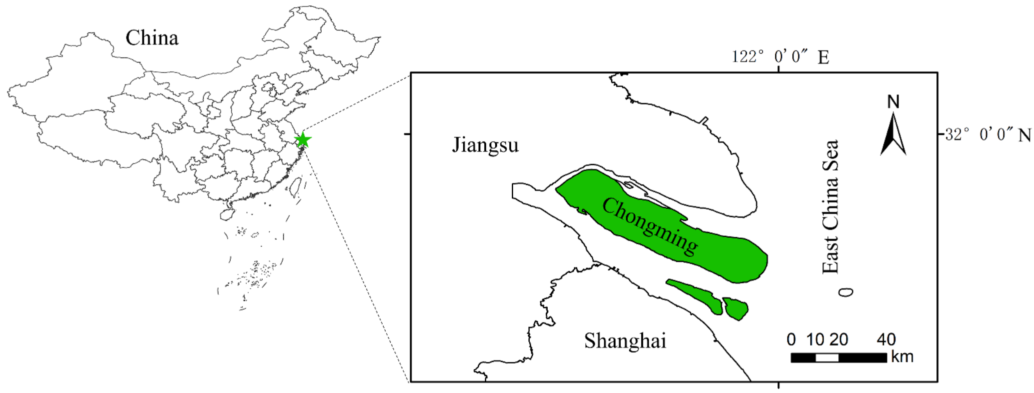

Fig. 3. Location of the study area.

DEM, slope, conventional statistical data, and carbon trading price. The land use data of Chongming District were obtained from the Resource and Environmental Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/data.aspx?DATAID=283). In model building, the original raster data are reclassified (Appendix A.7), based on the reference to the "Current land use classification (GB-T 21010-2017)". Administrative divisions and road data were obtained from the National Basic Geographic Information Center of the Ministry of Natural Resources (https://www.webmap.cn/commres.do?method=result100W). Digital Elevation Model (DEM) data and slope data were obtained from the SRTMDEMUTM 90M resolution data products and SRTMSLOPE 90M resolution slope data products of the Geospatial Digital Cloud Platform of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn). The statistical data were obtained from authoritative sources such as the Shanghai Statistical Yearbook and Chongming Statistical Yearbook. Eco-compensation standards were obtained from Chongming Forestry Station. Carbon quota and CCER trading prices were obtained from Shanghai Environment and Energy Exchange (https://www.cneeex.com).

3. Results

3.1. Carbon sink

The Carbon Storage and Sequestration module of the InVEST model reveals that the regional ecological carbon stock in Chongming District fluctuated between 2010 and 2020 (Table 1). Cropland is responsible for about half of the total carbon stock, making it the primary carbon sink. The growth of construction land and decrease in cropland have a negative impact on carbon sink, while an increase in forest land and grassland has a positive effect. Forest land experienced a net increase in carbon sink from the conversion of other land types to forest land, resulting in a gain of 51,935 t C in the period of 2010-2020.

In terms of land use change characteristics, the cropland area decreases by 3.73 % from 2010 to 2020, with an increased deceleration. Due to the large base of cropland, it is the land type with the largest amount of change in both periods. From 2010 to 2015, the reduction in cropland primarily occurred in Chengqiao Town and the southern region of Chongming Island, most being converted into construction land. From 2015 to 2020, the decrease in cropland was mainly observed in the northwestern part of Dongping Forest Park and Chengqiao Town, where it was transformed into construction land. Additionally, there was a conversion from cropland to forest land near existing forests and ecological corridors in the northwestern area of Chongming. From 2010-2020, the area of forest land increased by a total of 7.33 %, including a 0.05 % decrease from 2010-2015 and a 7.96 % increase from 2015-2020. It is related to the construction of the welfare forest and ecological corridor. Benefiting from the existing compensation mechanism, land conversion from cropland is the main contributing factor to carbon sink in forest land. The carbon sink from cropland to forest land was 56,374 t C from 2010 to 2015 and increased by 4.4 times to reach 305,233 t C from 2015 to 2020. In the Chongming District 2035 Plan, from the base year 2016 to the target year 2035, the cropland area will decrease by about 29.8 %, and the forest land area increase by about 114.8 %. It is consistent with the characteristics shown in this study, indicating that the plan has an implementation effect. These results suggest a strategic shift in land use from agricultural to more sustainable and ecologically beneficial uses, which could have implications for biodiversity, carbon sequestration, and overall environmental health. The data also underscores the importance of planning and policy in guiding sustainable development and land management practices.

Using the average price of CCER 5.10 US$/t CO_2eq in 2021, the carbon sink economic potential of the net increase of forest area from 2010 to 2020 is 998,500 US$. According to the eco-compensation standard of Chongming District (Appendix A.8), multiplying the net increase in forest area for 2010-2015 and 2015-2020 by the mean compensation standards respectively the total eco-compensation of forest land is about 3,254,800 US$. If the net increase of carbon sink on forest land is traded through a market mechanism, it is equal to 30.69 % of eco-compensation funds in that period. It demonstrates the efficacy of carbon sink market trading as a diversified form of eco-compensation. Combining both approaches can enhance the economic benefits and sustainability of forestland expansion.

Table 1
2010/2015/2020 regional carbon stock in Chongming District (area in km^2, carbon stocks in Kt C).

Land use types	2010		2015		2020	
	area	carbon stock	area	carbon stock	area	carbon stock
Cropland	1068.52(73.0 %)	3434.40	1056.82(72.2 %)	3396.80	1030.13(70.4 %)	3311.01
Forest land	31.87(2.2 %)	866.72	31.85(2.2 %)	866.17	34.39(2.4 %)	935.25
Grassland	3.83(0.3 %)	57.51	6.54(0.5 %)	98.21	5.9(0.4 %)	88.60
Wetland	110.69(7.6 %)	683.77	108.95(7.5 %)	673.03	106.83(7.3 %)	659.93
Water area	89.41(6.1 %)	725.12	93.56(6.4 %)	758.77	97.83(6.7 %)	793.40
Construction land	158.9(10.9 %)	802.45	165.51(11.3 %)	835.83	188.14(12.9 %)	950.10
Total	1423(100 %)	6569.97	1423(100 %)	6628.81	1423(100 %)	6738.29

3.2. Simulated land use change under different market scenarios

The model test shows that the global spatial fitting degrees of cropland, forest land, grassland, wetland, construction land and water are 98.6 %, 94.6 %, 82.6 %, 93.1 %, 70.8 %, and 98.2 %, respectively. Consistent with the map analysis, the model exhibits high accuracy in predicting changes in cropland, woodland, wetland, and water area, compared to construction land. This discrepancy can be attributed to the study's emphasis on farmers. Considering the restrictions on future construction land expansion in government planning and the research focus, this model is suitable for subsequent studies or similar research focusing on agricultural land.

The model simulates the results of the distribution of land types in 2025 under different scenarios (Table 2). When the eco-compensation standard is increased, the area of forest land increases while the area of cultivated land decreases. Comparing different scenarios, when the agents get additional compensation from the carbon market (Scenario B and Scenario C), the increase in forest land area is 12.1 % and 33.05 % compared with Scenario A, respectively.

In addition, the natural carbon sinks from land change in the period of 2020-2025 under the three scenarios are 963,440 tons, 1,084,022 tons, and 1,291,665 tons, respectively. Compared with 2020, in 2025, the carbon stock is expected to increase by 4.94 %, 5.46 %, and 6.33 % for the respective scenarios. Scenario B increases the standard of eco-compensation by 8.94 % and the increase of carbon sink by 12.52 % compared with Scenario A. While Scenario C increases the standard of eco-compensation by 41.46 % and the increase of carbon sink by 30.28 %. The findings demonstrate that incorporating carbon trading benefits as a supplementary measure to the existing fiscal-based eco-compensation is advantageous for enhancing carbon sinks. By including existing afforestation projects in the current CCER trading system, a substantial amount of funds can be provided by the market, thereby significantly increasing carbon sinks. Considering the upward trend in CCER prices, which may reach or even exceed the high carbon price scenario setting, there is greater potential to support local ecological development in the future.

From the spatial distribution (Fig. 4), scenarios B and C have more forest land parcels on the basis of scenario A, which are mostly distributed near the existing forest land. The scenario comparison shows that with the increase in carbon price and eco-compensation standard, some forest land tends towards being contiguous.

4. Discussion

4.1. The refined simulation based on agent decision behavior

This study explicitly considers that land evolution is influenced by both natural and socio-economic aspects, and thus proposes the ANN-ABM land evolution model. It reflects the interaction of natural processes, farmer agents, and socio-economic mechanisms of innovation at the micro level, also provides macro-level simulation results of land changes.

On the ABM model, an ANN model is introduced, which is able to simulate the complex nonlinear relationship between natural factors and land decision-making, compensating for the limited simulation effect of the natural driving factors by the ABM model. ABM models typically focus on agent decision algorithms, public policies, and spatial proximal attributes, limitations in the selection of natural elements may lead to biases in the results (Coelho & Ralha, 2022). While some studies used self-designed rules related to natural elements in analyzing the effectiveness of ecosystem service payments, researchers noted that these rules are not sufficient to simulate complex interactions in a system (Chen et al., 2014). Additionally, in some studies, ABM is coupled with CA, where the Logistic regression method is commonly used to obtain model parameters (Liu et al., 2013). The advantage of this approach is its simplicity and practicality, but linear models may struggle to reflect the nonlinear and complex features involved in land use change. The ANN model can incorporate more natural elements, addressing the limitations of ABM models in simulating the effects of natural driving factors. By training the neural network, it can flexibly handle new parameters and complex nonlinear relationships even when mathematical models have not been proposed in existing studies.

In constructing the ABM model, the model takes into account the farmers' decision-making under eco-compensation changes and models the decision-making process at the individual level. The study compiles literature on the agent behaviors and local situations to design attributes and decision rules for the farmers. The actual eco-compensation situation and policy scenarios are also introduced to achieve a small-scale refined simulation of the county area. Based on existing research that has demonstrated the critical role of farmers' diversified decision-making in shaping landscape structure (Valbuena et al., 2010), this study extends the mechanisms related to marketization and carbon sink enhancement. Previous case studies have focused more on how market mechanisms influence agent behavior (Chang et al., 2022; Ren et al., 2020). This study utilizes the bottom-up characteristics of ABM to connect carbon prices with macro-level regional land changes and carbon sinks. This approach facilitates the comparison of simulation results with regional carbon goals and land management objectives. This describes how combining spatial regulation with carbon markets can significantly enhance carbon sinks, providing policymakers with an intuitive reference for understanding the efficacy of the carbon market.

Overall, the model provides a methodology for the simulation of complex systems under the combined effects of nature and society. The model framework can be used in other small-scale studies to simulate land evolution as a basis for analyzing the effects of compensatory changes.

4.2. Policy implications

(1) Optimize the ecological spaces through targeted investment in space and agents

The model simulation results indicate that the new forests are primarily located in close proximity to existing forested areas, with the majority of them filling the gaps between the pre-existing forest lands. Studies of land change under different scenarios show that forested land tends to expand into areas with healthy environments, stable climate conditions and low economic growth rates (Wang et al., 2022b). Considering the

Table 2
2025 area changes and ecological carbon stocks for different land types, under different scenarios (changes are based on 2020, in km^2, percentages in parentheses are the improvement when comparing with scenario A; carbon stocks are in Kt C).

Land use types	Scenario A			Scenario B			Scenario C		
	area	area change	carbon stock	area	area change	carbon stock	area	area change	carbon stock
Cropland	1009.3	-20.83	3244.1	1007.72	-22.41(-7.6 %)	3239.0	1004.88	-25.25(-21.2 %)	3229.9
Forest land	45.13	10.74	1227.3	46.43	12.04(+12.1 %)	1262.7	48.68	14.29(+33.1 %)	1323.9
Grassland	6.01	0.11	90.2	6.11	0.21(+90.9 %)	91.7	6.22	0.32(+190.9 %)	93.4
Water area	104.37	6.54	846.4	104.38	6.55(+0.2 %)	846.5	104.41	6.58(+0.6 %)	846.8
Wetland	110.28	3.45	681.3	110.45	3.62(+4.9 %)	682.3	110.9	4.07(+18.0 %)	685.1

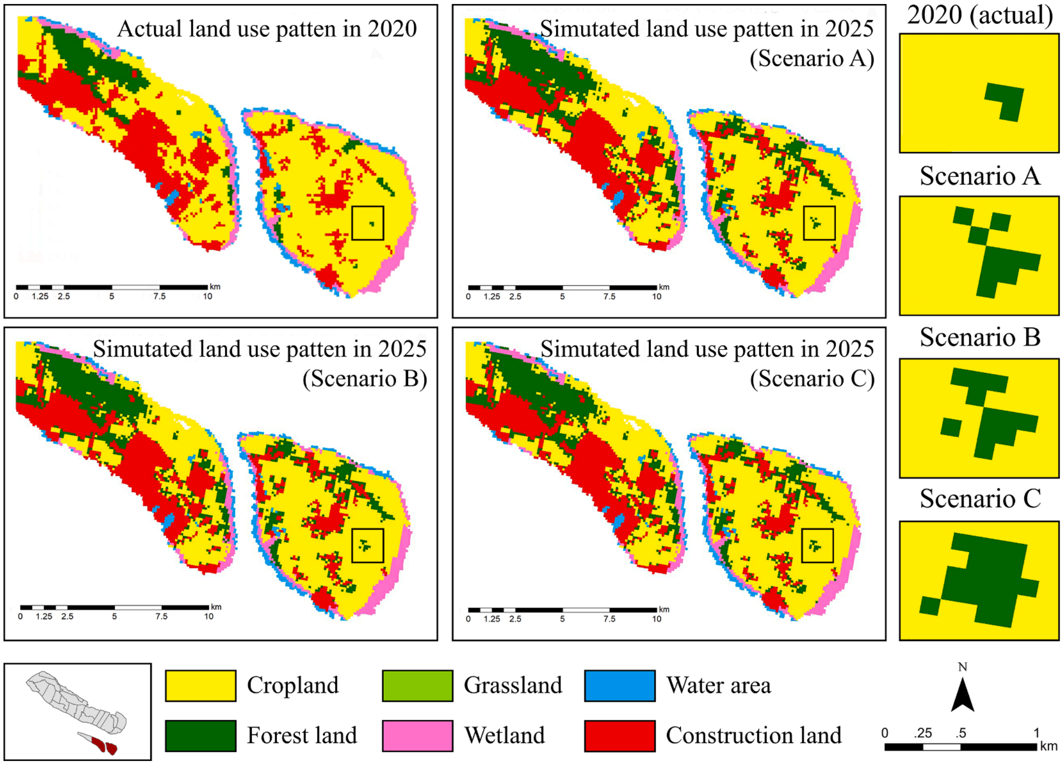

Fig. 4. Simulated maps of land types in Changxing and Hengsha Island in 2025 under different scenarios. (The right figure represents a localized simulation of the boxed area depicted in the left figures).

expansion pattern and ecological protection, contiguous-forest is easy to form and has better value in ecosystem services. In other words, for the same cost, these regions have better output. Similarly, in the discussion of agents, it is evident that different agents exhibit varying responses to the same compensation standard. It is necessary to further clarify the agent's behavior through mechanism research, and different strategies are needed to be designed for different agents. Existing studies mention that it is necessary to adjust compensation parameters in corresponding pilot projects to provide different compensation for agents with different natural and economic conditions, so as to improve the benefit distribution system and optimize the carbon sink enhancement effect (Miles & Kapos, 2008; Hoang et al., 2013). Future market mechanism interventions need to focus on such areas with greater potential and agents who are willing to change their land decisions at a lower cost. In addition, enhancing carbon stock in specific land use types is crucial for increasing regional carbon sinks. This can be achieved through measures such as forest conservation and the implementation of sponge cities (Yin et al., 2022; Gao et al., 2024). It is essential to enhance the compensation mechanism for these approaches. In this way, the carbon sink can be enhanced by expanding ecological space and improving regional ecological quality.

(2) Use the market mechanism to optimize the structure of eco-compensation funds.

The carbon market can effectively promote the green transformation of regional economies (Qian & Zhou, 2024), by increasing the market value of forest protection to enhance forest carbon sinks. In case studies, under higher carbon prices (17\$/t CO_2eq), sufficient incentives can enable farmers to participate in forestry carbon sink projects and maximize profits (Chang et al., 2022). Sinacore et al. (2023) note that a combination of carbon payments and subsidies is necessary for cash-strapped rural landowners in most cases, otherwise woodland restoration approaches may appear financially unviable. Our research demonstrates that carbon markets can be used in conjunction with eco- compensation, greatly increasing the available funds. The integration of forest carbon sinks into the carbon market enables a faster transition of alternative land uses to forest land. The Chongming District 2035 Plan aims to increase the forest area by 114.83 % compared to that in 2016, resulting in an estimated growth of 36.57 km^2. Use the average annual growth rate under different scenarios to roughly predict the composition of land types in 2035: It is estimated that the forest area in 2015-2035 will increase by 34.76 km^2, 38.66 km^2, and 45.41 km^2, respectively, under the three scenarios set in this study. These findings suggest that without adjusting the eco-compensation standard for forestry, it is difficult to achieve the forest growth target according to the predicted trend. However, under both the low-carbon price (1.34\$/t CO_2eq) and high-carbon price (6.27\$/t CO_2eq) scenarios, the target has a higher possibility of being successfully achieved. The results confirm that CCER, as an important mechanism in the carbon market, can help to achieve the forest land growth target. The market mechanism of compensation can make funding sources more diversified and alleviate financial pressure. It optimizes financial flows, which is essential for sustainable development. However, relying solely on government compensation or market mechanisms alone may face funding shortages (Chang et al., 2022). It is recommended to use diversified mechanisms to mitigate the risks of failure from a single mechanism.

(3) Improve market-related mechanisms as an important part of the overall plan for carbon sink enhancement

This study explores the potential of market mechanisms in promoting sustainable development in forestry, as well as advancing long-term carbon neutrality goals. The results indicate that carbon trading significantly enhances local residents' income and forest carbon sinks, providing valuable insights for the government in carbon trading and pricing. We recommend further refinement of market mechanisms to advance sustainable development in rural areas. In parallel, the market mechanism can be considered to be a necessary tool to help the transformation of carbon-neutral. As a significant step towards advancing market mechanisms, in 2024, China implemented legislation on eco-compensation, which highlights the importance of market mechanisms. However, application is still limited by technology and mechanisms, so further refinement of the regulations is necessary in order to expedite policy implementation. It is essential to optimize the mechanism for setting carbon prices, release positive and stable price signals to the market, and increase carbon trading prices through policy design and market regulation. In order to enhance participants' confidence, and fully leverage the role of forest carbon sinks in achieving long-term carbon neutrality goals (Huang et al., 2020). To support market development, the assessment system needs to be established and perfected, taking into account monitorability, reportability, and verifiability when expanding tradable carbon sinks. Simultaneously, establish and improve the trading and utilization mechanisms for carbon sink certificates, and implement incentive policies to encourage enterprises to participate in the purchase of the certificates. Studies on the implementation of compensation mechanisms indicate that, in addition to the level of payment, the benefit-sharing mechanism also plays a significant role in determining the realization of compensation (Sun et al., 2023; Hoang et al., 2013). Carbon sink revenue funds can be managed through carbon sink banks or other forms, and a reasonable compensation allocation mechanism for carbon sinks needs to be established. A good mechanism also lies in close cooperation, and it is necessary to mobilize related parties to participate in the development of local ecological carbon sinks.

4.3. Limitation and uncertainty

The study has established an ANN-ABM model, which provides a method for evaluating and simulating carbon sinks and their value. This model is applicable to regions with multiple decision-making agents and plans for enhancing carbon sinks. However, the limitations of the ANN-ABM model can be multifaceted, often involving issues related to data, model structure, and the generalizability of findings. In practical applications, it is important to make adjustments and evaluations according to specific situations in order to ensure the accuracy and reliability of the model.

(1) The current model simulates the ecological areas related to the croplands well, but it tends to underestimate the impact of land expansion due to planning. For instance, the limited simulation effect of land development can be attributed to the farmers as key players in this study. In fact, the process of urban expansion process is also influenced by participation behavior from government and other stakeholders. Considering the direct contribution of construction land to carbon sinks is limited, its impact on the overall simulation results can be disregarded, thereby allowing for the application of the model in analyzing future carbon sinks.
(2) The simplified modeling process also brings uncertainties to the results. This includes the modeling process of using random attribute assignments for the agents based on literature references, due to the difficulty of obtaining region-specific agent data. Better simulation results are expected by obtaining agent attributes with spatial information, or considering the spatial heterogeneity of agents and the spatial aggregation effect.
(3) The accuracy of results will be significantly impacted by the reasonableness of the parameters and decision-making rules in the methods. In this study, localized parameters and rules were set through credible literature survey. However, there are differences in the parameters of agents and the pricing of eco-compensation in different regions. This may lead to heterogeneity in the effectiveness of carbon markets (Qian & Zhou, 2024). If this model is to be used in other areas, relevant parameters need to be reset. In addition, the application of the model should consider the main decision-making agents, and further improve the relevant decision-making rules of other agents according to the characteristics of the study area. More case studies are encouraged to demonstrate the effectiveness of market mechanisms in enhancing carbon sequestration.
(4) Due to the lack of an effective local market mechanism, an ideal carbon trading market is assumed in this study, and the accounting of carbon sink value potential is based on the average price in the carbon market. The actual trading process has price fluctuations, and the transaction price and transaction probability of carbon sink transactions are also influenced by the attributes and behaviors of buyers and sellers. In future research, the price setting of this model can be dynamically optimized by combining the relevant models of the market mechanism.

5. Conclusion

One of the challenges that developing countries face in transitioning to sustainable development is the transformation of ecological advantages into economic gains. One feasible approach is to utilize market mechanisms to compensate for ecological conservation efforts. This study aims to quantify the potential transaction value of previous forestry projects. Additionally, through scenario simulations, it analyzes the variability in the impact of carbon prices on carbon sinks, providing specific references for government carbon pricing. More importantly, a bottom-up approach is proposed to evaluate the role of carbon trading in enhancing regional carbon sinks.

Based on county-scale studies, it was found that the potential value of increased forest carbon sink in Chongming District from 2010 to 2020 is comparable to 30.69 % of the eco-compensation in the same period. This suggests that carbon sink market trading can offer a means for diverse forms of eco-compensation. Furthermore, in order to understand the relationship between compensation and land evolution within a marketized context, this study introduces a simulation model that combines Artificial Neural Network (ANN) and Agent-Based Model (ABM). The ABM model incorporates varying decision-making rules related to eco-compensation for farmer agents, providing insight into micro-level behavior and its macro-level effects. The ANN model is used to simulate the complex dynamics of natural drivers on land change, compensating for the shortcomings of ABM. The test proves that it works well in the study with farmers and cultivated land as the main target. The simulation results of the land changes in 2025 show that the carbon trade, as a supplement to the existing fiscal-based eco-compensation, can increase the probability of converting land near existing ecological space to high carbon sink land, which makes the ecological space expand and increases the carbon storage.

This study concluded that the market-based eco-compensation mechanism should be further improved to support the development of ecological carbon sinks. Meanwhile, land planning around forest land should be emphasized to build a connected ecological spatial layout. In the carbon neutral action, a carbon sink enhancement action plan combined with the market mechanism should be developed to achieve sustainable development transformation.

This study presents a practical framework for the valuation and simulation of carbon sinks, while the ANN-ABM model offers a means to examine changes in ecological patterns resulting from individual behavior. It can serve as a foundation for exploring the interaction of natural processes, individuals, and innovations in socio-economic mechanisms. The case study assists researchers and policymakers in deepening their understanding of the market mechanisms affecting land change and provides theoretical support for relevant policy development.

CRediT authorship contribution statement

Ruimin Lin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Ru Guo:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Yunyang Li:** Methodology, Formal analysis, Data curation, Conceptualization. **Guanghui Shao:** Writing – review & editing, Investigation. **Yuhao Zhang:** Writing – review & editing, Investigation. **Kaiming Peng:** Writing – review & editing, Project administration. **Xiangfeng Huang:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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