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The stakeholder game mechanisms in land use change of Caohai National Nature Reserve

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Understanding the decision-making mechanisms of stakeholders in land use changes within wetland areas is critical for managing land resources effectively and mitigating conflicts. This study applies a game-theoretic approach to examine the strategic interactions among key stakeholders—managers, developers, and residents—within the Caohai National Nature Reserve (CNNR) in China. By integrating real data on land use changes, ecological quality indices, and economic incentives, this study identifies the driving forces behind stakeholder behavior and land use evolution from 2000 to 2020. The land use changes and ecological effects in the CNNR can be divided into two main stages: From 2000 to 2010, the primary direction of land use change was the conversion of grassland into construction land and farmland, resulting in the deterioration of ecological environment quality. From 2010 to 2020, the main direction of land use change shifted to the conversion of farmland into grassland and forest land, leading to an improvement in ecological environment quality. Game-theoretic analysis demonstrates that managers play a decisive role in shaping stakeholder strategies through regulatory mechanisms, such as land rent adjustments, penalties, subsidies, and ecological compensation. Stronger enforcement of penalties and incentives significantly enhances cooperative behavior among stakeholders, reducing land use conflicts and promoting ecological recovery. These findings emphasize the necessity of targeted governance strategies to align stakeholder interests and balance ecological conservation with socio-economic development. The insights from this study provide valuable guidance for policymakers and land managers in designing effective land use policies and improving conservation efforts in wetland-protected areas.

Keywords Land use, Game theory, Multi-stakeholder interactions, Strategic equilibrium

Land use refers to the human activities involved in developing and utilizing land resources, shaping the environment and ecosystems[1]. Changes in land use result from complex interactions among various stakeholders, including government agencies, developers, and local communities[2,3]. Understanding these changes is crucial for identifying their impacts on biodiversity and ecosystem services, and for developing conservation strategies that balance ecological preservation with socio-economic development[4,5]. Land use conflicts often arise when the needs of different stakeholders—such as farmers, urban developers, and environmental organizations—clash over the use, ownership, or management of land[6,7]. These conflicts can intensify as urbanization and industrialization place increasing pressure on land resources, particularly in areas with high ecological value[8,9]. Resolving these conflicts requires understanding the strategic decisions of stakeholders and creating policies that align their interests to achieve sustainable land use outcomes. Game theory offers a powerful tool for analyzing such conflicts, as it models the strategic interactions among stakeholders with competing or complementary interests[10–13]. By focusing on the decision-making processes of rational actors, game theory can provide insights into how stakeholders might behave in situations involving competition, cooperation, and negotiation[14,15]. In environmental studies, game theory has been applied to various issues, such as stakeholder coordination in environmental regulation[16] and cross-jurisdictional water pollution management[17]. More recently, scholars have applied game theory to land use conflicts[18,19], examining the strategies of stakeholders involved in land acquisition[20], land conversion[21], and farmland protection[22]. However, traditional game theory models often rely on assumptions of perfect rationality and static decision-making, which do not always reflect the real-world complexities of land use conflicts. In practice, stakeholders face uncertainty and asymmetry of information,

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which can lead to suboptimal decision-making. Dynamic game models, which incorporate limited rationality and allow for evolving strategies over time, offer a more realistic approach to modeling stakeholder interactions[23,24].

Wetlands, especially those within nature reserves, present a unique context for land use analysis due to the presence of multiple stakeholders and the delicate balance between conservation and development[25–28] (Sun et al. 2015). The Caohai National Nature Reserve (CNNR), a subtropical karst plateau wetland in southwest China, exemplifies the complex interactions between ecological protection and socio-economic development. Land use in the CNNR has been increasingly influenced by competing interests, including tourism development, agriculture, and conservation efforts, leading to significant land use conflicts and environmental degradation[29–31]. This study focuses on the CNNR, aiming to analyze the evolution of land use in this wetland area using a game-theoretic framework. Specifically, we seek to understand the dynamics of stakeholder strategies and their impact on land use outcomes. This research builds on previous studies of land use in wetlands, extending them by incorporating real data from surveys and remote sensing images, and providing a more nuanced understanding of the stakeholder interactions driving land use changes.

The objectives of this study are as follows: 1. To examine the spatiotemporal patterns of land use and ecological quality changes in CNNR over the past two decades. 2. To identify the driving mechanisms behind these changes by constructing a stakeholder game model. 3. To analyze the influencing factors and interactive mechanisms of stakeholder strategy choices through numerical simulations. By addressing these objectives, this study aims to provide valuable insights for policymakers and land managers in CNNR, offering strategies for resolving land use conflicts and promoting the sustainable development of both the environment and local communities.

Materials and methods

Study area

Located in Weining Autonomous County, Guizhou Province of China, Caohai National Nature Reserve (CNNR) is a typical karst plateau wetland ecosystem, listed as one of the world's top ten highland wetland birdwatching areas (Fig. 1). Its geographical coordinates range from 26° 47′ 32″ N to 26° 52′ 52″ N and from 104° 10′ 16″ E to 104° 20′ 40″ E. Characterized by a subtropical semi-humid monsoon climate, it boasts an average annual temperature of approximately 10.6 °C, with an average relative humidity of 79% and an average annual precipitation of about 950.9 mm. Adjacent to Weining County, Caohai faces increasing challenges due to rapid urbanization and population growth, leading to escalating pollution, ecological degradation, and encroachment with the phenomenon of "urban expansion, lake retreat" becoming more pronounced. Particularly, the "enclosure of lakes for cultivation" initiated in 1958 drastically reduced the water area of Caohai to only about 5 km^2 by 1972. In order to effectively conserve the ecological environment of Caohai wetlands, water storage restoration commenced in 1982, followed by the establishment of Caohai Protection Area approved by the

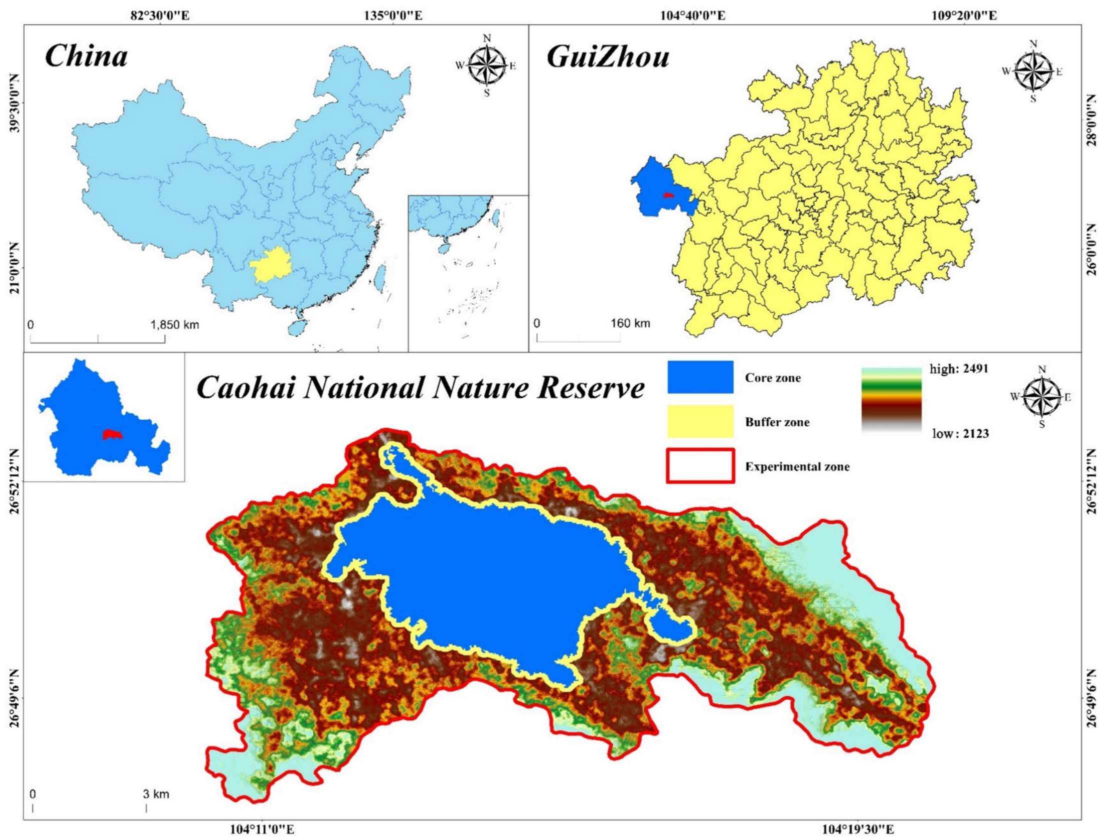

Fig. 1. Location of the study area. The figure is created using ArcMap10.7, https://www.arcgis.com.

Guizhou Provincial Government in 1985, and its subsequent upgrade to a national-level nature reserve by the State Council in 1992. With a total area of 96 km^2, the CNNR is divided into three functional zones: core zone, buffer zone, and experimental zone. The core zone, approximately 21.62 km^2 in area, is defined by the water area, herbaceous swamp, grassland, and distribution areas of aquatic vegetation formed during the highest water level period within a year. The buffer zone, extending approximately 100–500 m from the periphery of the core zone, covers about 5.40 km^2. The remaining area beyond the buffer zone constitutes the experimental zone, covering approximately 68.98 km^2. The CNNR ecosystem, with its long history of natural evolution marked by periods of extinction and recovery, serves as a quintessential case study for investigating the impact of human activities on the natural environment. It represents a comprehensive embodiment of natural history, playing an irreplaceable role in maintaining and regulating the sustainable development of local and surrounding ecological environments.

Data sources and research framework

The primary data sources for this study consist of two components: (1) vector data, including land use/land cover, administrative boundary vectors, and Digital Elevation Model (DEM). The land use/land cover data for three time periods (2000, 2010, and 2020) with a resolution of 30 m are obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (RESDC) (http://www.resdc.cn/, accessed on January 21, 2024), administrative boundary vectors is from the National Geomatics Center of China (https://www.ngcc.cn/), while the Digital Elevation Model is sourced from Geographic Spatial Data (https://www.gscloud.cn/). These datasets, based on Landsat TM/ETM and Landsat 8 satellite remote sensing data, are constructed through interactive visual interpretation and primarily employed for analyzing changes in land use and ecological environment quality. (2) Statistical data encompass field survey questionnaire data, socio-economic statistical yearbooks of the CNNR, and data from major development strategies and planning policies formulated in recent years. Prior to the formal investigation, a preliminary field survey was conducted in the study area to understand the current status of land use in the CNNR. Additionally, based on the fieldwork, the main stakeholders of land use and their basic interrelationships were identified. Subsequently, a questionnaire was developed based on the findings from the preliminary survey. The questionnaire consisted of both quantitative and qualitative questions, designed to gather a wide range of information regarding the stakeholders' interests, preferences, and strategic decisions. The main content of the questionnaire included three sections (see Appendix A for details). The first section requests respondents to provide basic personal information. In the second section, respondents are asked to evaluate the strategic choices of land use stakeholders. Finally, the third part of the survey requires respondents to assess the interrelationships among the three parties based on the behaviors of the tripartite stakeholders in land use. The broad range of questions across these categories ensured that we captured a holistic view of the land use decision-making process, making the data both comprehensive and valid. By including both open-ended and closed-ended questions, we were able to obtain both in-depth qualitative insights and quantifiable data, which we could use to parameterize the game model effectively. Furthermore, the survey was piloted with a smaller sample to test for clarity, reliability, and validity of the questions, leading to refinements before full implementation. The survey results were collected face-to-face from July 23 to 25, 2023, with a total of 400 questionnaires distributed. The survey targeted a representative sample of stakeholders directly involved in land use decisions, including landowners, government officials, environmental groups, and local community residents. Among the 400 questionnaires, 392 were valid, resulting in a response rate of 98%.

The research framework is depicted in Fig. 2. Initially, based on remote sensing image data, the study investigates the area and extent changes of different land use types in the CNNR from 2000 to 2020, revealing corresponding variations in the ecological environment quality of the reserve and identifying different developmental stages concerning economic, social, and ecological aspects. For details on this part, please refer to our previous article[32]. Simultaneously, a land use evolution game model of the reserve is constructed based on statistical and questionnaire survey data. Subsequently, the process of land use evolution game in the reserve is analyzed, integrating empirical research results of land use into equilibrium point analysis of evolutionary game strategies to quantify the parameters of the evolutionary game model and identify constraints on stable strategies of stakeholders' land use in different periods. Finally, numerical simulation of the land use evolution game process in the reserve is conducted using Matlab to explore factors influencing the selection of stakeholder strategies.

Methods

Sample size determination using the Kukran Formula

To determine the appropriate sample size for the questionnaire, we applied the Kukran formula[33], which is expressed as:

$$n = \frac{Nt^2 s^2}{Nd^2 + t^2 s^2} \tag{1}$$

where n is the required sample size, N is the total population, t represents the percentage of the standard error corresponding to the accepted coefficient of determination, d denotes the confidence level or acceptable margin of error, and s is the proportion of the population without a specific characteristic. This formula accounts for population size and variability, ensuring a statistically reliable sample while balancing precision and feasibility. In this study, the total population $N = 44{,}000$, $t = 1.96$, $d = 0.05$, $s = 0.5$.

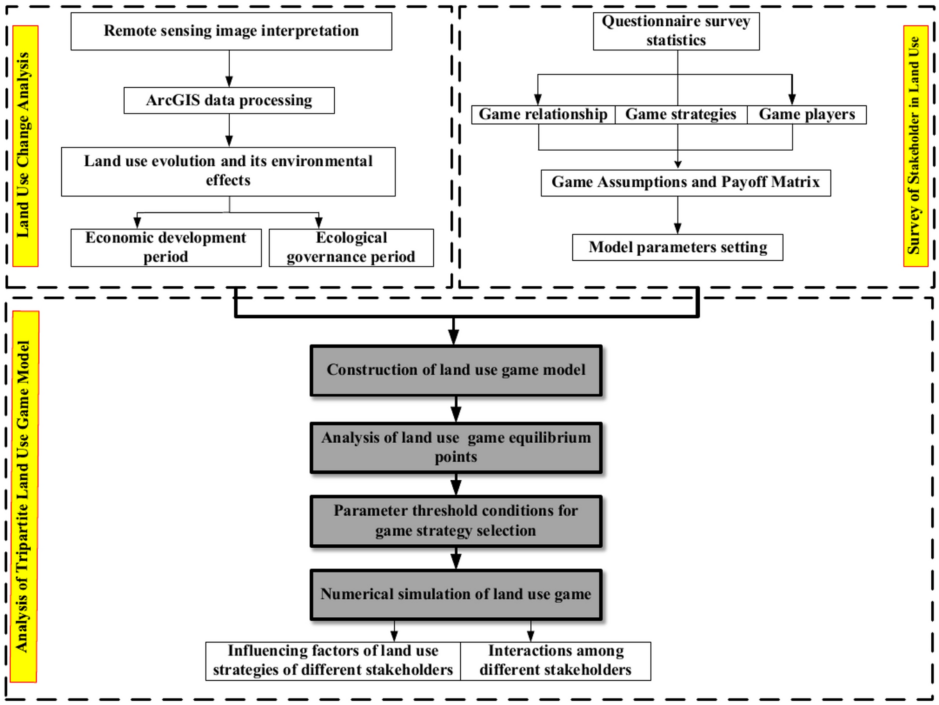

Fig. 2. Research framework of the study.

The game model of the CNNR

The temporal and spatial characteristics of land use can unveil surface reasons for land use conflicts. However, the fundamental causes leading to issues such as territorial competition and ecological degradation stem from the unequal distribution of socioeconomic or ecological benefits among various stakeholders involved in land development[34,35]. Based on actual land use and questionnaire survey results in the CNNR, three categories of stakeholders—managers, developers, and residents—are selected as the focus of land use interest in the study area, where their strategic gains equal strategic income minus strategic costs.

(1) Assumption of players.

a. Managers refer to the multi-level governmental entities responsible for the construction and administration of the CNNR. This includes both local and central government agencies, such as the reserve management bureau, forestry department, environmental protection department, and land resources department. Managers function as policymakers, implementers, and regulators, providing technical, financial, and administrative support for the reserve's sustainable development while overseeing and guiding the actions of other stakeholders.
b. Developers encompass socio-economic entities operating within or near the CNNR, including factories, tourism agencies, hospitality businesses, and retail enterprises. These actors utilize the reserve's ecological resources for economic activities, contributing to local development but also posing potential environmental risks, necessitating regulatory oversight.
c. Residents are individuals living within or near the CNNR whose livelihoods are partly dependent on its resources. Their interests often intersect with conservation efforts, requiring policy interventions to balance economic needs and environmental protection. Residents play a dual role as beneficiaries and active participants in conservation initiatives.

(2) Payoff matrix and strategies.

From the actual situation of land use and ecological environment changes in the CNNR over the past 20 years, the period from 2000 to 2010 can be characterized as a stage of rapid socioeconomic development, while the period from 2010 to 2020 can be characterized as a stage of ecological governance. Therefore, strategies for different stakeholders in land use conflicts in the study area are established based on these two aspects. Assuming all three parties act with bounded rationality, according to the principle of maximizing interests, when the manager chooses to supervise, the probability is denoted as x. Consideration includes providing subsidies for green development to developers and penalties for illegal development, as well as additional subsidies for residents, including land acquisition compensation, wetland restoration compensation, and rewards for reporting illegal activities. When the manager chooses not to supervise, the probability is $1-x$, considering the bribes received from developers and the losses incurred by forcibly acquiring land from residents. When developers choose green development, the probability is denoted as

Parameters	Description	Parameters	Description
m	Land price (RMB yuan/km^2)	S_1	Managers levy the area used for construction (km^2)
n	Managers levy land prices for cultivated land (yuan/km^2)	S_2	The area of cultivated land transferred to construction land (km^2)
θ	Managers provide compensation to residents for land retirement (yuan/km^2)	S_3	Residents occupying land designated for cultivation (km^2)
λ	Managers provide subsidies to developers for green development (yuan/km^2)	S_4	The area of land retired by residents from cultivation (km^2)
α	Managers impose penalties on developers for polluting behavior (yuan)	S_5	The area of cultivated land expropriated by managers (km^2)
η	Residents fined for illegal land occupation (yuan/km^2)	S_6	The area of cultivated land rented by developers from residents (km^2)
Ug	Developers bribing managers (yuan)	h	The agricultural income from land by residents (yuan/km^2)
P	Managers reward residents for supervising developers (yuan)	f	Rent paid by developers for leasing agricultural land from residents (yuan/km^2)
β	Developers' profits from land development (yuan/km^2)	R	Socio-economic benefits per unit of land-use intensity(M)
ω	Illegal gains from developers' unauthorized development (yuan)	G	Ecological benefits per unit of Ecological Environment Quality Index (EEQI)
A	The economic impact on residents from developers' illegal development (yuan)	W	$W = M \cdot R + EEQI \cdot G$ W: Total socio-economic and ecological benefits of the protected area

Table 1. Parameters and their meanings in the game model.

Strategy selection	Managers: Supervision *(x)*	Managers: No supervision *(1 – x)*
Developers		
Green development *(y)*		
Residents		
Cooperation *(z)*	$W + (S_1 + S_5)(m - \lambda) - nS_5 - \theta S_4$ $(S_1 + S_5)(\lambda - m) - fS_6 + (S_1 + S_2)\beta$ $fS_6 + nS_5 + \theta S_4 - h(S_2 + S_4)$	$(S_1 + S_5)m - nS_5$ $(S_1 + S_2)\beta - (S_1 + S_5)m - fS_6$ $fS_6 + nS_5 - hS_2$
Non-cooperation *(1 – z)*	$(S_1 + S_5)(m - \lambda) - nS_5 + \eta S_3$ $(S_1 + S_5)(\beta + \lambda - m)$ $nS_5 - h(S_5 - S_3) - \eta S_3$	$(S_1 + S_5)m - nS_5 - W$ $(S_1 + S_5)(\beta - \mathrm{m})$ $nS_5 - h(S_5 + S_3)$
Illegal development*(1 – y)*		
Residents		
Cooperation *(z)*	$(S_1 + S_5)m - nS_5 - \theta S_4 + \alpha - P$ $(S_1 + S_2)\beta - (S_1 + S_5)m - fS_6 - \alpha + \omega - A$ $fS_6 + nS_5 + \theta S_4 - h(S_2 + S_4) + P$	$(S_1 + S_5)m - nS_5 + Ug - W$ $(S_1 + S_2)\beta - (S_1 + S_5)m - fS_6 + \omega - Ug$ $fS_6 + nS_5 - hS_2 - A$
Non-cooperation *(1 – z)*	$(S_1 + S_5)m - nS_5 + \alpha + \eta S_3$ $(S_1 + S_5)(\beta - m) - \alpha + \omega$ $nS_5 - h(S_5 + S_3) - A - \eta S_3$	$(S_1 + S_5)m - nS_5 + Ug - W$ $(S_1 + S_5)(\beta - m) + \omega - Ug$ $nS_5 - h(S_5 + S_3) - A$

Table 2. Payoff matrix of the game model in the CNNR.

y, considering dividends for managers and land rent for residents. When developers choose illegal development, the probability is *1 – y*, considering the illegal gains of developers and the economic losses incurred by residents. When residents choose to cooperate, the probability is *z*, considering the lawful income from land use. When residents choose not to cooperate, the probability is *1 – z*, considering the penalties for residents' illegal occupation of land. The specific settings of the game model parameters and the payoff matrix are shown in Tables 1 and 2 respectively.

(3) Managers' expected benefits.

Managers can either supervise or not supervise land use activities. V_1 (Supervision Strategy): Managers receive land pricing revenue (*n*). They collect penalties (*α, η*) from illegal activities. They distribute rewards (*P*) to residents who report violations. They help improve economic and ecological outcomes (*W*). V_2 (Non-Supervision Strategy): Managers receive bribes (*Ug*) from developers. They avoid enforcement costs but contribute to illegal development. However, reduced supervision leads to lower overall benefits (*W*), harming long-term socio-economic stability.
Managers face a trade-off—enforcing regulations for long-term sustainability or accepting bribes for short-term personal gain. The expected benefits for managers from choosing supervision and non-supervision strategies are respectively V_1 and V_2.

$$\begin{aligned} V_1 &= yz(W + (S_1 + S_5)(m - \lambda) - nS_5 - \theta S_4) + y(1 - z)((S_1 + S_5)(m - \lambda) - nS_5 + \eta S_3) \\ &+ (1 - y)z((S_1 + S_5)m - nS_5 - \theta S_4 + \alpha - P) + (1 - y)(1 - z)((S_1 + S_5)m - nS_5 + \alpha + \eta S_3) \end{aligned} \tag{2}$$

$$
\begin{aligned}
V_2 &= yz((S_1+S_5)m - nS_5) + y(1-z)((S_1+S_5)m - nS_5 - W) \\
&+(1-y)z((S_1+S_5)m - nS_5 + Ug - W) + (1-y)(1-z)((S_1+S_5)m - nS_5 + Ug - W)
\end{aligned} \tag{3}
$$

(4) Developers' expected benefits.

Developers decide between two strategies: E_1 (Green Development): Developers receive subsidies (λ) for green projects. They generate profits from legal development (β). However, they may need to pay rent (fS_6) to lease land from residents. E_2 (Illegal Development): Developers gain illegal profits (ω) from unauthorized projects. They avoid paying land rent (fS_6) and some regulatory costs. However, they face penalties (α) for pollution and potential bribery costs (Ug) to managers.
Developers choose green development if subsidies and profits outweigh illegal gains. Otherwise, they may attempt illegal development, especially if enforcement is weak. The expected benefits for developers from choosing green development and illegal development strategies are respectively E_1 and E_2.

$$
\begin{aligned}
E_1 &= xz((S_1+S_5)(\lambda - m) - fS_6 + (S_1+S_2)\beta) + x(1-z)((S_1+S_2)\beta - (S_1+S_5)m - fS_6) \\
&+(1-x)z((S_1+S_5)(\beta+\lambda-m)) + (1-x)(1-z)((S_1+S_5)(\beta-m))
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
E_2 &= xz((S_1+S_2)\beta - (S_1+S_5)m - fS_6 - \alpha + \omega - A) + x(1-z)((S_1+S_2)\beta - (S_1+S_5)m - fS_6 + \omega - Ug) \\
&+(1-x)z((S_1+S_5)(\beta-m) - \alpha + \omega) + (1-x)(1-z)((S_1+S_5)(\beta-m) + \omega - Ug)
\end{aligned} \tag{5}
$$

(5) Residents' expected benefits.

Residents decide whether to cooperate (retiring land for conservation) or not cooperate (illegally occupy land). N_1(Cooperation Strategy): Residents receive compensation (θ) for land retirement. They earn rent (fS_6) if developers lease their land. They may also receive rewards (P) for reporting illegal development. However, they lose agricultural income (hS_2) from retiring land. N_2 (Non-Cooperation Strategy): Residents continue farming and avoid losing agricultural income. They may illegally occupy land (S_3) for their own benefit. However, they risk penalties (η) for illegal occupation.
Residents are more likely to cooperate if financial compensation is sufficient; otherwise, they may resort to illegal land occupation to sustain their livelihood. The expected benefits for residents from choosing cooperation and non-cooperation strategies are respectively N_1 and N_2.

$$
\begin{aligned}
N_1 &= xy(fS_6 + nS_5 + \theta S_4 - h(S_2+S_4)) + x(1-y)(fS_6 + nS_5 + \theta S_4 - h(S_2+S_4) + P) \\
&+(1-x)y(fS_6 + nS_5 - hS_2) + (1-x)(1-y)(fS_6 + nS_5 - hS_2 - A)
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
N_2 &= xy(nS_5 - h(S_5 - S_3) - \eta S_3) + x(1-y)(nS_5 - h(S_5+S_3) - A - \eta S_3) \\
&+(1-x)y(nS_5 - h(S_5+S_3)) + (1-x)(1-y)(nS_5 - h(S_5+S_3) - A)
\end{aligned} \tag{7}
$$

According to Eqs. (6) and (7), the replicator dynamic equation for managers in the evolutionary game model is given by:

$$
F_{(x)} = x(1-x)[W + \alpha + \eta S_3 - Ug + (Ug - \alpha - (S_1+S_5)\lambda)y - (P + \theta S_4)z - Pyz] \tag{8}
$$

Similarly, the replicator dynamic equation for developers in the game model is given by:

$$
F_{(y)} = y(1-y)[Ug - \omega + (\alpha - Ug + (S_1+S_5)\lambda)x + Axz] \tag{9}
$$

The replicator dynamic equation for residents in the game model is given by:

$$
F_{(z)} = z(1-z)[fS_6 - (S_2+S_3-S_5)h + (A + P + \eta S_3 - S_4 h + \theta S_4)x - (A+P)xy] \tag{10}
$$

Combining Eqs. (8), (9), and (10), we obtain the replicator dynamic system for the evolutionary game as follows:

$$
\begin{cases}
F_{(x)} = \frac{d_x}{d_t} = x(1-x)[W + \alpha + \eta S_3 - Ug + (Ug - \alpha - (S_1+S_5)\lambda)y - (P+\theta S_4)z - Pyz] \\
F_{(y)} = \frac{d_y}{d_t} = y(1-y)[Ug - \omega + (\alpha - Ug + (S_1+S_5)\lambda)x + Axz] \\
F_{(z)} = \frac{d_z}{d_t} = z(1-z)[fS_6 - (S_2+S_3-S_5)h + (A + P + \eta S_3 - S_4 h + \theta S_4)x - (A+P)xy]
\end{cases} \tag{11}
$$

According to the replicator dynamic system, setting $F_{(x)} = F_{(y)} = F_{(z)} = 0$, we obtain the evolutionary game system equilibrium points as: (0, 0, 0), (0, 0, 1), (0, 1, 0), (0, 1, 1), (1, 0, 0), (1, 0, 1), (1, 1, 0), and (1, 1, 1). The stability of strategy combinations in the game system is a sufficient and necessary condition that requires the eigenvalues of the Jacobian matrix to have negative real parts. If there exists at least one eigenvalue with a positive real part, the equilibrium point is unstable. Therefore, (0,1,0) and (0,1,1) are not stable points of system evolution. The eigenvalues of the Jacobian matrix for the equilibrium points of the game model are shown in Table 3.

Equilibrium points	λ_1	λ_2	λ_3	Positive and negative signs
(0,0,0)	$W + \alpha + \eta S_3 - Ug$	$Ug - \omega$	$S_6 f - (S_3 + S_6)h$	$(*, -, *)$
(0,1,0)	$W - (S_1 + S_5)\lambda + \eta S_3$	$\omega - Ug$	$S_6 f - (S_3 + S_6)h$	$(*, +, *)$
(0,0,1)	$W + \alpha - \theta S_4 - P - Ug$	$Ug - \omega$	$(S_3 + S_6)h - S_6 f$	$(*, -, *)$
(0,1,1)	$W - \theta S_4 - (S_1 + S_5)\lambda$	$\omega - Ug$	$(S_3 + S_6)h - S_6 f$	$(*, +, *)$
(1,0,0)	$Ug - W - \alpha - \eta S_3$	$\alpha + (S_1 + S_5)\lambda - \omega$	$A + P + \eta S_3 + S_6 f + \theta S_4 - (S_3 + S_6 + S_4)h$	$(*, *, *)$
(1,1,0)	$(S_1 + S_5)\lambda - \eta S_3 - W$	$\omega - \alpha - (S_1 + S_5)\lambda$	$\eta S_3 + S_6 f + \theta S_4 - (S_3 + S_6 + S_4)h$	$(*, *, *)$
(1,0,1)	$Ug + P - W + \theta S_4 - \alpha$	$\alpha + (S_1 + S_5)\lambda + A - \omega$	$(S_3 + S_6 + S_4)h - S_6 f - P - A - \theta S_4 - \eta S_3$	$(*, *, *)$
(1,1,1)	$(S_1 + S_5)\lambda + \theta S_4 - W$	$\omega - \alpha - A - (S_1 + S_5)\lambda$	$(S_3 + S_6 + S_4)h - S_6 f - \eta S_3 - \theta S_4$	$(*, *, *)$

Table 3. Equilibrium points and their eigenvalues for the evolutionary game model. *Uncertainty in the sign of the eigenvalues, indicating that under certain conditions, the eigenvalues are negative, suggesting stability.

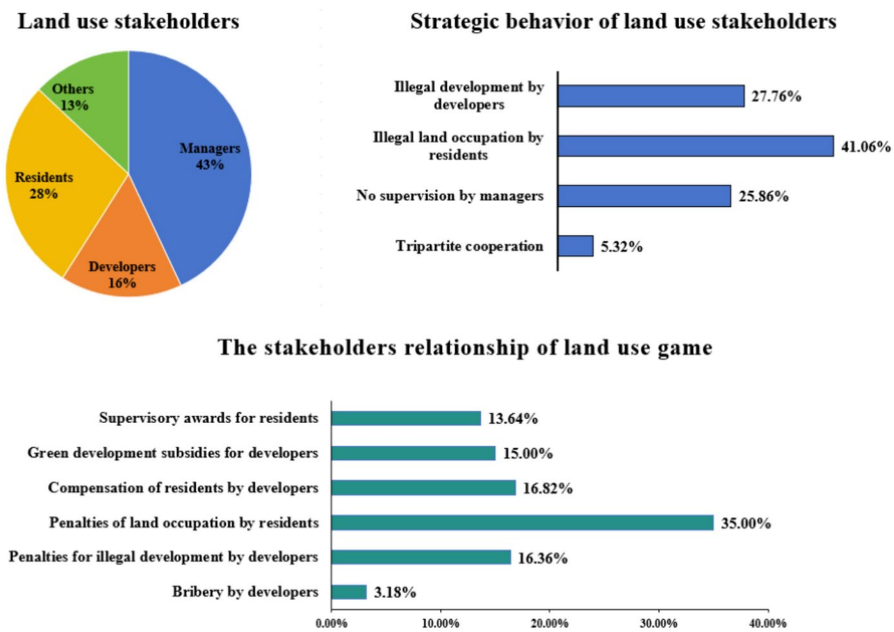

Fig. 3. Distribution of land use stakeholders and their strategic behaviors, derived from survey responses.

Results

Summary of field questionnaire survey statistics

The questionnaire results provide insights into the composition and strategic behaviors of key stakeholders involved in land use decisions within the CNNR. As shown in Fig. 3, managers represent the largest stakeholder group (43%), followed by residents (29%) and developers (16%), with other stakeholders accounting for 13%. Regarding strategic behaviors, illegal land occupation by residents (41.06%) was identified as the most frequent issue, followed by illegal development by developers (27.76%) and lack of supervision by managers (25.86%), while tripartite cooperation remains relatively rare (5.32%). The analysis of stakeholder interactions highlights the role of penalties and incentives in shaping land use decisions. The most prominent measure is penalties for land occupation by residents (35.00%), followed by compensation of residents by developers (16.82%) and penalties for illegal development by developers (16.36%). Additionally, supervisory awards for residents (13.64%) and green development subsidies for developers (15.00%) suggest efforts to encourage compliance and sustainable practices. Bribery by developers (3.18%) appears to be a minor but notable factor. These findings underscore the complex dynamics of land use conflicts and the critical role of governance mechanisms in regulating stakeholder behavior.

Game analysis of land use stakeholders in the CNNR

Analysis of equilibrium point of game model

From Table 3, it can be observed that potential equilibrium points for the strategies of managers, developers, and residents are (0,0,0), (0,0,1), (1,0,0), (1,1,0), (1,0,1), and (1,1,1). Below, we will provide a deeper logical analysis and discuss the practical significance of these six scenarios, highlighting the underlying dynamics that drive stakeholders' strategic decisions at different stages of economic development and ecological management.

Scenario One: When $Ug > W + \alpha + \eta S_3$ and $h > \frac{S_6}{S_6+S_3} f$, managers refrain from supervision, developers engage in illegal development, and residents lean towards non-cooperation (Fig. 4b), the equilibrium point tends towards (0,0,0). In this scenario, the lack of oversight from managers facilitates illegal activities by developers, leading to environmental degradation and increased competition for land among residents. The absence of cooperation exacerbates conflicts and makes it difficult to establish any mutually beneficial solutions. The ecological quality of the environment deteriorates significantly, with long-term implications for both economic and ecological systems. This equilibrium highlights the failure of both regulatory frameworks and community engagement, emphasizing the need for stronger governance and cooperation among stakeholders to prevent land-use conflicts and environmental harm. The practical significance of this equilibrium represents a worst-case scenario, where the interests of all stakeholders are compromised, leading to an unsustainable land use trajectory. Policymakers should aim to avoid such an equilibrium by strengthening regulatory mechanisms and fostering cooperation among stakeholders.

Scenario Two: When $Ug > W + \alpha - \theta S_4 - P$ and $f > \frac{S_6+S_3}{S_3} h$, managers refrain from supervision, developers engage in illegal development, and residents lean towards cooperation (Fig. 4a), the equilibrium point tends towards (0,0,1). In this case, the absence of managerial oversight allows developers to continue their illegal activities, causing environmental harm. Although residents are cooperative, they fail to receive adequate compensation for their efforts in maintaining ecological balance. The resulting conflicts between residents and developers can undermine both the social fabric and environmental health. While some cooperation exists, the lack of effective regulation prevents meaningful progress toward sustainable development. This scenario indicates that while residents may be willing to cooperate, their efforts are insufficient without the necessary regulatory frameworks and incentives. The practical takeaway here is that effective supervision and ecological compensation are critical for achieving sustainable land use and resolving stakeholder conflicts.

Scenario Three: When $Ug - (W + \eta S_3) < \alpha < \omega - (S_1 + S_5)\lambda$ and $h > \frac{A+P+S_6 f+\eta S_3+\theta S_4}{S_6+S_3+S_4}$, managers supervise land use, developers engage in illegal development, and residents lean towards non-cooperation (Fig. 4c), the equilibrium point tends towards (1,0,0). In this scenario, managers' efforts to enforce regulations help curb illegal activities by developers, but residents' non-cooperation hampers the effectiveness of these efforts. This tension highlights the challenge of balancing regulatory enforcement with community engagement. While some level of order is restored through managerial oversight, the lack of cooperation from residents leads to ongoing land-use conflicts, making it difficult to achieve long-term ecological and economic stability. This equilibrium reflects a transitional phase where management efforts can prevent the worst outcomes, but the lack of full stakeholder cooperation limits the potential for sustainable land use. Policymakers should focus on fostering better communication and collaboration with residents to strengthen the overall effectiveness of land use governance.

Scenario Four: When $\omega - \alpha < (S_1 + S_5)\lambda < W + \eta S_3$ and $h > \frac{\eta S_3+S_6 f+\theta S_4}{S_6+S_3+S_4}$, managers supervise land use, developers engage in green development, and residents lean towards non-cooperation (Fig. 4e), the equilibrium point tends towards (1,1,0). In this scenario, effective managerial policies, including rewards and penalties, help promote environmentally friendly development by developers. However, the lack of cooperation

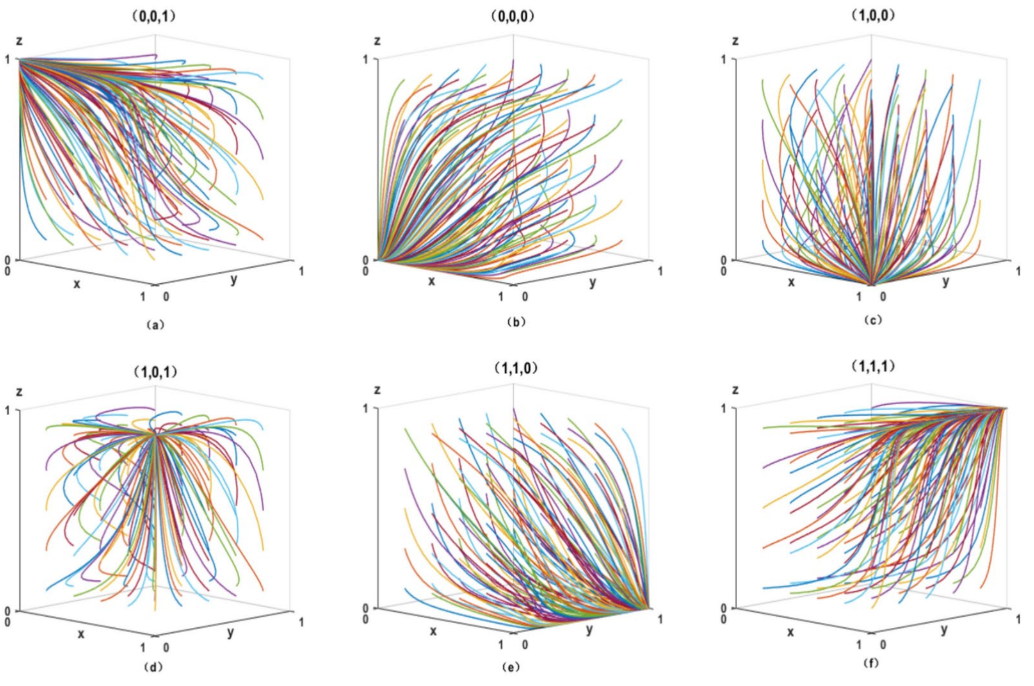

Fig. 4. Equilibrium scenarios of different strategies in the evolutionary game model.

from residents means that the broader social and economic benefits of green development are not fully realized. This highlights the importance of not only regulatory enforcement but also the need for social cohesion and collaborative efforts across all stakeholder groups. This equilibrium represents a scenario where environmental goals are largely achieved, but social and economic development are hindered due to non-cooperation from residents. The key takeaway is that fostering stakeholder engagement is crucial to achieving coordinated development of both the ecological environment and the social economy.

Scenario Five: When $Ug + P + \theta S_4 - W < \alpha < \omega - (S_1 + S_5)\lambda - A$ and $h < \frac{A+P+S_6 f+\eta S_3+\theta S_4}{S_6+S_3+S_4}$, managers supervise land use, residents cooperate, and developers engage in illegal development (Fig. 4d), the equilibrium point tends towards (1,0,1). Here, managerial oversight and residents' cooperation help maintain a degree of ecological balance, but developers' illegal activities continue to pose a threat. Although residents are active in promoting ecological preservation, the persistence of illegal development practices highlights the need for stronger enforcement and more effective incentives to curb developers' illegal activities. This scenario reflects a partial success in ecological management, where cooperation between managers and residents helps mitigate some environmental degradation, but illegal development continues to undermine progress. To resolve this, there needs to be greater alignment between enforcement efforts and economic incentives for developers to shift towards sustainable practices.

Scenario Six: When $\omega - \alpha - A < (S_1 + S_5)\lambda < W - \theta S_4$ and $h < \frac{\eta S_3+S_6 f+\theta S_4}{S_6+S_3+S_4}$, managers supervise land use, developers engage in green development, and residents cooperate (Fig. 4f), the equilibrium point tends towards (1,1,1). This represents the most desirable scenario, where effective managerial policies enable developers to adopt green development practices, while residents actively cooperate with both developers and managers to promote sustainable land use. The alignment of economic, ecological, and social interests creates a synergistic environment where all stakeholders benefit, leading to harmonious and sustainable land use. This equilibrium represents the ideal state of coordinated land use, where the interests of all parties are maximized. It underscores the importance of aligning incentives, fostering cooperation, and creating policies that incentivize sustainable development practices. Achieving this equilibrium is crucial for ensuring long-term ecological health and high-quality economic development.

Numerical simulation of land use game strategies

Due to the fluctuations in the interests among the three stakeholders, which vary with the development of the ecological environment and socio-economic factors in the CNNR, there exists the potential for the six points to become stable points at different stages of development in the reserve. As observed from Table 3, each characteristic value is indicative of the relationship between the incremental benefits derived from different land-use types and the associated costs. These values reflect the dynamics of benefits and costs, ultimately influencing the strategic choices of each stakeholder. Opting for a particular land-use strategy is deemed optimal when the internal and external benefits outweigh the costs following changes in various land-use types. In reality, due to the influence of socio-economic factors and policies, the interests of the three parties are interdependent, fostering symbiotic development. The selection of a strategy by one party is contingent upon the strategies chosen by the other two, hence all parties exhibit bounded rationality. Under the constraint that all characteristic values are less than 0, the aforementioned equilibrium points can serve as stable points in the evolutionary game among the three stakeholders, each representing distinct strategies. To further delineate the constraints necessary for reaching a particular stable point, this study incorporates the actual land-use change data from 2000 to 2020 into the parameters associated with different strategies within the evolutionary game model[32]. During the economic development period of the CNNR from 2000 to 2010, the corresponding transformation parameters for land types are: $S_3 = 9.86$ km^2, $S_6 = 3.21$ km^2, $M = 5.45$ and $EEQI = -0.018$. Conversely, during the ecological governance period from 2010 to 2020, the respective area transformation parameters for land types are as follows: $S_1 = 3.59$ km^2, $S_2 = 2.39$ km^2, $S_3 = 5.07$ km^2, $S_4 = 11.37$ km^2, $S_5 = 1.67$ km^2, $S_6 = 0.72$ km^2, $M = -1.08$ and $EEQI = 0.038$. This provides the constraints on model parameters under each equilibrium point, as detailed in Table 4.

In six stable points, three different initial probabilities of stakeholders' strategies in land use conflict were selected for numerical simulation. Due to the land use changes in the CNNR from 2000 to 2020, the study is divided into two scenarios: the economic development phase of the CNNR from 2000 to 2010, and the ecological governance phase from 2010 to 2020.

(1) Economic Development Phase of the CNNR (2000–2010)

Periods	Parameter constraints		Point
2000–2010 Economic development period	$\omega > Ug > 5.45R - 0.018G + \alpha + 9.86\eta$	$h > 0.032f$	(0,0,0)
		$h < 0.032f$	(0,0,1)
2010–2020 Ecological governance period	$Ug + 11.37\theta + P + 1.08R - 0.038G < \alpha < \omega - A - 5.26\lambda$	$h > 0.296\eta + 0.663\theta + 0.042f + \frac{A+P}{17.158}$	(1,0,0)
		$h < 0.296\eta + 0.663\theta + 0.042f + \frac{A+P}{17.158}$	(1,0,1)
	$0.19(\omega - \alpha) < \lambda < 0.007G - 0.205R - 2.16\theta$	$h > 0.296\eta + 0.663\theta + 0.042f$	(1,1,0)
		$h < 0.296\eta + 0.663\theta + 0.042f$	(1,1,1)

Table 4. Constraints on the equilibrium points.

Figure 5 illustrates the evolution of stakeholder strategies and their corresponding stable states within the Caohai National Nature Reserve (CNNR), highlighting the dynamics between managers, developers, and residents. At the stable state (0,0,1), the system converges rapidly to 0 (non-supervision), regardless of the initial probability assigned to managerial strategies. This occurs due to bribery by developers, leading to lenient penalties for illegal activities, which encourages developers to pursue high-pollution, high-profit illegal development. Consequently, both managerial supervision and developers' inclination towards green development remain low, resulting in increased ecological pollution. Developers, in turn, offer higher land rents to residents, fostering cooperation, but this ultimately converges to 1 (cooperation). While this phase sees rapid economic growth driven by developers, it also leads to gradual ecological degradation. At the stable state (0,0,0), both managers and developers gradually shift towards non-cooperation, with managerial strategies converging to 0 (non-supervision) first. Eventually, residents' strategy choices also converge to 0 (non-cooperation). The extent of initial cooperation between managers and developers influences residents' cooperation, but collusion between managers and developers harms residents' interests, especially when the land rent paid to residents is lower than their land's benefits. As a result, residents' willingness to cooperate steadily declines, leading to bottlenecks in socio-economic development and further ecological deterioration. In summary, during the economic development phase of CNNR, non-supervision by managers leads to developers' preference for illegal development strategies, outpacing residents' choices between cooperation and non-cooperation, thereby driving rapid economic growth but exacerbating environmental degradation.

(2) Ecological Governance Phase of the CNNR (2010–2020)

As shown in Fig. 6, at the stable point (1,0,0), the probability of managerial supervision converges to 1, while the strategies of developers and residents converge to 0, indicating illegal development and non-cooperation, respectively. This outcome arises as managers recognize the unsustainable trajectory of economic and ecological conditions in the reserve, opting to implement supervision and provide subsidies for green development. Despite these measures, developers remain inclined toward illegal development due to high economic incentives, compounded by lenient penalties. As compensation and land rents to residents decrease, residents' cooperation wanes, shifting towards non-cooperation. However, if compensation and land rents increase, surpassing the benefits residents gain from land use, their willingness to cooperate grows, moving towards the stable point (1,0,1), where economic development begins transitioning and the ecological environment improves. At the stable point (1,1,0), both managers and developers adopt cooperative strategies, with managers implementing supervision and increasing green development subsidies, while developers engage in more environmentally friendly practices due to stricter penalties for illegal activities. Despite initial reluctance, residents eventually cooperate as land acquisition compensation and pollution compensation improve, leading to the stable state (1,1,1), where both economic and ecological development are synchronized. In summary, during the ecological governance phase, managerial choices and the game dynamics between developers and residents influence the reserve's evolution. When developers favor illegal development, higher initial supervision from managers reduces the likelihood of illegal activities, while slower convergence occurs in residents' non-cooperation. Conversely, when developers lean towards green development, the probability of residents' cooperation increases, with a faster convergence towards green strategies than towards cooperation.

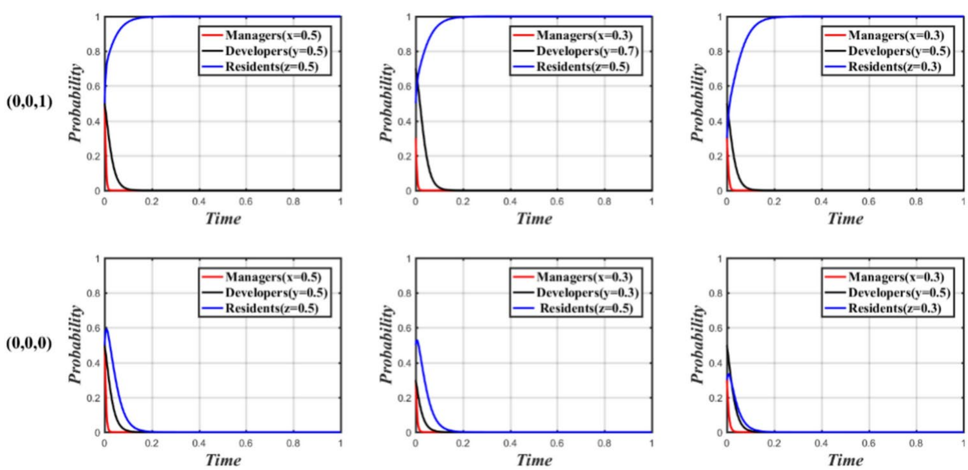

Fig. 5. The numerical simulation results of stakeholders in the economic development period.

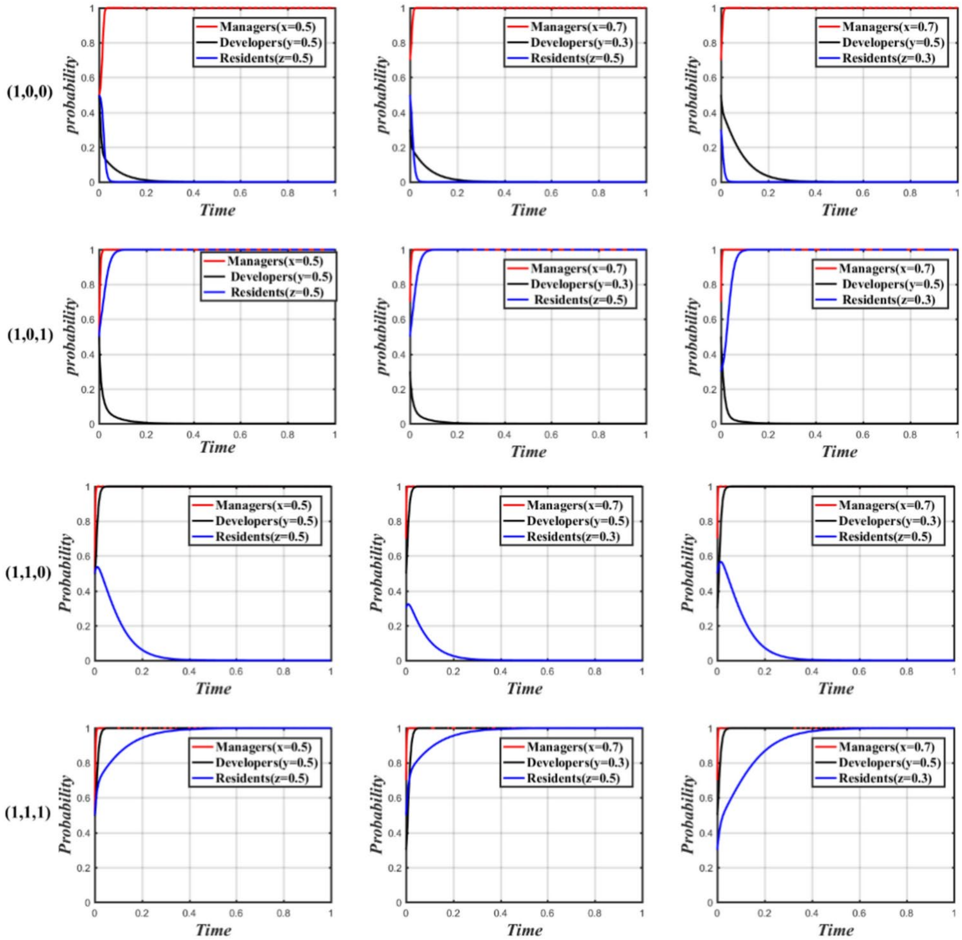

Fig. 6. The numerical simulation results of stakeholders in the ecological governance period.

Quantification of factors influencing strategy choices among stakeholders in the CNNR

(1) Economic Development Phase of the CNNR (2000–2010)

During the economic development phase, when managers opt for non-supervision, several key factors influence the strategy choices of developers and residents. For developers, the primary factors include: Penalties (α) imposed by managers for pollution, Bribery (Ug), where developers may engage in corrupt practices to avoid penalties, Profits (ω) derived from illegal development activities, which act as an incentive to continue such practices. For residents, the strategy choices are primarily influenced by: Profits (h) from land cultivation, Land rent (f) paid by developers to lease residents' land, which serves as a source of income. As shown in Fig. 7a, when the profits from illegal development exceed the costs associated with bribery and penalties, developers are inclined to choose illegal development as a strategy. As the profits from illegal development rise exponentially, the likelihood of developers choosing this strategy increases significantly, rapidly converging towards illegal development (i.e., the strategy where developers prioritize economic gains over environmental sustainability). This dynamic reflects the real-world incentive for developers to bypass regulations when the costs of non-compliance (such as penalties or bribery) are outweighed by the profits. The threshold for residents' shift between cooperation and non-cooperation occurs when their profits from land cultivation are equal to 0.032 times the land rent provided by developers. If their cultivation profits exceed this value, residents are less likely to cooperate and will prefer to retain their land. If their profits fall below this threshold, cooperation with developers becomes more likely.

(2) Ecological Governance Phase of the CNNR (2010–2020)

During the ecological governance phase, when managers opt for supervision, the primary factors influencing developers' strategy choices include: Subsidies (λ) provided by managers to encourage green development, Penalties (α) imposed for pollution, Profits (ω) from illegal development activities, which still act as a strong driver for developers to continue with unsustainable practices if not adequately countered. For residents, the key influencing factors are: Profits (h) from land cultivation, Land rent (f) paid by developers

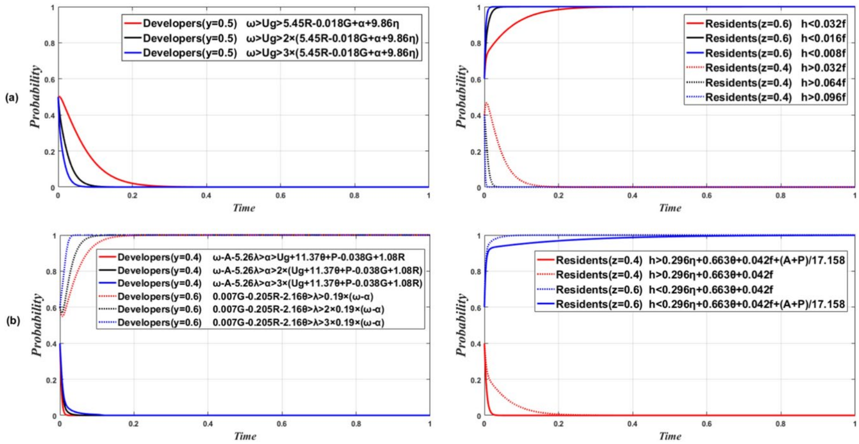

Fig. 7. Factors influencing stakeholders' strategy.

for leasing land, Ecological compensation (θ) provided by managers to incentivize land conservation or ecological restoration, Penalties (η) for illegal land occupation by residents. As illustrated in Fig. 7b, the threshold for developers' transition between illegal development and green development is determined when the subsidies provided by managers exceed 0.19 times the difference between the illegal profits and the penalties for pollution. If subsidies exceed this threshold, developers are more likely to adopt green development practices. Otherwise, the profitability of illegal development remains more attractive, and developers may continue with unsustainable practices.

The key threshold for residents' shift between cooperation and non-cooperation is when their profits from land cultivation are equal to 0.296 times the penalties for land occupation, plus 0.663 times the ecological compensation, and 0.042 times the land rent. If residents' cultivation profits exceed this value, they are less inclined to cooperate with ecological governance policies, as the economic benefits from land use outweigh the incentives for cooperation. If their cultivation profits fall below this threshold, they are more likely to cooperate and participate in ecological restoration or conservation efforts.

Discussion and policy implication

Discussion

This study establishes an evolutionary game model of land use change based on land use and ecological environmental changes in the CNNR from 2000 to 2020, along with field survey data from relevant stakeholders. It calculates strategic equilibrium solutions involving multiple stakeholders, analyzes variations in their strategic choices at different stages, and quantifies the relationships between factors influencing these choices. The findings provide valuable insights for optimizing land use in the reserve and achieving coordinated socioeconomic and ecological development.

Land is a scarce resource that combines economic and ecological values, and stakeholders in land development and utilization compete because of their different or opposing values and interests. Inconsistencies and imbalances in regional socio-economic and ecological development needs can have negative impacts, leading to conflicts over land use[36]. Therefore, stakeholder identification and strategy evaluation are the most basic and important aspects of land use conflict resolution. The utilization of questionnaires has been demonstrated to be an effective method for the examination of land use stakeholder relationships within a designated study area. For example, Mbonile[37] employed a combination of surveys and interviews to examine the competing interests between constructed and agricultural land in the context of land use. However, this aspect is often overlooked in the analysis of land use game modeling, which raises concerns about the reliability of the research findings. In this study, we collected data through field questionnaires and presented them in the form of charts. This approach allowed us to identify the actual strategic behaviors of key stakeholders, including managers, developers, and residents, in the context of land use. It improves the accuracy of the game model and provides reliable data support for the research results.

Spatio-temporal change of land use is an objective phenomenon of different subjects pursuing their own interests in the process of land resources development and utilization, and its research and practice should consider the actual evolution process of land use in different socio-economic development periods[38]. However, existing game theory research has not accounted for the inherent evolution and development process of land use conflicts. Instead, it relies on a single questionnaire data set to qualitatively analyze the contradictory relationship between stakeholders. This approach would significantly constrain our understanding of the impacts of land use change on regional social, economic, and ecological environments. More critically, it could result in excessively subjective model parameterization, thereby hindering a quantitative analysis of the factors influencing each strategy[39]. According to our previous research findings, from 2000 to 2010, the main direction of land use change in the protected area was the conversion of grassland into construction land and farmland. The rapid increase in construction land and farmland led to the deterioration of the ecological environment quality. Influenced by policies such as returning farmland to forest and wetland restoration, from 2010 to 2020, the main direction of land use change in the protected area shifted to the conversion of farmland into grassland and forest land. The increase in grassland and forest land contributed to the improvement of ecological environment quality. In essence, human land activities degrade ecological environmental quality, consistent with the findings of Sun et al.[40]. Meanwhile, in order to dig deeper into the reasons behind the causes of these results and to study the driving mechanisms behind the land use change game among the stakeholders in CNNR, we investigated the equilibrium points of the land use strategies of managers, developers, and residents. Among the six equilibrium scenarios identified, Scenarios 1 and 2 corresponded to the analysis of land use transfer and ecological environmental quality changes in the CNNR from 2000 to 2010. During this period, the focus of managers was primarily on economic development, resulting in lax supervision. Residents encroached upon grasslands and forests, leading to a rapid increase in cultivated land. Developers may have engaged in various illegal activities, exacerbating conflicts of interest among stakeholders and causing land shortages, resource depletion, and environmental degradation within the reserve. Scenarios 3, 4, 5, and 6 aligned with the analysis of land use transfer and ecological environmental quality changes in the CNNR from 2010 to 2020. During this phase, managers intensified supervision, offering incentives and penalties to developers and residents, actively promoting cooperation between them. Residents engaged in land reclamation while developers underwent production transformation. These measures gradually safeguarded the interests of all parties, improved the ecological environment of the reserve, alleviated land use conflicts, and effectively realized the coordinated development of ecology and economy.

One major contribution of this paper is the integration of real data on land use change into numerical simulation models of tripartite land use games. By quantifying the relationships influencing the strategic choices of land use stakeholders, we not only identify the primary factors affecting the strategy choices of each stakeholder but also indirectly regulate their strategic behaviors. Through numerical simulation of land use game strategies in the reserve, we find that the strategy choices of managers significantly influence those of developers and residents. Managers play a decisive role in land use within the reserve, consistent with previous research findings[41]. Furthermore, we observe that the land use conflicts between managers and developers primarily manifest in the game relationship between managers' subsidies for green development, pollution penalties, and developers' profits from illegal development. When managers choose not to regulate and do not provide subsidies for green development, with pollution penalties within acceptable ranges for developers, the developers' strategy tends toward illegal development. However, when managers choose to supervise, provide subsidies for green development, and simultaneously penalize illegal development, and the profits from illegal development are insufficient to cover costs, developers opt for green development. Moreover, as the subsidy intensity increases, the rate of response to green development by developers accelerates. The conflicts of interest between managers and residents mainly manifest in the variation of managers' ecological compensation, land occupation penalties, and the profits obtain from land cultivation for residents. The strategy choices of residents are influenced by multiple factors. If the benefits to residents from managers' compensation for reclamation, as well as penalties for land occupation, are sufficient to offset residents' land cultivation profits, residents choose to cooperate by voluntarily engaging in reclamation, such as returning cultivated land to forests and wetlands. Additionally, as ecological compensation and land occupation penalties increase, the rate of cooperation among residents accelerates. Conversely, residents choose not to cooperate when these conditions are not met. The relationship between developers and residents primarily revolves around land rent and the economic impact of development activities on residents. When developers' land rent is sufficient to offset residents' land cultivation profits, residents also choose to cooperate with developers.

This study makes up for the shortcomings of existing studies that do not take into account the actual evolution of land use, integrates the parameters involved in the process of land use change, such as area and index, into the model, and then quantifies the magnitude of the relationship between the various influencing factors, which complements and improves the evolutionary game model. However, it must be recognized that there are still some limitations in the process of analyzing land use games. First, land use is a complex human activity process full of uncertainty and has a strong territoriality[42]. In this study, the basis for modeling and the actual data are only for CNNR, considering the different cultural and social backgrounds, economic development strategies, and natural ecological environments of each region, more regional studies are needed in the future to further validate the generalizability and feasibility of the models. In addition, the accuracy and validity of the model used in this study are closely tied to the assumptions made during its construction, particularly regarding parameter settings. For example, the parameters for penalties, subsidies, land rents, and ecological compensation are derived from real data such as questionnaires and remote sensing images. While these data sources are valuable, they may still introduce uncertainty due to their reliance on sample data and the subjective interpretation of stakeholder preferences. Moreover, the game theory model's reliance on these parameters assumes that stakeholders make rational decisions based on these fixed parameters, but in reality, human behavior often exhibits unpredictability and irrationality, especially in complex socio-environmental contexts. Therefore, the conclusions of this study may be sensitive to slight changes in these parameter values, which could affect the strategic choices of stakeholders and the resulting equilibrium points. Future research could improve the model by incorporating more dynamic and adaptive parameters that reflect changes in stakeholder behavior over time. While this study provides valuable insights into the dynamics of land use conflicts and stakeholder strategies, the limitations discussed above suggest that the conclusions should be interpreted with caution. Future studies should refine the model's parameters by incorporating more comprehensive data and accounting for the dynamic nature of land use decision-making. Additionally, expanding the study to other regions and incorporating cross-disciplinary approaches will help validate the robustness of the model and provide a more complete understanding of land use dynamics. This, in turn, will lead to more reliable and comprehensive guidance for regional land management and development.

Policy implication

Effectively addressing the multi-stakeholder game of land use in the CNNR requires a reassessment of the strategic behaviors and influencing factors of various stakeholders, along with the establishment of effective institutional arrangements, policy measures, and incentive mechanisms. Based on the research findings and numerical simulation results, this paper suggests the following actions for better addressing the economic development and ecological environmental conflicts caused by land use and resolving conflicts among stakeholders.

Firstly, collaborative efforts among stakeholders involved in land use are crucial for achieving coordinated and sustainable development of both the socio-economic and ecological environments within the reserve. To this end, it is essential to establish formal agreements for land use cooperation among managers, developers, and residents. Such agreements provide a foundational framework for effective land use planning. These agreements should clearly delineate the rights and obligations of all parties, thus ensuring rational and orderly land development.

Secondly, the study demonstrates that the reward and punishment mechanisms enforced by managers significantly influence the strategic decisions of both developers and residents. Managers should design and implement reward and penalty systems based on the principle of shared benefits. These mechanisms must not only specify the criteria, channels, and standards for rewards but also define the reasons, scope, and forms of penalties. Within the reward framework, managers could offer enhanced policy support and green development subsidies to small and medium-sized developers, establishing tiered subsidy criteria that direct resources towards environmentally sustainable enterprises. Additionally, managers should facilitate land use cooperation among developers, promote green development practices, foster ecological alliances, and support innovation within the industry. Furthermore, managers should engage in dialogue and negotiation with local residents, providing fair compensation for land acquisition and effectively managing resettlement processes, thereby fostering stronger cooperation with residents and encouraging their participation in land development activities. With regard to ecological governance, managers should implement reasonable ecological compensation for local residents to mitigate the economic losses associated with cultivated land reclamation. Furthermore, managers should strengthen oversight and incentivize mutual monitoring between developers and residents. In the context of the penalty system, managers must intensify supervision of developers, impose penalties for illegal land development activities, and encourage developers to adopt more sustainable production models. Similarly, stricter penalties should be imposed on residents involved in illegal land occupation to ensure adherence to established ecological land use boundaries.

Thirdly, the study finds that land rent paid by developers has a significant influence on the strategic decisions of residents. Developers can raise land rental rates while ensuring that residents' income sources remain protected, thereby incentivizing local residents to participate in land development activities. This approach not only supports the developers' business interests but also creates a cyclical structure of shared land use benefits, fostering mutual development among multiple stakeholders.

Conclusions

This study analyzes the changes in land use and ecological environmental quality in the CNNR through the land use transfer matrix, land use intensity, ecological environmental quality index, and ecological contribution rate. It incorporates actual land use data into an evolutionary game model, quantifying parameters of model equilibrium points. Numerical simulations are used to explore changes in stakeholder strategies and influencing factors, leading to the following conclusions:

(1) In the tripartite game of land use stakeholders—managers, developers, and residents—managers dominate and influence the strategic choices of both developers and residents. Developers' decisions also impact residents' strategies. Regardless of whether managers enforce supervision, residents adapt their strategies faster than developers, except at the equilibrium point (1,0,0), where developers respond more quickly.

(2) Key factors influencing stakeholder decisions include land rent, penalties for illegal activities, policy subsidies, and ecological compensation. Increasing the strength of rewards and penalties promotes cooperation among stakeholders. Developers tend to adopt green strategies when subsidies exceed 0.19 times the difference between the illegal gains from unauthorized activity and penalties for polluting behavior. Residents are more likely to cooperate when profits from cultivation are no more than 0.296 times the penalties for land occupation, plus 0.663 times the compensation for land retirement, and 0.042 times the land rent.

(3) Quantifying the relationships between these influencing factors and stakeholder strategies using real data allows policymakers to adjust indicators and alleviate land use conflicts. A tripartite evolutionary game model can balance stakeholder interests and promote coordinated sustainable development in the CNNR. This study addresses the limitations of previous research by considering all relevant stakeholders in land use and validating the evolutionary game relationships through empirical data. It clarifies the evolutionary game mechanism from both socio-economic and ecological perspectives. Future research will focus on the impact of individual differences among developers and residents on strategies to mitigate land use conflicts.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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