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Governments' behavioral strategies in cross-regional reduction of inefficient industrial land: learned from a tripartite evolutionary game model

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Disorderly urban expansion has resulted in inefficient industrial land, impeding sustainable urban development. Reducing inefficient industrial land (RIIL) is crucial for controlling pollution and bolstering industrial vitality. However, previous studies have overlooked the quantitative analysis of the intergovernmental interest game involved in cross-regional RIIL, essential for determining project outcomes. This study employs evolutionary game theory to explore the decision-making behavior and stabilization strategies of three stakeholders, including the superior government and two local governments in cross-regional RIIL. First, a tripartite evolutionary game model was formulated. We then examined the evolutionarily stable strategies and their associated conditions. Finally, case analysis and numerical simulation illustrated the government's behavioral strategies and their sensitivity to influencing factors in cross-regional RIIL. The results indicate that positive benefits encourage local governments to cooperate. The superior government's supervision strategy can compel local governments to collaborate on cross-regional RIIL. Optimizing the allocation ratios of the project and enhancing potential benefits can mitigate the negative effects of special funding disparities, thereby fostering intergovernmental cooperation. Ensuring the efficiency of cross-regional RIIL projects requires strengthening social consensus, improving formal institutions, and optimizing governance institutions.

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Introduction

In the context of rapid urban sprawl, the expansion of construction land is inevitable. As one of the primary categories of construction land, the efficiency of industrial land utilization significantly affects the sustainable development of cities (W Song et al., 2023; H Zhang et al., 2024). Compared to residential land and commercial land, inefficient industrial land has exacerbated environmental issues (Yan, Wang (2023); C Bai et al., 2024). In Europe and the United States, abandoned and polluted industrial land, commonly known as brownfield, have been regenerated into green ecological land to improve the urban habitat environment (PD Preston et al., 2023). A similar policy has been introduced by the Chinese government, particularly in metropolitan regions, such as Shanghai, called the reduction of inefficient industrial land (RIIL) (Gu et al., (2018); Jia Li et al., 2023). Through a combination of policies and engineering techniques, the Chinese government aims to restore industrial land with poor utilization efficiency and high ecological risks, converting it to ecological or agricultural use (S Lu et al., 2021; G Wu et al., 2024). By 2021, the national industrial land area accounted for about 19% of the total urban construction land area in China, a decrease of about 1% from 2018 to 2021 (Ministry of Housing and Urban-Rural Development of the People's Republic of China MOHURD (2021); Gu et al., (2022)). Recently, RIIL has not only been implemented in Shanghai, but has been gradually spread throughout China.

However, the utilization efficiency of industrial land exhibits spatial heterogeneity. Inefficient industrial land is typically concentrated in suburban areas with poor industrial development (K Wang et al., 2021). As industrial land is a cornerstone of regional economic development, the implementation of RIIL by local governments inevitably has short-term regional economies consequences (Z Zhang et al., 2019). Some studies suggest that the RIIL with regional differences may transfer land development rights from economically disadvantaged areas to wealthier areas, negatively affecting spatial justice (Y Cao et al., 2020; K Wang et al., 2023). As a result, local governments are often cautious about cross-regional RIIL, fearing that it will restrict economic development within their jurisdiction. Unlike other production resources, industrial land is difficult to optimize allocation through digital development (S Zhao et al., 2018; H Wu et al., 2023), making it imperative to optimize the spatial pattern of industrial land across regions. Regarding the cross-regional allocation of land quotas, some studies have explored various methods, such as the "*Dipiao*" system and cross-regional land quota transactions (Y Cao et al., 2020; W Hu, 2022). However, limited studies have focused on RIIL across administrative regions.

Governments at various levels play crucial roles in cross-regional RIIL, engaging in all phases of project implementation (Zhou et al., 2022). Additionally, the superior government needs to assume a supervisory role, while local governments are responsible for cooperation to ensure complete the success of cross-regional RIIL. The interests of these governments differ: the superior government focuses on the gross construction land quotas obtainable from RIIL, whereas local governments are concerned about the special funds they can receive to support local development and reaping potential benefits from projects. These divergent objectives, coupled with information asymmetry and bounded rationality, complicate the decision-making process. Consequently, the strategic choices made by governments are critical to the successful completion of cross-regional RIIL. Nonetheless, there has been scant scholarly attention devoted to examining governmental strategic decision-making related to reducing inefficient industrial land.

Given the limited efficiency of industrial land use within a single administrative region, coordinating the development of different regions necessitates the launch cross-regional RIIL (K Wang et al., 2023; W Yang et al., 2023). In urban agglomerations with developed industries, such as the Yangtze River Delta region, cross-regional RIIL serves as an important means to adjust the spatial mismatch of industrial land (C Zhang et al., 2022). With the emergence of concepts such as urban-rural integration and common prosperity, the focus of governmental bodies on cross-regional land planning and optimization has heightened. From 2022, the Zhejiang Provincial People's Government has launched 33 cross-township comprehensive land consolidation pilots[1]. In 2023, the first cross-regional land and space planning was implemented in the Yangtze River Delta Demonstration Zone[2]. Other regions, such as Jiangsu Province, have also initiated cross-regional industrial land reduction surveys[3]. Although several studies have investigated the logical interplay within China's multi-level governmental administrative governance, particularly focusing on environmental pollution control (L Suo et al., 2023; L Wu et al., 2023), there is a gap in research addressing the economic dynamics and governmental decision-making behavior in the context of cross-regional RIIL.

The dynamics of intergovernmental interests in industrial land reduction become more apparent in comparison to environmental pollution control, as land use allocations play a crucial role in shaping the future developmental trajectory of a region (K Wang et al., 2023). Recognizing the gaps in existing research, our study aims to meticulously examine the decision-making tendencies and interactive dynamics among multi-level governments, encompassing the superior government and local governments. This scrutiny unfolds within diverse contextual scenarios, utilizing the lens of evolutionary game theory. The evolutionary game model offers a systematic framework for analyzing the evolution of behaviors and strategies of all parties involved in intergovernmental interactions, thereby elucidating the mechanisms of supervision and cooperation. Ultimately, our study seeks to enhance the formulation and implementation of public management policies by deepening understanding of multi-level government interactions, providing decision-making support tools, and fostering inter-governmental cooperation and win-win strategies.

This study delineates the following research questions: What constitutes the stabilized equilibrium conditions conducive to the smooth execution of the RIIL project? How do governments' strategic choices and related factors affect the evolutionary trajectory of equilibrium states? To gain further clarity, we have developed a tripartite evolutionary game model. The primary purposes of this study are as follows: (1) modelling the tripartite evolutionary game model to explain the influencing factors and interaction mechanisms among the governments' behavioral strategies in RIIL; (2) revealing the impact of main parameters such as the distribution ratio of RIIL, the completion ratio of RIIL projects, local potential benefits, and supervision costs on stakeholder groups via numerical simulation analysis based on an actual case; (3) proposing how to achieve a sustainable win-win strategy among governments, based on the results and studies related to the RIIL.

The sections of our manuscript are structured as follows: Section "Literature review" presents a review of extant literature germane to the domain of our study. Section "Tripartite evolutionary game modeling" introduces the research framework, delineating the construction of a tripartite evolutionary game model encompassing the superior government and two local governments. Section "Numerical example analysis" employs numerical simulations to elucidate influencing factors. In Section "Discussion and implications", we have proposed policy optimization directions based on study results. Last, Section

"Conclusion" concludes the study and outline study limitations, pointing out future study direction.

Literature review

This section is divided into 3 subsections to systematically explore governments' strategies in cross-regional RIIL. Firstly, it synthesizes existing studies on this topic, establishing a comprehensive understanding and identifying gaps. Secondly, it examines literature that considers governments as pivotal stakeholders, shedding light on their roles and decision-making dynamics. Lastly, it explores the application of evolutionary game theory to analyze strategic interactions, offering insights into the complexities of their strategies. This approach enables a thorough examination of governments' involvement in cross-regional RIIL.

Studies on RIIL. Studies on the RIIL share similarities with brownfield regeneration efforts in Europe and the United States (Gu et al., (2018)). Brownfields, which originated in the US in 1980 under the Comprehensive Environmental Response, Compensation, and Liability Act (Y Sun et al., 2022). Regenerating these brownfields into green infrastructure revitalizes land, making it compatible with various land-use options, including recreational areas and communal gardens (G Atkinson et al., 2014). Some brownfields are also repurposed for housing and commercial development (X-H Weng et al., 2019). In Eastern Europe, economic changes have led to numerous brownfields, necessitating the exploration of reuse methods (F Alexandrescu et al., 2014; S Martinat et al., 2018). Brownfield reuse aligns with local social needs (J Navrátil et al., 2023), and studies have investigated spatial patterns and factors contributing to successful regeneration (B Frantál et al., 2015; R Osman et al., 2015; M Burinskienė et al., 2017). Governments play an essential role in promoting urban sustainability through policy design for brownfield regeneration (Oudes, Stremke (2020); C Bianchi et al., 2021; R Osman et al., 2023). In China, brownfield research is expanding, particularly focusing on abandoned mining sites and polluted industrial lands. Studies cover soil investigation, contamination assessment, and strategies for contaminated sites (Guidi Nissim, Labrecque (2021); Y Sun et al., 2022). Additional research explores planning, ecological benefits, and parcel identification for redevelopment (Y Wang et al., 2020; D Hou et al., 2023). In China, brownfields are often representative of inefficient industrial land. While RIIL and brownfield regeneration share similarities in implementation, they differ in spatial scale and scope. Brownfield regeneration focuses on specific plots of land, whereas RIIL impacts entire administrative areas.

RIIL aims to mitigate pollution, improves industrial land efficiency, and promotes urban spatial agglomeration. Inefficient industrial land includes polluted, low-yield or discontinued plots. The Chinese government manages this issue through urban construction land quotas (Zhu, Tang (2018); Fang, Tian (2020)), which enhance social and ecological benefits (Z Zhang et al., 2019). Studies have discussed location choice, success factors, and barriers in reducing industrial land (Q Li et al., 2022; J-H Zhou et al., 2022). Implementing cross-regional reduction quotas can boost economic potential, especially for inefficient industrial land (K Wang et al., 2021). Successful cross-regional management relies on local government support, making policy endorsement critical (X-H Weng et al., 2019; Q Li et al., 2022). Current research often focuses on land spatial patterns and market transactions (T Zhou et al., 2022; Jia Li et al., 2023). However, reducing inefficient industrial land is closely related to government planning (X Ye et al., 2023). Conflicts between different levels of government significantly impact regional implementation in RIIL, which warrants further study (Zhu, Tang (2018)). Despite the importance of these issues, intergovernmental interactions in the management of industrial land management have received relatively little scholarly attention, especially compared to environmental, social, and spatial considerations. This oversight may stem from the high autonomy that local governments have in supplying and using industrial land (P Tang et al., 2021).

Consider governments as stakeholders in the RIIL. Achieving equilibrium amidst the frequently conflicting objectives across different stages of brownfield policymaking and implementation is crucial. This equilibrium is necessary not only horizontally between levels of government, but also vertically across diverse sectoral interests (A Mehdipour et al., 2024). Unlike European and American countries, which rely on community guidance to reduce inefficient industrial land, China's RIIL project exhibits a greater degree of government intervention (T Zhou et al., 2022; C De Sousa et al., 2023). In China, the government plays multiple roles in the RIIL process, acting as policymakers, project initiators, financiers, implementers, beneficiaries, and supervisors.

According to Chinese Land Use General Plan, construction land quotas owned by higher-level governments can limit the use of construction land quotas by lower-level governments (T Zhou et al., 2022). This provides higher-level governments the incentive to optimize the spatial pattern of construction land, including industrial construction land. Therefore, RIIL projects are predominantly government-initiated, often requiring state-owned assets platforms for financing (Z Jiang et al., 2023). Local governments are involved in the entire process of project implementation and acceptance, while superior governments act as supervisors (J-H Zhou et al., 2022).

In a study on rural-urban construction land consolidation and allocation, considered another form of RIIL, government functions are not only involved in all aspects of the project but also have significant autonomy in directing the project (Y Tang et al., 2015). Thus, resistances, such as compensation needs and difficulties in enterprise demolition can be seen as costs of government implementation (Z Jiang et al., 2023). Despite recognizing the importance of government involvement in reducing inefficient industrial land in existing studies, the majority tend to treat government intervention as an independent variable, overlooking the interplay between various levels of government and the dynamics of cooperation and competition among governments at the same level. When cross-regional demolition compensation is enacted, it amplifies intergovernmental resistances in RIIL project implementation, an aspect often overlooked in current studies. To address this gap, we consider local governments and their superior government as key stakeholders. We present the interaction process among different levels of government using an evolutionary game model, offering a clearer explanation of the challenges inherent in cross-regional RIIL projects.

Game theory in the RIIL. Game theory provides a robust mathematical foundation for cross-regional research, particularly in addressing the challenge of heterogeneity inherent in cross-regional governance dynamics (M Zhang et al., 2019). As a leading tool in economic analysis, game theory is instrumental in exploring conflict and cooperation within decision-making frameworks (M Yuan et al., 2022). Classical game theory assumes that all participants are wholly rational and the information is fully accessible. However, in the complex real world, stakeholders are often not completely rational, and player information is not completely transparent. Consequently, many refinements of game models have been studied, such as Pareto optimality, risk advantage, focus results, etc. Although these refinements remain within the framework of classical game theory, they pave the way for the concept of bounded rationality (Szabó, Fáth (2007)). The evolutionary game model amalgamates classical game trajectories with dynamic evolution, employing bounded rationality as the analytical framework. This approach enhances the alignment of theoretical outcomes with real-world phenomena (Traulsen, Glynatsi (2023)).

Game-theoretic approaches have been widely used in the field of land management. For example, game models have been used to study the relationship between land rights owners, users and market leaders, helping to alleviate the occurrence of regional violence (Amman, Duraiappah (2004)). In land acquisition issues, game-theoretic models have been employed to analyze the logic and strategies of conflicts between local governments and farmers, providing directions for policy optimization in land acquisition and conflict management (Hui, Bao (2013)). Game-theoretic approaches combined with genetic algorithms have been used to optimize the spatial pattern of land use (J Maleki et al., 2020). Evolutionary game-theoretic approaches have been applied in land inspectorate studies (X Zhang et al., 2015). Additionally, a game-theoretic framework has been shown to better simulate stakeholders' behavior in land-use changes compared to multi-agent systems and conventional decision-making frameworks, thereby enhancing urban planning effectiveness (S Abolhasani et al., 2023).

In the realm of industrial land, game theory and graph model have been employed to analyze land use conflicts, and multi-agent game models have been applied to land reduction studies (AH Aghmashhadi et al., 2022; Z Jiang et al., 2023). However, in practical settings, governmental decision-making often deviates from perfect rationality in project implementation due to the presence of incomplete information and asymmetric knowledge. This makes the analysis of intergovernmental behavior using evolutionary game theory particularly pertinent. Despite the extensive application of game-theoretic approaches in various aspects of land management, their use in the context of RIIL remains underexplored, especially regarding the application of evolutionary game models to government decision-making processes.

Tripartite evolutionary game modeling

Adoption of evolutionary game approaches. Local governments propose their RIIL strategies based on their development perspective, while the superior government chooses intervention strategies considering available benefits. However, the divergent interests of local and superior governments can complicate the RIIL process (Z Zhang et al., 2019). As these parties often hold unequal positions, their interaction resembles more of a game than a negotiation (M Yuan et al., 2022). Classical game theory assumes rationality and complete information among players, yet governments may initially struggle to select optimal response strategies. Therefore, this study employs evolutionary game theory, allowing imperfect players to learn through game observation (J Lv et al., 2021). By adjusting the game model's variables, the study elucidates the strategic decision-making processes of local and superior governments in cross-regional RIIL.

There are two reasons that explain the applicability of evolutionary game theory in our study. First, the assumption of the evolutionary game is that every player has bounded rationality and operates in an environment of incomplete information (M Zhang et al., 2019). In this study, local governments lack fully insight into each other's intentions, the superior government is not fully aware of local governments' strategies, and neither party has complete knowledge of the environmental information. Governments tend to be bounded rationality in their decision-making processes (L Wang et al., 2023). Therefore, evolutionary game models provide a framework for analyzing the dynamic relationships among these governmental entities. Second, evolutionary game models are suitable for analyzing the dynamic changes of strategies. In the game, various strategies will take turns occupying the dominant position, and the evolution dynamics show different oscillation periods for each strategy (M Yuan et al., 2022). In the cross-regional RIIL, involved governments continuously compare the benefits of their strategies during the game process and adjust their actions accordingly.

Game theory has been applied to explain intergovernmental interactions in industrial land management, confirming the utility of evolutionary game theory as a robust method for formulating policies related to industrial land reduction (J Luo et al., 2022). Evolutionary game theory effectively explains the long-term strategy selection of bounded rational governments as they navigate the dynamic game processes involved in the implementation of cross-regional RIIL.

Assumptions of evolutionary game model. In cross-reginal RIIL, it is essential to define the interest relationships among different levels of government. For the superior government (such as county or municipal governments), construction land quotas for industry development can be obtained. The explicit income of local governments (such as township or county governments) mainly comes from special funds from state-owned enterprise groups controlled by superior government. Although the standards for special funds are set by the superior government, local governments have the right to negotiate adjustments (J Gyourko et al., 2022).

The total scale of the cross-regional RIIL is determined through surveys conducted by the superior government. Similar to the study on environmental governance, different local governments are assigned different RIIL ratios (M Zhang et al., 2019). Based on the RIIL ratios and special fund standards, the explicit benefits for local governments can be calculated. However, there is a possibility of failing to complete the cross-regional RIIL task, necessitating the introduction of an "actual completion ratio" parameter. This parameter directly affects the amount of construction land available to the superior government, potentially leading to a reduction in the land available if tasks are not fully completed (Heberer, Trappel (2013)).

When the superior government is willing to incur the cost of supervising the local governments, it can ensure the completion of the RIIL task. Failure to supervise adequately can damage the superior government's reputation (Z Zhang et al., 2019). For local governments, completing RIIL tasks brings potential benefits, including eco-environmental benefits (Z Zhang et al., 2019; K Wang et al., 2021). Participating local governments can access each other's RIIL ratios, but acquiring other information, such as details on special financial support, through official channels is challenging. This phenomenon can be attributed to the significant autonomy and independence of local governments, coupled with the superior government's strategy to implement diversified funding methods to mitigate the costs associated with cross-regional RIIL projects. The relationships among these entities, their roles, and their interactions are shown in Fig. 1.

Assumption 1. The two local governments and the superior government involved in the game exhibit bounded rationality. They are capable of making independent decisions and aim to

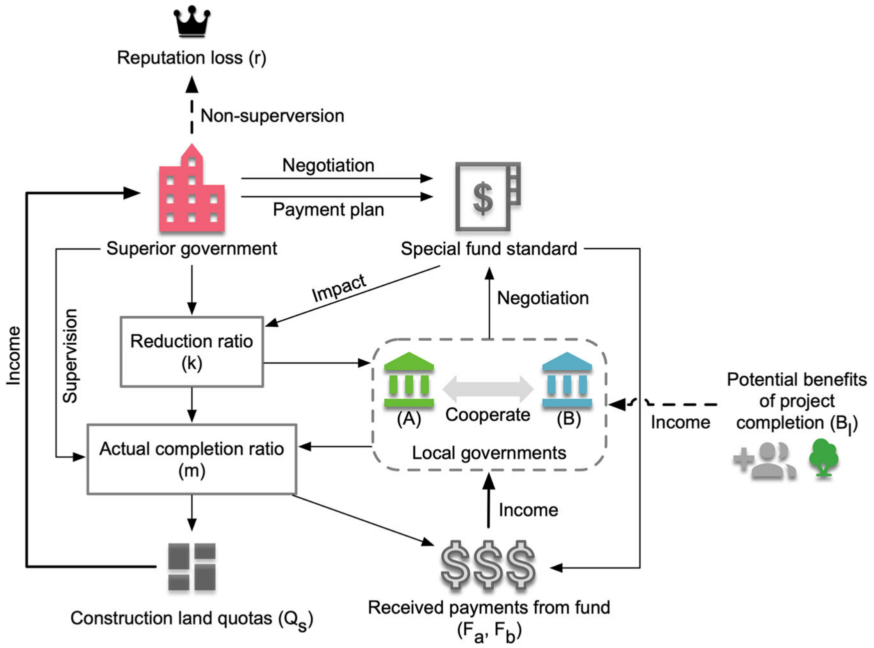

Fig. 1 The interaction mechanism among the superior government and local governments in cross-regional RIIL.

maximize their own interests. Moreover, their strategic choices are expected to evolve and gradually converge toward optimal outcomes.

Assumption 2. The two local governments will adjust their choices based on the RIIL ratio of the other party. Similarly, the superior government will modify its probability of supervision according to the choices of the local governments. Local governments implement RIIL projects by obtaining special funds from the superior governments. Upon project completion, both local governments stand to gain potential benefits, typically in the form of political incentives from the superior government, such as recognition and other non-monetary rewards. We also hypothesize that increasing of ecosystem service value can refer to potential benefits stemming from political incentive provided by superior government (AM Tedesco et al., 2023). When both local governments choose the "cooperation" scenario, the RIIL project will be successfully completed, and political incentive will be awarded. When only one side chooses the "cooperation" scenario, there may be a risk that the RIIL project will not be completed (m ratio), and if it cannot be completed, neither local government will receive potential benefits.

Assumption 3. The superior government's income in the cross-regional RIIL project is assumed to be tied to the completion of the RIIL. The superior government has two pure strategies: to supervise the implementation of RIIL, or not to supervise the implementation of RIIL. In the case of "non-supervision", the superior government will suffer certain losses due to the reduction in the actual scale of RIIL, resulting in a reduction in the construction land quotas it can obtain, and its reputation will also be damaged due to the lack of a supervisory role. If local governments are unwilling to cooperate in the implementation of RIIL, the superior government will compulsorily ensure its completion and impose penalties. Moreover, the financing issues of superior governments are not within the scope of this study. We assume that financing channels are open and funds are stable.

Assumption 4. The probability of local government A implementing cooperation is x ($0 \le x \le 1$), and the probability of local government B choosing cooperation is y ($0 \le y \le 1$). The probability of the superior government opting for supervision is z ($0 \le z \le 1$). The total area of RIIL has been set as 1 mu (1/15 ha) to simplify mathematical analysis.

In the planning and implementation process of cross-regional RIIL, the superior government and two local governments make strategic choices based on their development needs. This study emphasizes the interconnectedness and reciprocal interactions among these three parties. The decision of one-party influences, and is influenced by the other two, making RIIL a dynamic phenomenon. To analyze the benefits and costs of their decisions, we've defined relevant parameters detailed in Table 1.

Based on the above assumptions, a game tree is established for the expected payoffs, as shown in Fig. 2. The detailed situations of each decision are shown in Table 2.

Model establishment and evolutionarily stable strategy analysis

Derivation of replicator dynamic equation. The replicator dynamic equation was derived based on stakeholders' decision-making processes. The expected payoffs of local government A choosing the "cooperation" and "non-cooperation" strategies were EX_1 and EX_2, respectively. The average expected payoff is $\overline{EX}$ (details provided in Supplementary Information).

The Malthusian dynamic equation states that for a strategy to adapt effectively to group evolution and mutation, it should outperform the average income of other strategies in the gaming context (D Friedman, 1991). Utilizing the equations of EX_1, EX_2, and $\bar{EX}$, the replicator dynamic equation for the local government A could be obtained, as follow:

$$F(x) = dx/dt = x\left(EX_1 - \overline{EX}\right) = x(1-x)\left(EX_1 - EX_2\right) = x(1-x)f\left(y, z\right) \tag{1}$$

Subsequently, the expected payoffs of local government B choosing the "cooperation" and "non-cooperation" strategies were denoted as EY_1 and EY_2, respectively. The average expected payoff of local government B is $\overline{EY}$ (details provided in Supplementary Information).

Based on the equations of EY_1, EY_2, and $\overline{EY}$, the replicator dynamic equation for the local government B choosing the

Table 1 Details of model's parameters.

Parameters	Definitions	Value range	References
k	Local government A's RIIL ratio coefficient.	$0 < k < 1$	(M Zhang et al., 2019)
m	When the local government A is unwilling to cooperate, it can complete the ratio coefficient of RIIL.	$0 < m < 1$	(Heberer, Trappel (2013))
B_l	Potential benefits to local governments if RIIL is completed (ecosystem service value).	$B_l \geq 0$	(M Masiero et al., 2022; AM Tedesco et al., 2023)
C_a	Cost of local government A's RIIL (engineering costs, compensation payments, and potential costs).	$C_a \geq 0$	(F Wu, 2022)
C_b	Cost of local government B's RIIL (engineering costs, compensation payments, and potential costs).	$C_b \geq 0$	(F Wu, 2022)
F_a	Local government A can obtain financial special funds from the superior government through RIIL.	$F_a \geq 0$	(Z Jiang et al., 2023)
F_b	Local government B can obtain financial special funds from the superior government through RIIL.	$F_b \geq 0$	(Z Jiang et al., 2023)
Q_s	Benefits to superior government from RIIL (urban construction land quotas).	$Q_s > 0$	(Z Zhang et al., 2019)
r	The reputation loss of superior government.	$r > 0$	(M Zhang et al., 2019)
c	The administrative cost of superior government.	$c > 0$	(M Zhang et al., 2019)
p	The penalty for non-cooperative local government behaviors, including shirking responsibility and delaying the implementation of projects.	$p > 0$	(M Zhang et al., 2019)

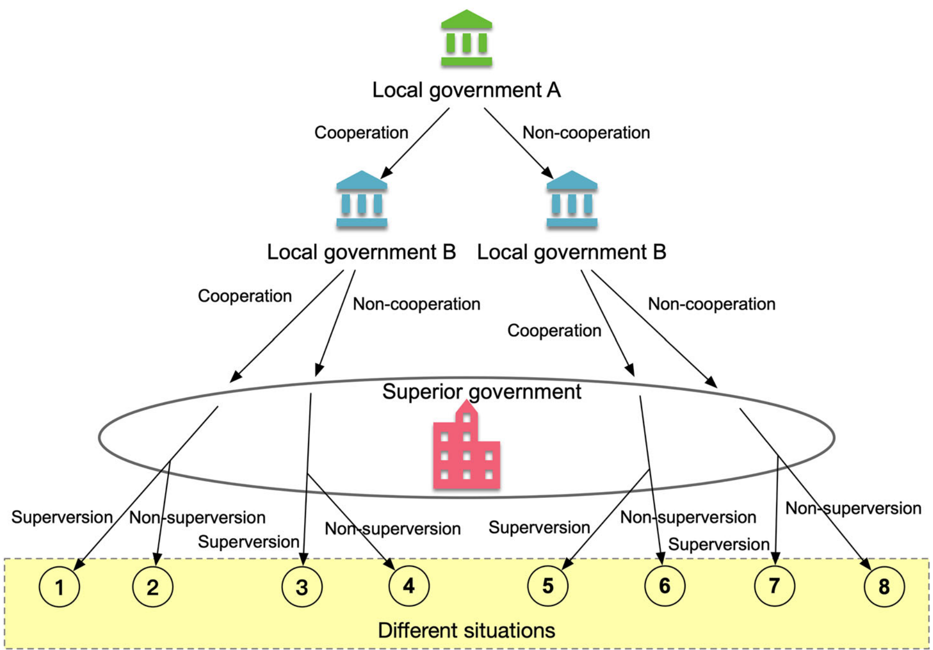

Fig. 2 The evolutionary game process and different situations for cross-regional RIIL.

"cooperation" strategy is formulated as follow:

$$F(y) = dy/dt = y(EY_1 - \overline{EY}) = y(1-y)(EY_1 - EY_2) = y(1-y)f(x,z) \quad (2)$$

Similarly, the expected payoffs of superior government choosing the "supervision" and "non-supervision" strategies were made as EZ_1 and EZ_2, respectively. The average expected payoff of superior governm ent is $\overline{EZ}$ (details in Supplementary Information).

Based on equations of EZ_1, EZ_2, and $\overline{EZ}$, the replicator dynamic equation for the superior government choosing the "cooperation" could be obtained, as follow:

$$F(z) = dz/dt = z(EZ_1 - \overline{EZ}) = z(1-z)(EZ_1 - EZ_2) = z(1-z)f(x,y) \quad (3)$$

Consequently, Eqs. (1–3) are combined into a system of equations to model the evolutionary game dynamics, as follow.

$$\begin{cases} F = x(1-x)[y(1-z)B_l + pz - k(1-m)(1-z)(F_a - C_a)] \\ F(y) = y(1-y)[x(1-z)B_l + pz - (1-k)(1-m)(1-z)(F_b - C_b)] \\ F(z) = z(1-z)(2p + r - c - (1-m)\{k(1-x)F_a + F_b(1-k)(1-y) \\ \quad + p(x+y) + Q_s[kx + (1-k)y - 1]\}) \end{cases} \quad (4)$$

Analysis of equilibrium solution. Let F(x), F(y), and F(z) in the three-dimensional dynamical system covering the local governments and superior government be 0 at the same time, and 8 pure strategy Nash equilibrium points can be obtained, including $E_1(1,1,1)$, $E_2(1, 1, 0)$, $E_3(1, 0, 1)$, $E_4(1, 0, 0)$, $E_5(0, 1, 1)$, $E_6(0, 1, 0)$, $E_7(0, 0, 1)$, and $E_8(0, 0, 0)$. In addition, a mixed-strategy

Table 2 The payoff matrix for the game model.

Situations	Local government A (x)	Local government B (y)	Superior government (z)
①	$k(F_a\text{-}C_a)+B_l$	$(1\text{-}k)(F_b\text{-}C_b)+B_l$	$Q_s\text{-}[kF_a+(1\text{-}k)F_b]\text{-}c$
②	$k(F_a\text{-}C_a)+B_l$	$(1\text{-}k)(F_b\text{-}C_b)+B_l$	$Q_s\text{-}[kF_a+(1\text{-}k)F_b]\text{-}r$
③	$k(F_a\text{-}C_a)+B_l$	$(1\text{-}k)(F_b\text{-}C_b)\text{-}p+B_l$	$Q_s\text{-}[kF_a+(1\text{-}k)F_b]\text{-}c+p$
④	$k(F_a\text{-}C_a)$	$m(1\text{-}k)(F_b\text{-}C_b)$	$(k+m\text{-}mk)Q_s\text{-}kF_a\text{-}m(1\text{-}k)F_b\text{-}r$
⑤	$k(F_a\text{-}C_a)\text{-}p+B_l$	$(1\text{-}k)(F_b\text{-}C_b)+B_l$	$Q_s\text{-}[kF_a+(1\text{-}k)F_b]\text{-}c+p$
⑥	$mk(F_a\text{-}C_a)$	$(1\text{-}k)(F_b\text{-}C_b)$	$(mk+1\text{-}k)Q_s\text{-}mkF_a\text{-}(1\text{-}k)F_b\text{-}r$
⑦	$k(F_a\text{-}C_a)\text{-}p+B_l$	$(1\text{-}k)(F_b\text{-}C_b)\text{-}p+B_l$	$Q_s\text{-}[kF_a+(1\text{-}k)F_b]\text{-}c+2p$
⑧	$mk(F_a\text{-}C_a)$	$m(1\text{-}k)(F_b\text{-}C_b)$	$m[Q_s\text{-}kF_a\text{-}(1\text{-}k)F_b]\text{-}r$

equilibrium point may also exist, denote as $E^*(x^*, y^*, z^*)$. The point conformed to Eq. (5), and $E^* \in (0, 1)$. Given that the evolutionary game model does not rely on entirely rational decision-making processes, and participants do not select different strategies in a probabilistic distribution, the mixed strategy Nash equilibrium point E^* should be discarded. As noted in previous studies, only at the pure strategy Nash equilibrium point, the strategy combination is asymptotically stable in the dynamic replication system of a multi-party evolutionary game (R Selten, 1980; Ritzberger, Weibull (1995)). Therefore, our focus is solely on analyzing the stability of the above 8 pure-strategy Nash equilibrium points.

$$\begin{cases} y(1-z)B_l + pz - k(1-m)(1-z)(F_a - C_a) = 0 \\ x(1-z)B_l + pz - (1-k)(1-m)(1-z)(F_b - C_b) = 0 \\ 2p + r - c - (1-m)\{k(1-x)F_a + F_b(1-k)(1-y) + p(x+y) \\ +Q_s[kx + (1-k)y - 1]\} = 0 \end{cases} \tag{5}$$

Asymptotic stability. According to the method proposed by D Friedman (1991), the local asymptotic stability of equilibrium points can be examined using the Jacobian matrix of those replicator dynamic equations. Consequently, the Jacobian matrix of the evolutionary game model can be constructed based on the replicator dynamic equations as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} =$$

$$\begin{bmatrix} 1-2x\begin{pmatrix} y(1-z)B_l + \\ k(1-m)(1-z)(F_a-C_a) \\ +pz \end{pmatrix} & x(1-x)\big((1-z)B_l\big) & x(1-x)\begin{pmatrix} k(1-m)(C_a-F_a) \\ +p-B_l y \end{pmatrix} \\ y(1-y)\big((1-z)B_l\big) & 1-2y\begin{pmatrix} x(1-z)B_l + \\ (1-k)(1-m)(1-z)(F_b-C_b) \\ +pz \end{pmatrix} & y(1-y)\begin{pmatrix} (1-k)(1-m)(C_b-F_b) \\ +p-B_l x \end{pmatrix} \\ z(1-z)\big(k(1-m)(F_a-Q_s)-p\big) & z(1-z)\big((1-k)(1-m)(F_b-Q_s)-p\big) & 1-2z\begin{pmatrix} 2p+r-c-(1-m)\{k(1-x)F_a \\ +F_b(1-k)(1-y)+p(x+y) \\ +Q_s[kx+(1-k)y-1]\} \end{pmatrix} \end{bmatrix} \tag{6}$$

Following the derivation of mixed-strategy equilibrium point, the details of the Jacobian matrix's elements were presented in Eq. (6). By substituting the x, y, and z values of each equilibrium point to obtain the matrix' eigenvalues at the equilibrium point.

Analysis of evolutionarily stable strategy. After substituting and calculating Eq. (6), the eigenvalues of the Jacobian matrix for all equilibrium points are provided in Table S1. According to Lyapunov's analysis, if all eigenvalues have negative real components, the equilibrium point is asymptotically stable (sink); however, if at least one eigenvalue has a positive real component, the equilibrium point is considered unstable (AM Lyapunov, 1992). The eigenvalues show that the status of 5 points is indeterminate, and 3 points are unstable, including $E_3(1, 0, 1)$, $E_5(0, 1, 1)$, and $E_7(0, 0, 1)$. Firstly, the Jacobian matrix of the equilibrium point $E_1(1, 1, 1)$ is following:

$$J_1 = \begin{bmatrix} -p & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & c-r \end{bmatrix} \tag{7}$$

The eigenvalues of matrix J_1 are $\lambda(x) = \lambda(y) = \text{-}p$ and $\lambda(z) = c\text{-}r$, respectively. The $\lambda(x)$ and $\lambda(y)$ are negative. According to judgment, E_1 is sink, when $r > c$.

Similarly, the Jacobian matrix of $E_2(1, 1, 0)$ is following:

$$J_2 = \begin{bmatrix} k(1-m)(C_a-F_a)-B_l & 0 & 0 \\ 0 & (1-k)(1-m)(C_b-F_b)-B_l & 0 \\ 0 & 0 & r-c \end{bmatrix} \tag{8}$$

The eigenvalues of matrix J_2 are $\lambda(x) = k(1\text{-}m)(C_a\text{-}F_a)\text{-}B_l$, $\lambda(y) = (1\text{-}k)(1\text{-}m)(C_b\text{-}F_b)\text{-}B_l$, and $\lambda(z) = r\text{-}c$, respectively. Therefore, E_2 is sink, when $C_a \le F_a$, $C_b \le F_b$, and $c > r$.

Table 3 The stability conditions for each equilibrium point.

Equilibrium points	Conditions of ESS
$E_1(1, 1, 1)$	$r > c$
$E_2(1, 1, 0)$	$C_a \le F_a$, $C_b \le F_b$, $c > r$
$E_4(1, 0, 0)$	$C_a < F_a$, $(1-k)(1-m)(C_b-F_b) > B_l$, $c > (1-k)(1-m)(Q_s-F_b)+p+r$
$E_6(0, 1, 0)$	$k(1-m)(C_a-F_a) > B_l$, $C_b < F_b$, $c > k(1-m)(Q_s-F_a)+p+r$
$E_8(0, 0, 0)$	$F_a < C_a$, $F_b < C_b$, $c > (1-m)[Q_s-(1-k)F_b-kF_a]+2p+r$

Similarly, the Jacobian matrix of $E_4(1, 0, 0)$ is following:

$$J_4 = \begin{bmatrix} k(1-m)(C_a-F_a) & 0 & 0 \\ 0 & B_l-(1-k)(1-m)(C_b-F_b) & 0 \\ 0 & 0 & (1-k)(1-m)(Q_s-F_b)-c+p+r \end{bmatrix} \quad (9)$$

The eigenvalues of matrix J_4 are $\lambda(x) = k(1-m)(C_a-F_a)$, $\lambda(y) = B_l-(1-k)(1-m)(C_b-F_b)$, and $\lambda(z) = (1-k)(1-m)(Q_s-F_b)-c+p+r$, respectively. Thus, E_4 is sink, when $C_a < F_a$, $(1-k)(1-m)(C_b-F_b) > B_l$, and $c > (1-k)(1-m)(Q_s-F_b)+p+r$.

Correspondingly, the Jacobian matrix of $E_6(0, 1, 0)$ is following:

$$J_6 = \begin{bmatrix} B_l-k(1-m)(C_a-F_a) & 0 & 0 \\ 0 & (1-k)(1-m)(C_b-F_b) & 0 \\ 0 & 0 & k(1-m)(Q_s-F_a)-c+p+r \end{bmatrix} \quad (10)$$

The eigenvalues of matrix J_6 are $\lambda(x) = B_l-k(1-m)(C_a-F_a)$, $\lambda(y) = (1-k)(1-m)(C_b-F_b)$, and $\lambda(z) = k(1-m)(Q_s-F_a)-c+p+r$, respectively. E_4 is sink, when $k(1-m)(C_a-F_a) > B_l$, $C_b < F_b$, and $c > k(1-m)(Q_s-F_a)+p+r$.

The Jacobian matrix of $E_8(0, 0, 0)$ is following:

$$J_8 = \begin{bmatrix} k(1-m)(F_a-C_a) & 0 & 0 \\ 0 & (1-k)(1-m)(F_b-C_b) & 0 \\ 0 & 0 & (1-m)[Q_s-(1-k)F_b-kF_a]-c+2p+r \end{bmatrix} \quad (11)$$

The eigenvalues of matrix J_8 are $\lambda(x) = k(1-m)(F_a-C_a)$, $\lambda(y) = (1-k)(1-m)(F_b-C_b)$, and $\lambda(z) = (1-m)[Q_s-(1-k)F_b-kF_a]-c+2p+r$, respectively. E_4 is sink, when $F_a < C_a$, $F_b < C_b$, and $c > (1-m)[Q_s-(1-k)F_b-kF_a]+2p+r$.

Game scenarios. Based on the analysis of evolutionarily stable strategy (ESS), 5 equilibrium points are identified as the sink points, as shown in Table 3. There are 4 possible game scenarios.

Scenario 1. Under $E_1(1, 1, 1)$, local governments opt for cooperation, with the superior government overseeing cross-regional RIIL progress (Cooperation-Supervision scenario). Regardless of local governments' cooperation choice, cross-regional RIIL completion occurs under the superior government supervision. Choosing cooperation entails no penalties and potential rewards, while opting for non-cooperation leads to penalties alongside completion under supervision. Thus, despite potential losses, given the inevitable supervision, local governments can only passively cooperate to complete the cross-regional RIIL.

Scenario 2. For $E_2(1, 1, 0)$, local governments still choose the cooperation scenario without supervision from the superior government (voluntary cooperation scenario). When the special funds available to the local governments is higher than or equal to the cost of cross-regional RIIL, the local governments do not need to be supervised and will cooperate voluntarily to complete the project. In the scenario, the cost of supervision is higher than value of reputation. Therefore, the superior government is not willing to supervision.

Scenario 3. Under $E_4(1, 0, 0)$ and $E_6(0, 1, 0)$, one of the local governments is unwilling to cooperate and only partially completed the cross-regional RIIL project without supervision (unilateral cooperation scenario). If superior government choose non-supervision, it reduces the local government's losses caused by the choice of non-cooperation. There are differences in the project cost among different local governments. When cross-regional RIIL requires local government to pay more costs than they receive, local government will choose non-cooperation to control the possible losses caused by the project. At the same time, if the benefits of cross-regional RIIL are higher than the costs, the local government will choose the cooperation scenario. However, the cooperation of only one party is not enough to complete the project, which will cause the party who chooses cooperation also lose the political incentive that can be obtained for completing the cross-regional RIIL.

Scenario 4. For $E_8(0, 0, 0)$, neither local governments nor the superior government are unwilling to cooperate or supervise (passive RIIL scenario). When the local government needs to pay more than the special funds for RIIL and the superior government also needs to spend more than the income to supervise, there will be a situation where the all parties are unwilling to guarantee the completion of the cross-regional RIIL.

Numerical example analysis

The case description. This study employs a cross-town land comprehensive consolidation (CTLCC) project in Xiaoshan District, Hangzhou City, Zhejiang Province (Fig. 3), as a case study to illustrate the proposed evolutionary game modeling framework

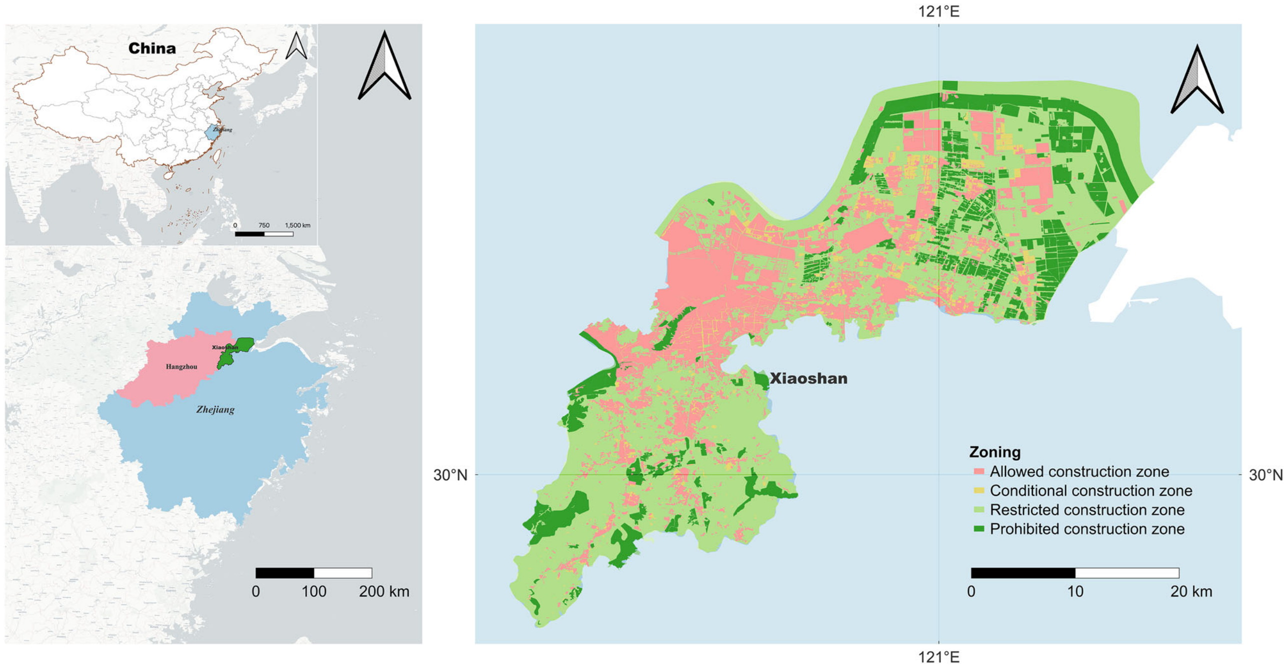

Fig. 3 Location of the case study.

and solution algorithm. The main purpose of the CTLCC project is to revitalize the regional economy and achieve high-quality regional development. The CTLCC project includes cross-regional RIIL, which played an important role but also caused the project's progress to slow. In response to this dilemma, we conducted a comprehensive survey of the current situation of the region and government staff, using it as a case study in this study.

The CTLCC project in Xiaoshan District provides a useful case for understanding the challenges encountered in cross-regional RIIL. The private industry in the research area is highly developed. In 2016, the world-renowned G20 summit was held in Hangzhou, and Xiaoshan, as the core area of conference activities, came to the center of the world stage. There are 800 industrial enterprises in the cluster, with the cluster's scale exceeding 250 billion yuan. By the end of 2022, the number of private economic market entities in the region exceeded 220000. In this context, private enterprises are mainly located in townships, which provides the township governments (local) with the capital to negotiate with the district government (superior). In addition, the superior government transferred the power of administrative punishment to townships, which further strengthened the autonomy of local governments[4]. The phenomenon of strong local governments is not uncommon in Zhejiang (Wang, Shi (2015)). Therefore, this study can provide a reference for cross-regional RIIL.

Our investigation provided insights into intergovernmental dynamics. In 2022, Zhejiang Province initiated the CTLCC project, and we helped design the project plan. After its launch in August 2022, we assessed the industrial land scale in participating towns and gathered information on inefficient industrial land and production conditions through surveys. Based on the survey results, the district-level natural resources and planning department formulated the total RIIL scale and determined each township's proportion based on socioeconomic factors. Township feedback led to adjustments, resulting in the final cross-regional RIIL plan. Nevertheless, issues arose during the process. Some townships were reluctant to finalize the cross-regional RIIL plan. Townships with stronger industrial development believed the poor economic situation was temporary, and the RIIL would hinder future development space. Townships with weaker industrial development considered the RIIL unfair, seeking more benefits as the disadvantaged party. The absence of a specific fund standard from the district government exacerbated the situation. This was mainly because the district government aimed to understand the actual costs and scale of RIIL that the township governments could achieve through negotiations before establishing the standard to reduce expenditure costs. As one township official stated, " Adequate compensation could lead to the reduction of all industrial land." In this case, the criteria for special funds provided by the superior government are uncertain and opaque. We formulated assumptions about the relevant parameters based on existing policy documents.

Given that township governments have objections to their existing compensation standard documents, it is necessary to summarize the compensation standards from different townships in the study area to create potential cross-township combinations. This will help verify the broad applicability of the game model. According to the status quo and survey data of the study area, we established cross-township combinations comprising township types characterized by varying levels of development (Table 4). It is imperative to elucidate the configuration of pertinent parameters. In terms of RIIL ratio (k) and actual completion ratio (m), we have set both to 0.5 to create a fairness condition. For the potential benefits of project completion (B_l), mainly ecological ecosystem value, we have set 0.1×10^5 yuan per mu to refer to benefits based on changes in the value of ecosystem services in Hangzhou (Y Wu et al., 2023)[5]. The cost of RIIL in town A (C_a) and B (C_b) are set at different values under different cross-township combinations. Since the project is still in progress, the values of C_a and C_b are assumed based on the multiple townships' corporate demolition compensation standards[6] (Table S2). Initially, the Local government A (F_a) and B (F_b) can obtain financial special funds are assumed to have the 3 levels of 9.5×10^5, 11×10^5, and 12×10^5 yuan per mu[7]. Subsequently, for further analysis, we'll consider F_a and F_b to be distinct values based on the discrepancy between C_a and C_b. For construction land quotas (Q_s), we set as 6.5×10^5 yuan per mu, based on the sales data of industrial land in Xiaoshan District in the past 6 years[8]. The

Table 4 Different cross-township combinations based on township differences.

Combination types	Description	Assignment of core parameters †
Cross-township combination 1	The RIIL implementation costs of township governments are the same ($C_a = C_b$).	$C_a = C_b = 8.5$ ($F_a = F_b = 9.5$ OR $F_a = F_b = 11$ OR $F_a = F_b = 12$) $C_a = C_b = 13$ ($F_a = F_b = 9.5$ OR $F_a = F_b = 11$ OR $F_a = F_b = 12$)
Cross-township combination 2	The costs of implementing RIIL for township governments vary ($C_a > C_b$ OR $C_a < C_b$).	$C_a = 8.5$, $C_b = 13$ ($F_a = F_b = 9.5$ OR $F_a = F_b = 11$ OR $F_a = F_b = 12$ OR $F_a = 9.5$, $F_b = 12$) $C_a = 13$, $C_b = 8.5$ ($F_a = F_b = 9.5$ OR $F_a = F_b = 11$ OR $F_a = F_b = 12$ OR $F_a = 12$, $F_b = 9.5$)

† The cross-regional RIIL implementation costs borne by the towns participating in the project are uncertain and fluctuating. As a result, there may be situations where the costs are either equal ($C_a = C_b$) or unequal ($C_a > C_b$ OR $C_a < C_b$). Financial special funds allocations (F_a and F_b) are differentiated based on the multiple townships' corporate demolition compensation standards.

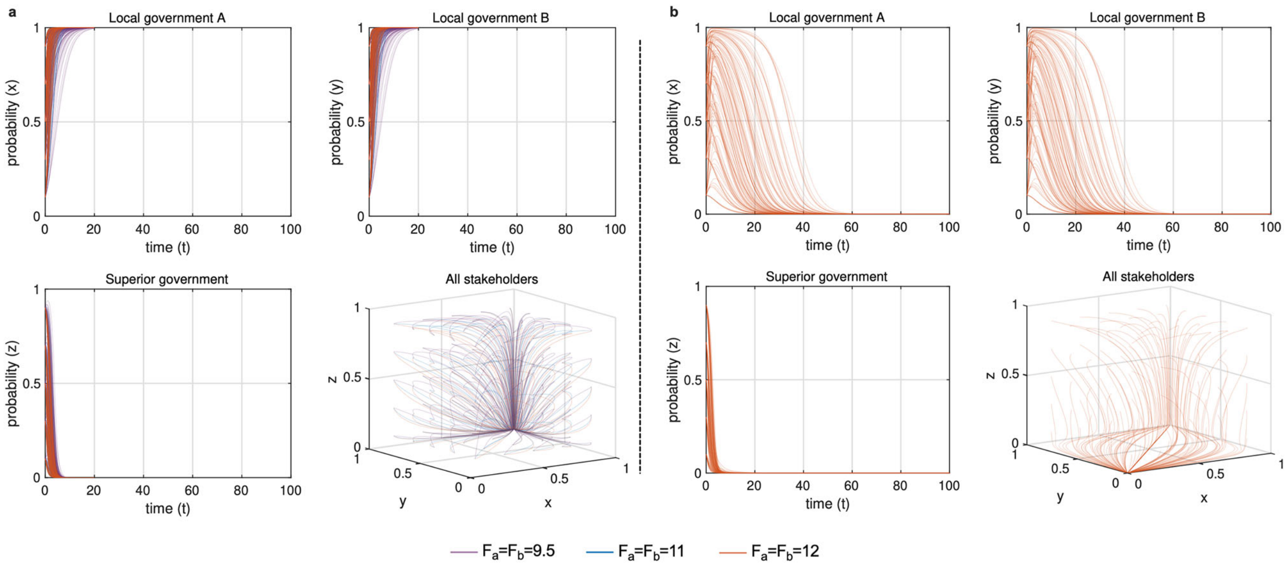

Fig. 4 Evolutionary convergence to sink equilibria E_2 and E_8. The evolution towards the sink $E_2(1, 1, 0)$ and $E_8(0, 0, 0)$, when $C_a = C_b = 8.5$ (**a**) and $C_a = C_b = 13$ (**b**).

reputation value (r) is set as 0.6×10^5 yuan, based on the increase in tax revenue per mu[9]. Based on studies related to the costs and fines of environmental inspections, we assume that the values of supervision cost (c) and penalty (p) are the same (Z Chu et al., 2021). The cost of supervision (c) and penalty (p) are set at same value 2×10^5 yuan per mu based on the Hangzhou Municipal Natural Resources Administrative Penalty Discretionary Standards (Land Category)[10]. Then, different cross-township combinations are presented in Table 4.

Numerical simulation in the case

Scenarios of cross-township combination 1. Voluntary cooperation scenario (Scenario 2). When the condition is set as $k = 0.5$, $m = 0.5$, $B_l = 0.1$, $C_a = C_b = 8.5$, $F_a = F_b = 9.5$ or 11 or 12, $Q_s = 6.5$, $r = 0.6$, $c = 2$, and $p = 2$ (Table 4), the sink $E_2(1, 1, 0)$ becomes the unique ESS. Township governments can make profits by executing RIIL projects. Meanwhile, the district government will choose a strategy of non-supervision, given the cooperation of township governments. As shown by the evolution iteration speeds in Fig. 4a, we can see that the higher the F_a and F_b that the district government can pay, the faster it will promote cooperation between township governments. The "voluntary cooperation scenario" represents an ideal state. In the study area, when the amount of special funds available to the township government is greater than the cost of RIIL, there is no need for the supervision of the district government. Meanwhile, the cost of the district government is also high, leading to the choice of the "non-supervision" strategy. With the voluntary cooperation of two township governments, the supervision of the district government is no longer needed, and the most economical and efficient scenario is realized.

Passive RIIL scenario (Scenario 4). When the condition is set as $k = 0.5$, $m = 0.5$, $B_l = 0.1$, $C_a = C_b = 13$, $F_a = F_b = 12$, $Q_s = 6.5$, $r = 0.6$, $c = 2$, and $p = 2$. When we set $F_a = F_b = 14$, the sink $E_8(0, 0, 0)$ become the unique ESS. As the simulation progresses, the township governments and district government adopt a specific strategy (x, y, z), with the probabilities of these strategies converging to $E_8(0, 0, 0)$ over successive iterations (Fig. 4b). The high implementation costs of RIIL reduce the enthusiasm of township governments and district government to participate in the project. As the dynamic evolution proceeds, all stakeholders will finally choose the strategy $E_8(0, 0, 0)$.

Unstable scenario. When the condition is set as $C_a = C_b = 13$, $F_a = F_b = 9.5$ or 11, it means that both township governments need to pay excessive costs in the implementation of the cross-regional RIIL project. According to the results of simulation (Fig. S2), it is evident that the district government and township governments are ensnared in a dynamic game state marked by recurrent oscillations, ultimately precluding attainment of a sink. By comparing $F_a = F_b = 12$ and $F_a = F_b = 9.5$, it becomes clear that when the special funds paid by the district government are low, it is more inclined to strengthen supervision.

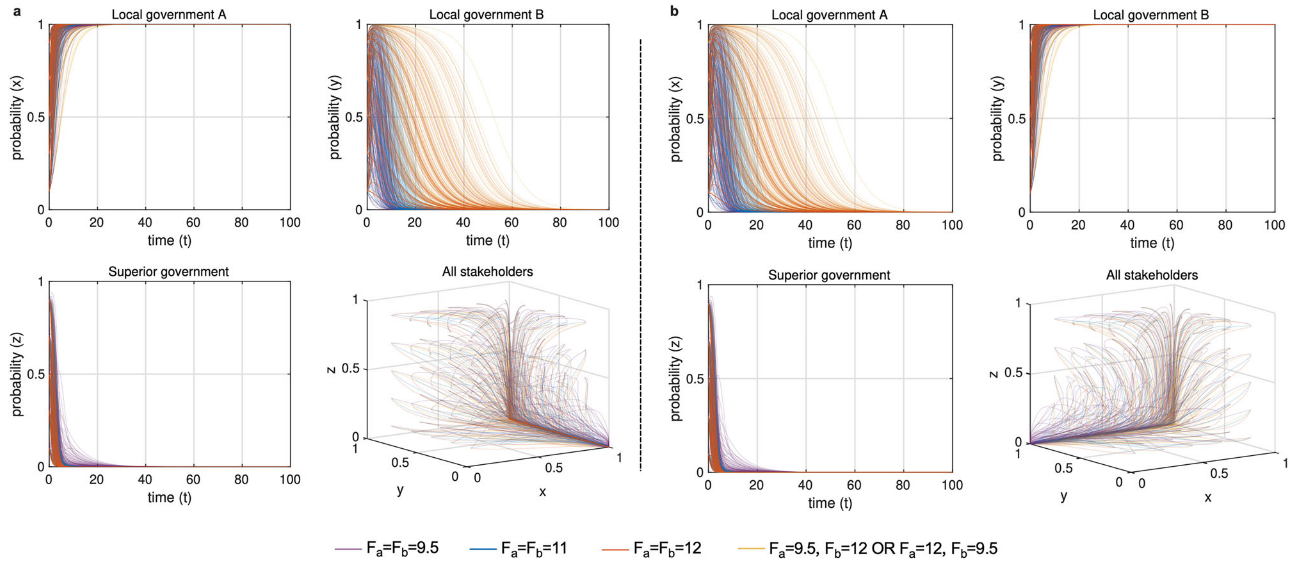

Fig. 5 Evolutionary convergence to sink equilibria E_4 and E_6. The evolution towards the sink $E_4(1, 0, 0)$ and $E_6(0, 1, 0)$, when $C_a = 8.5$, $C_b = 13$ (**a**) and $C_a = 13$, $C_b = 8.5$ (**b**).

Scenarios of cross-township combination 2. Unilateral cooperation scenario (Scenario 3). When the condition is set as $k = 0.5$, $m = 0.5$, $B_l = 0.1$, $C_a = 8.5$, $C_b = 13$, $F_a = F_b = 9.5$ or 10 or 12 ($F_a = 9.5$ and $F_b = 12$), $Q_s = 6.5$, $r = 0.6$, $c = 2$, and $p = 2$ (Table 4), the sink $E_4(1, 0, 0)$ becomes the unique ESS. Moreover, when $C_a \le F_a$, $C_b \le F_b$, and $c > r$, the sink $E_6(0, 1, 0)$ also emerges as the unique ESS. When the condition is set as $k = 0.5$, $m = 0.5$, $B_l = 0.1$, $C_a = 13$, $C_b = 8.5$, $F_a = F_b = 9.5$ or 10 or 12 ($F_a = 12$ and $F_b = 9.5$), $Q_s = 6.5$, $r = 0.6$, $c = 2$, and $p = 2$ to analyze the ESS. Simulation results showed that local governments and superior government would select a specific strategy (x, y, z), and their probabilities eventually converge to $E_4(1, 0, 0)$ or $E_6(0, 1, 0)$, as the iterations continue (Fig. 5). The "unilateral cooperation scenario" will occur when the cost of RIIL for one of the local governments is higher than the available special funds. This is a prevalent scenario because local development is spatially heterogeneous. In the study area, this scenario is also the first to appear. One of the towns has relatively good economic development and has high costs to reduce inefficient land use. In the absence of supervision from the district government, planners have no access to township leaders, causing delays in implementing the project. If this trend persists, the scenario represented by $E_4(1, 0, 0)$ or $E_6(0, 1, 0)$ will eventually emerge.

Sensitivity analysis of different parameters in scenarios. In this section, we initialize the starting point at Sp(0.5, 0.5, 0.5). Subsequently, through manipulation of various parameter values, we investigate the resultant alterations in the trajectory of the game. Given the absence of policy document backing for certain parameter data settings, such as the RIIL ratio (k), the RIIL completed ratio (m), the potential benefit of RIIL completion (B_l), and the supervision cost (c), we adjusted these parameter values, using available academic literature. This approach allowed us to conduct a sensitivity analysis on the model.

The sensitivity analysis of RIIL ratio (k). The sensitivity analysis of RIIL ratio in different scenarios is shown in Fig. 6. The k value represents local government A's RIIL ratio, which is subject to change. The parameter k ranges between 0 and 1, and its specific values are determined according to cross-regional research on ecological compensation (J Ding et al., 2022). Therefore, we set it to 0.1, 0.5, and 0.9 to see the impact of its value on the probability of x, y, and z. In $E_2(1, 1, 0)$, the changes in k value did not impact the convergence results of the game. While varying parameter values may induce fluctuations in the curve, both local governments will inevitably opt for a "cooperative" strategy, with no "supervision" from the superior government. In $E_8(0, 0, 0)$ and the unstable scenario, the changes in k caused different results. Figure 6 illustrates that variations in the k value led to shifts in the evolutionary direction, while distinct financial support yields diverse outcomes in game decision-making. When the implementation cost of RIIL is high ($C_a = C_b = 13$) and the superior government can offer funds that are relatively close ($F_a = F_b = 12$), it results in a deceleration of the evolutionary speed across all curves (Ep5, Ep8, and Ep9). When there exists a substantial disparity in the ratio of RIIL completion between two local governments ($k = 0.9$ or 0.1), the local government with lower costs tends to incline towards cooperation (Ep3 and Ep4, Ep6 and Ep7). When $k = 0.5$, the low funds ($F_a = F_b = 9.5$), the superior government tended to make a "supervision" decision. In $E_4(1, 0, 0)$ and $E_6(0, 1, 0)$, the changes in k primarily influence the decision-making of local governments facing high costs in implementing RIIL. When a local government with high implementation costs for RIIL is allocated a small RIIL ratio, there may still be a tendency towards cooperation (Ep3). Moreover, when the funds allocated by the superior government fail to cover the costs of implementing RIIL for both local governments, adjusting the RIIL ratio by the superior government has a more pronounced effect than maximizing financial support (Ep2 and Ep3).

The sensitivity analysis of RIIL completed ratio (m). The varying ratio of RIIL completion can change the stakeholders' strategic choices (Fig. 6). The parameter m also ranges between 0 and 1, which was learned from the extent of the local government's implementation of environmental regulation (H Yu et al., 2019). We set it to 0.1, 0.5, and 0.9. In $E_2(1, 1, 0)$, the value of m does not affect the choice of strategy because the benefits from completing the RIIL are always greater than the costs. However, in $E_8(0, 0, 0)$ and the unstable scenario, the size of m shows the proportion of local governments that can actually implement RIIL. When both local governments achieved only a fraction of the RIIL project (Ep1), they quickly adopt a "non-cooperation" strategy. On the other hand, when the percentage of local governments capable of

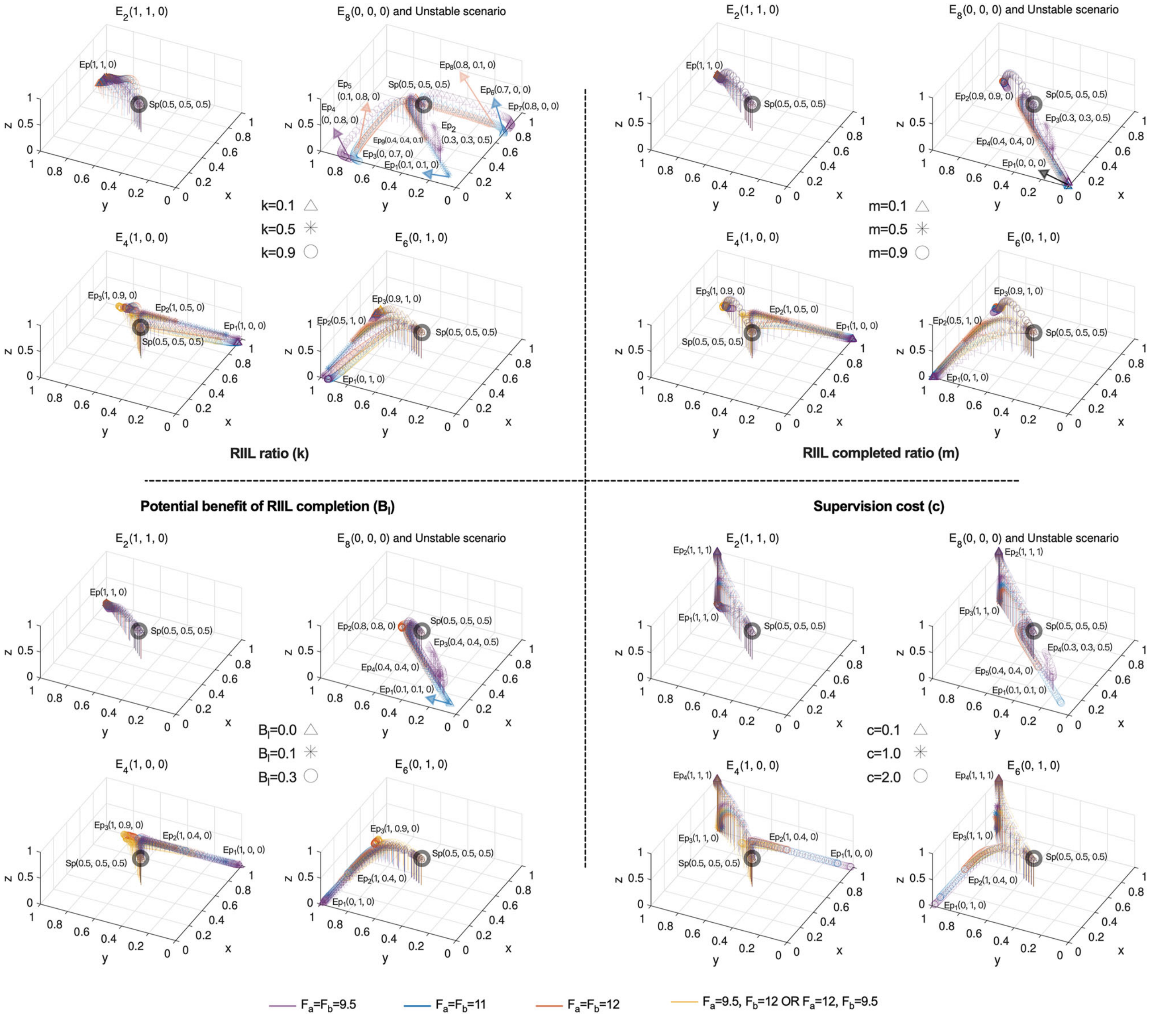

Fig. 6 The sensitivity analysis of parameter alterations on the behavior evolution of governments in scenarios. Sp indicated starting point and Ep indicated ending point. Following the rounding principle, one decimal place is retained after the decimal point.

completing RIIL projects is high (i.e., m = 0.9), irrespective of the level of financial support available, local governments are inclined to opt for a "cooperation" strategy (Ep2). When two local governments possess the capacity to accomplish half of the RIIL project (m = 0.5), and the superior government may implement a "supervision" strategy ($F_a = F_b = 9.5$), they will enter into a series of iterative interactions with the superior government (Ep3). In E_4(1, 0, 0) and E_6(0, 1, 0), the impacts of the m values are comparable to those of the k values. When a local government with negative benefits achieves a high rate of RIIL completion (m = 0.9), they are more inclined to cooperate to mitigate potential losses resulting from penalties (Ep3). Moreover, the results also indicate that when the local government's positive or negative benefits remain unchanged, the level of financial support from the superior government can influence the pace of game evolution, yet it lacks the capability to alter the overall trajectory of evolution (Ep2).

The sensitivity analysis of the potential benefit of RIIL completion (B_l). The potential benefits of RIIL completion are obtained by local governments, so the size of potential benefits will affect the strategic choices of local governments (Fig. 6). According to the research on ecosystem service valuation, the values of B_l are set as $B_l = 0$, $B_l = 0.1$, and $B_l = 0.3$, respectively (Y Wu et al., 2023). In E_2(1, 1, 0), variations in B_l do not significantly impact strategic choices, consistent with the results of m and k. In E_8(0, 0, 0) and the unstable scenario, changes in B_l generally do not cause directional shifts in the evolutionary trajectory of the game model. However, when B_l is equal to 0.3 and financial support closely matches the implementation cost, local governments' propensity for "non-cooperation" decision-making slows down, indicating a trend towards cooperation (Ep2). In E_4(1, 0, 0) and E_6(0, 1, 0), when B_l is equal to 0.3, it exerts a specific incentive effect on local governments with negative benefits, decelerating the pace of evolution or even altering its direction (Ep2 and Ep3).

The sensitivity analysis of the supervision cost (c). Changes in supervision cost are associated with the superior government's decisions (Fig. 6). Given the likelihood that the supervision cost does not surpass the penalty value in practice, the model utilizes c = 2 as the upper threshold for sensitivity analysis. Furthermore, the lower limit of supervision cost is established at 0.1, derived from research on farmland fallow (H Xie et al., 2018). In $E_2(1, 1, 0)$, changes in supervision cost affect the evolution rate and direction. The lower the supervision costs, the greater the inclination of the superior government to engage in supervision (Ep2). In terms of $E_8(0, 0, 0)$ and the unstable scenario, when the supervision cost decreases to 1 or less, the local governments become apprehensive about potential sanctions from the superior government and opt for a "cooperation" strategy (Ep2 and Ep3). In $E_4(1, 0, 0)$ and $E_6(0, 1, 0)$, distinct supervision costs produce diverse evolutionary game trajectories, unaffected by fluctuations in the financial support from the superior government.

Discussion and implications

Interaction mechanism among governments in cross-regional RIIL. In China, there is a close relationship between the land use efficiency of industrial land and the government (Zhou, Chan (2022)). For the management of inefficient industrial land, Chinese local governments often have great management authority because of decentralized reforms (L Zhang et al., 2018; Z Liu et al., 2023). However, the performance and evaluation of local governments are contingent upon decisions made by the superior government (P Tang et al., 2021). Given the need for cross-regional government cooperation to optimize the spatial allocation of industrial land and enhance its efficiency, our study explores the interaction mechanism among multi-level governments involved in the cross-regional RIIL, from the perspective of intergovernmental game theory—an area rarely addressed in previous research. Based on our findings, the primary contributions can be summarized as follows: first, this study reveals the mechanisms of multi-level government interactions within cross-regional RIIL; second, it elucidates the key factors influencing intergovernmental cooperation; and third, it offers multi-dimensional perspectives for optimizing the management system of inefficient industrial land use.

Promoting the emergence of the "cooperation" strategy. According to the game model results, it is clear that the adoption of a "cooperation" strategy by local governments leads to the achievement of project goals at reduced costs (E_2, "voluntary cooperation"). Consistent with a previous study, when explicit benefits outweigh costs, both parties' willingness to cooperate increases (Junqiang Li et al., 2023). A critical step following the RIIL is the establishment of a reasonable compensation mechanism to safeguard participants' rights and interests (Gu et al., (2018)). Our fundings suggest that benefits need not greatly surpass costs (approximately 11% more), and effective cost control can achieve the goal more economically. Furthermore, this scenario exhibits significant stability and resilience to fluctuations in other parameters, with the exception of supervision costs. Nevertheless, different local governments often encounter varying RIIL implementation costs. In recent years, superior governments may opt for reduced financial support to complete cross-regional RIIL projects amid concerns about debt and economic downturn (M Chen et al., 2023). This makes the "unilateral cooperation scenario" more consistent with current realities. The emergence of a "passive RIIL scenario" or an "unstable scenario" is also conceivable.

In the case study, we observed that governments had a limited understanding of the benefits and costs associated with cross-regional RIIL. Although the CTLCC project was initiated with approval from all levels of government, local governments actually held less decision-making authority compared to the superior government (Tsui, Wang (2004); SE Anderson et al., 2019). As a result, the project plan was initially submitted for approval, with implementation considerations following. This sequential approach allows for project plan revisions even after approval, leading to fluctuations in the government decision-making. During the planning phase, the district government persuades township governments to participate by highlighting potential benefits. Simultaneously, township governments, grappling with their own development challenges, aim to leverage special funds to optimize industrial land use and stimulate economic growth. At this point, the dynamics among the multi-level governments shift towards "voluntary cooperation". Both township governments anticipate positive outcomes from collaborative efforts, while the district government focuses on achieving effective supervision at minimal cost. However, further investigation reveals that the actual implementation costs of cross-regional RIIL exceed initial estimates, potentially resulting in negative outcomes. If the district government fails to adopt a "supervision" strategy at this stage, the project may shift towards a "unilateral cooperation scenario", "passive RIIL scenario", or "unstable scenario", all of which could cause project failure.

By disregarding the "supervision" strategy implemented by the superior government, altering the RIIL ratio, the RIIL completed ratio, or potential benefits, can affect the trajectory and pace of evolution. In both the "passive RIIL scenario" and the "unstable scenario", variations in potential benefits have negligible effects. A township with a lower RIIL ratio and one with a higher RIIL completion ratio are both inclined towards cooperation. In the "unilateral cooperation scenario", augmenting potential benefits, akin to alterations in ratios, can similarly enhance the likelihood of cooperation between the two township governments. Nevertheless, based on the ESS criteria, alterations in these parameters do not fundamentally alter the outcomes of non-cooperation or instability. Therefore, we argue that through the reasonable modification of parameters, along with supervision from the superior government, the ultimate outcomes of the evolutionary game can be more effectively influenced. This underscores the vital role of superior governmental supervision in land management (Junqiang Li et al., 2023).

Superior governmental "supervision" aids project completion. In our case, given that the supervision cost surpasses the reputation of the superior government, the evolutionary game does not result in a scenario where the superior government oversees the project. However, if the supervision cost is low, the superior government is more likely to supervise and compel local governments to complete the RIIL (E_1). In the "passive RIIL" and "unstable" scenarios, when the supervision cost is below 1, "non-cooperation" local governments shift towards cooperation, with a probability exceeding 0.95. Numerical simulations show that when local governments can accomplish 90% of the project ($m = 0.9$) and the superior government's supervision cost is 1 ($c = 1$), the project is likely to be completed even without sufficient special funds. In such cases, although the superior government may not directly implement supervision, local governments are still likely to cooperate, driving the game towards the E_2 (Fig. S3). This confirms that a carrot-and-stick approach also effectively explains the interactions among governments in cross-regional RIIL projects (Z Hu et al., 2024).

The decision of the superior government to engage in supervision, as outlined by E_1, is influenced not only by the associated costs but also by the perceived value of its reputation. According to our model and previous research, the superior government's reputation is strongly linked to its ability to successfully complete relevant projects (Y Zhao et al., 2023). This suggests that the success of cross-regional RIIL projects could be enhanced through increased involvement of the superior government in related initiatives. However, there remains a significant research gap in this area, particularly regarding the valuation of government reputation. We argue that the importance placed by the superior government on such projects likely increase the value of reputation. Additionally, as existing research suggests, the valuation of government reputation may be more closely aligned with the costs of supervision Li, Wang (2023).

Exclusive reliance on supervision from the superior government is insufficient to voluntary cooperation between local governments. In this case, our investigation revealed that during the project planning stage, the implementation costs and financial funds were unclear, which facilitated project approval. However, as the project progressed, variations in costs and benefits led to disagreements between local governments. To enhance the robustness of our model results, we incorporated existing standards and selected representative amounts for cost and funding settings. This allowed our findings to account for a range of possibilities influenced by variations in these variables. In the context of cross-regional RIIL, how can we promote voluntary cooperation between local governments and reduce supervision costs? We believe the solution lies in systematic policy optimization.

Policy implications. The strongest resistance to the RIIL comes from the challenge of balancing local governments' cost-benefit considerations and the imperfect allocation of resources. Using Williamson's institutional analysis framework, it becomes clear that improving resource allocation institutions requires the support of informal institutions, formal institutions, and governance institutions (OE Williamson, 2000). Therefore, current policies could be optimized from three different institutional perspectives.

From the standpoint of informal institutions, social consensus and cultural customs are needed to enhance the potential benefits of RIIL. For instance, policy support for social surveys of inefficient industrial land should be improved from the perspectives of companies' willingness to vacate, feedback from surrounding residents, and landscape ecological conditions. Quantifying the social and ecological benefits that can be considered as potential benefits and generated by RIIL can draw insights from brownfield regeneration (G Atkinson et al., 2014). This would require integrating cross-regional RIIL with industrial land surveys, ecological environment surveys, and overall land spatial planning. It is essential to ensure that the industrial land earmarked for withdrawal is genuinely inefficient and does not pose a threat to residents' livelihood security. Furthermore, lessons from energy management research suggest that public engagement in supervision can be a cost-effective way to diminish the superior government's supervision costs (W Yang et al., 2022).

Regarding formal institutions, the superior government should improve relevant policies from three aspects to incentivize local governments to adopt a "cooperation" strategy. First, standard documents for special funds should be formulated and issued as soon as possible to ensure that funds are in place and provide confidence to local governments. Second, the superior government should optimize the penalty system by introducing a staged approach to penalties, anchored on a transparent total fine structure, while encouraging local governments to embrace "cooperation" strategies in project implementation. Finally, the superior government should establish a policy foundation for enhancing local potential benefits by refining the incentive system and quantitative evaluation systems for ecological and social values.

As for governance institutions, the formulation of policies associated with the RIIL should consider the local socioeconomic status quo. When determining the scope and scale of RIIL, it is essential to consider the varying levels of the difficulty and costs that different local governments face in implementing projects, thus ensuring spatial justice (K Wang et al., 2023). Furthermore, adjusting the project completion deadline appropriately and implementing the RIIL in phased stages can help reduce project implementation costs. Ultimately, and significantly, it is crucial for governments at all levels to enhance the transparency of governance institutions by financial support standards, up-to-date policy requirements, and actual implementation capabilities. This is essential to mitigate the issue of ambiguous delineation of responsibilities.

Conclusions

The government's behavioral decisions are pivotal to the success or failure of cross-regional RIIL. However, there is a notable lack of quantitative studies concerning governmental behavior strategies in this context. Diverging from spatial optimization-focused studies, we specifically address the interactive mechanisms among stakeholders in inefficient land reduction. In this study, we formulated a tripartite evolutionary game model, including the superior government and two local governments, to examine the behavioral dynamics and strategic adaptation mechanisms inherent to these stakeholders. Local governments are incentivized to cooperation only when they anticipate positive benefits. Our findings systematically improve the theoretical understanding of multi-agent gaming in land governance. They reveal that increasing potential benefits and optimizing RIIL ratios can increase the likelihood of cooperation. Local governments with higher RIIL completion capabilities are more inclined to cooperate. When the supervision cost for the superior government is moderate and there is a tendency to supervise, local governments are more likely to adopt proactive cooperation strategies. The case study also demonstrates that low supervision costs will incentivize the superior government to choose a "supervision" strategy. A carrot-and-stick approach can contribute to project success at a lower cost in cross-regional RIIL.

This study aims to optimize policy-making by analyzing intergovernmental decision-making choices in cross-regional RIIL. Based on Williamson's four-level institutional analysis framework, we optimized cross-regional RIIL's resource allocation mechanism from multiple institutional perspectives. The study contributes to the enhancement of supervisory mechanisms within the superior government and bolsters the incentive structures for local government cooperation, thereby facilitating the formulation of enduring strategic decisions by the stakeholders. Since 2025, cross-regional RIIL projects have been rapidly implemented in China's eastern coastal provinces (e.g., Fujian, Jiangsu)[11,12]. The study provides both theoretical support and practical guidance for these ongoing projects.

This study explains the decision-making behavior and stabilization strategies of governments at various levels under different scenarios in cross-regional RIIL. However, this study only focused on some major factors. Due to limited literature and data availability, we were unable to conduct an in-depth analysis of all potential influences. Future research will incorporate a broader range of impact factors into the game model, drawing on additional case studies for a more comprehensive analysis.

Data availability

All data generated or analysed during this study are included in this article.

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Notes

1 Zhejiang Provincial People's Government (2022), Opinions of the Zhejiang Provincial People's Government on the Pilot Program of Cross-town Comprehensive Land Consolidation. https://www.zj.gov.cn/art/2022/11/25/art_1229700890_2457875.html (in Chinese). Accessed 14 Nov 2022.

2 Jiaxing Municipal People's Government (2023), Approved! The first cross-regional land and space planning was implemented in the Yangtze River Delta Demonstration Zone, which clarified these key points! https://www.jiaxing.gov.cn/art/2023/2/22/art_1578783_59569459.html (in Chinese). Accessed 22 Feb 2023.

3 Kunshan Municipal Natural Resources and Planning Bureau (2023), Our bureau carries out a special survey on comprehensive land consolidation across townships. http://zrzy.jiangsu.gov.cn/szks/gtzx/gzdt/202306/t20230613_1427522.htm (in Chinese). Accessed 13 Jun 2023.

4 People's Government of Xiaoshan (2022), Announcement of the People's Government of Xiaoshan District, Hangzhou City on the transfer of the administrative punishment power of some departments in Xiaoshan District to 21 towns (streets) such as Linpu Town and Chengxiang Street, and the dynamic adjustment of the list of empowerment items in Guali Town. http://www.xiaoshan.gov.cn/art/2022/5/27/art_1302905_59073293.html (in Chinese). Accessed 27 May 2022.

5 Through the deduction of the ecosystem service value associated with construction land from the mean ecosystem service value observed across all non-construction land types, we ascertained the potential benefit to be 0.1×10^5 yuan per mu.

6 Given the uncertainty and potential fluctuations in the final costs for the townships participating in the cross-regional RIIL implementation project, we utilized the existing industrial land demolition compensation standards from these townships and neighboring areas as a comprehensive reference for estimating RIIL implementation costs and determining the level of special fund support from the superior government. Acknowledging the inevitable disparity between the costs and the special fund, we selected two extreme values from the townships to illustrate the impact of benefit differentials. This method ensures a consistent imbalance between the costs and the available funds.

7 We identify two towns with RIIL implementation costs falling within the median range to serve as the upper and lower bounds for the financial special funds (F_a and F_b) feasible for the superior government. Additionally, we utilize the average cost from four towns as the midpoint (Table S2).

8 Department of Natural Resources of Zhejiang Province (2024), Zhejiang natural resource online trading center. https://www.zjzrzyjy.com/portalBrowse/home (in Chinese). Accessed 27 Feb 2024. In Xiaoshan District, data from 290 industrial land transactions shows a median price of 6.5×10^5 yuan per mu. The upper quartile stands at 7.3×10^5 yuan per mu, while the lower quartile is 5.5×10^5 yuan per mu (Fig. S1). We set construction land quotas is 6.5×10^5 yuan per mu.

9 Xiaoshan District Development and Reform Bureau (2023), Report on the implementation of the 2021 National Economic and Social Development Plan and the 2022 National Economic and Social Development Plan (draft) in Xiaoshan District, Hangzhou City. http://www.xiaoshan.gov.cn/art/2023/4/13/art_1229293119_4157344.html (in Chinese). Accessed 13 Apr 2024. "The campaign of 'vacating the cage for a bird, reviving a phoenix' was effectively implemented, comprehensively promoting the rectification of inefficient enterprises with an average tax revenue of less than 0.2×10^5 yuan per mu, and increasing the average tax revenue from 0.1×10^5 yuan per mu to 0.7×10^5 yuan per mu." Therefore, The reputation of the district government can bring an increase of 0.6×10^5 yuan in tax revenue per mu. On the contrary, we can assume that the loss of reputation means that the industrial land transformation project cannot be completed, which will not lead to an increase in tax revenue per mu.

10 Hangzhou Municipal Planning and Natural Resources Bureau (2022), Interpretation of Hangzhou Municipal Natural Resources Administrative Penalty Discretionary Standards (Land Category). https://www.hangzhou.gov.cn/art/2022/2/10/art_1229063385_1812817.html (in Chinese). Accessed 10 Feb 2022. If the township government insists on using the construction land that should be withdrawn, it may face penalties in Article 8 of the above standards "occupying construction land". The fine is 1.7×10^5 yuan per mu. At the same time, according to Article 16 "Refuse to perform land reclamation obligations", the township government still needs to pay more than three times the land reclamation fee, about 0.3×10^5 yuan per mu. Therefore, the total penalty is 2×10^5 yuan per mu.⑪ Xinhua Daily (2025), Jiangsu: "Five major paths" support rural revitalization. http://www.js.xinhuanet.com/20250317/b8cf9769e63c4c36abe5a0f354e9cbc1/c.html (in Chinese). Accessed 17 Mar 2025. "In 2025, the Provincial Department of Natural Resources will continue to give full play to the comprehensive effectiveness of comprehensive land consolidation in the entire region, establish and improve institutional mechanisms, carry out multi-scale reform practices in the entire county, across townships and within a single township according to local conditions and needs, coordinate the implementation of concentrated and contiguous consolidation of agricultural land, revitalization and utilization of inefficient and idle construction land, integrated protection and restoration of mountains, rivers, forests, fields, lakes, grasslands and deserts, improvement of rural public space governance, and introduction and cultivation of rural industries, promote urban-rural integrated development, and contribute more experience to the comprehensive promotion of livable, business-friendly and beautiful rural construction."⑫ Department of Natural Resources of Fujian Province (2025), Excellent case of natural resources | Quanzhou: Innovating a cross-township and full-region land comprehensive remediation model to help the comprehensive revitalization of rural areas. https://zrzyt.fujian.gov.cn/ztzl/sxzygwzxsqzx/zyzxzx/202501/t20250120_6705077.htm (in Chinese). Accessed 20 Jan 2025. "In recent years, Quanzhou City has made good use of the pilot policy of revitalizing and utilizing inefficient land granted by the state, fully considered the regional resource endowment, and targeted prominent problems that restrict development, such as spatial fragmentation of land elements, inefficient use of construction land, and low ecological environment quality. Taking Hui'an County as a pilot, it explored a cross-township and full-region land comprehensive remediation model that integrates regional elements, participates in the whole process, and shares rights and interests across the entire chain, realizing the organic unity of economic benefits, ecological benefits, and social benefits, and providing strong support for promoting high-quality development in all directions and promoting the comprehensive revitalization of rural areas."

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The authors declare no competing interests.

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