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Implementation of a multi-agent environmental regulation strategy under Chinese fiscal decentralization: An evolutionary game theoretical approach

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A B S T R A C T

Evolutionary game theory (EGT) provides a powerful tool with which to unpack the interactive strategies of polluting enterprises (PEs), local government regulators (LG), and central government planners (CG) in China. Here, the prevailing institutional system of fiscal decentralization sees regulatory mandates set by the CG and enforced at the LG level. This delegation shapes managers' incentives when deciding the degree to which firms will incur costs to reduce pollution and comply with state directives. Manager's choice sets draw shape from decisions at the LG level, where regulators balance the pursuit of environmental quality with the economic payoffs of tacit collusion with industry. LG and PEs incentives reciprocally shape and draw shape from outcomes at the CG level, where policymakers decide the degree to which they will support and supervise the behavior of LGs. By exploring the evolution of different participants' behavior and their evolutionary stable strategy (ESS) in line with the duplication of dynamic equations, EGT enables a robust, quantitative analysis of this iterative, interactive, three-player game. A numerical example serves to verify the theoretical results and support four key insights. First, the selection of environmental strategies manifest in a dynamic process of constant adjustment and optimization. Second, LGs outperform by integrating decisions from both CG and PEs in weighing alternative environmental strategies. Third, reducing regulatory costs at the CG level cascades to strengthen penalties for local violations and improve mitigation incentives in ways that aid an evolutionary game to converge on an ideal decision state. Fourth, a stable equilibrium cannot persist to allow LGs to sustain behaviors towards a “race to the bottom”, even in the total absence of central regulation or high levels of dominance of polluting firms of LG regulators. EGT thus not only outcomes shed light on the full variation set of game outcomes, it also reveals the consequences of variable levels of collusion between LGs and PEs and options for the redesign of incentive mechanisms to reform the regulatory regime and improve market outcomes in China.

1. Introduction

After more than 30 years of reform and expansion, China has made great economic and social progress (Lin et al., 2003). However, remarkable economic expansion has brought about an equally concentrated deterioration of environmental quality, as the environmental impacts seen over 100 years of industrialization in many developed countries have emerged in just 30 years. China's decentralized regulatory model of fiscal decentralization has played a central role in shaping this dynamic, recent history of rapid industrialization. Fiscal decentralization involves in a system grounded in top down policymaking, local implementation, and intensive levels of interregional competition (Montinola et al., 1995). Political leadership hinges on an ever-changing composition of multi-level government, regulatory powers and authority for environmental governance conform to administrative divisions,

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while multiple local governments (LGs) hold — and often share — legal property rights for environmental resources.

In examining tensions and trade-offs between rapid industrializations and environmental governance, mainstream literature on China's development has subscribed primarily to a perspective of competitive enterprise production aligned by efficient government regulation (Du et al., 2015; Zhao et al., 2015; Zhang et al., 2017). The implicit assumption holds that formal institutions strictly control China's environmental governance and performance. In other words, with a few notable exceptions (Yee et al., 2014; Cao et al., 2016) most studies assume that environmental regulation policies at the local government level are rational and effective.

However, recent strengthening of environmental regulation in China has appeared not to significantly arrest the deterioration of environmental quality (Li et al., 2016). For example, critics regularly cite ongoing struggles with very high levels of ambient air pollution (Sueyoshi and Yuan, 2015; Zhang et al., 2016), as observed in a classic case in 2013 when smog enveloped 25 provinces and more than 100 large and medium-sized cities in China to form the world's foremost wide scale environmental disaster (Chen and Chen, 2018). A major reason for the apparent lag in the literature to recognize the limitations of centralized reform lies in an absence of explicit recognition that local regulators face dual constraints of "political centralization and economic decentralization" (Chen and Gao, 2012).

Under a prevailing model of interregional competition, executives of environmental regulatory agencies embedded among local authorities have competing incentives to allow or even encourage polluting enterprises (PEs) to compete for limited environmental resources within a jurisdiction. To maximize economic outputs (He et al., 2016), local government (LG) administrators regularly subsume the autonomy of local environmental regulators to collude with polluting industries in a quintessential "race to the bottom" (Konisky, 2007; Tao et al., 2009). Firms also regularly take an active role in bribing or otherwise colluding with government officials (Jia and Nie, 2017) to transfer the external costs of production onto local residents and the environment (Zhou, 2007).

Thus, fragmentation of regulatory incentives across multiple structural levels may undermine the driving force of China's environmental governance — the central mandate — enervating the power of the state to preserve environmental quality (Zhao and Sun, 2016). In view of the huge environmental rent-seeking persisting under the current arrangement (Chen et al., 2016), strategic interactions between the CG, LGs and PEs warrants additional study to inform the future of environmental regulation in China.

The fiscal decentralization literature (Han and Kung, 2015; He, 2015; Yang, 2016) has made systematic advances in modeling the overlay of incentives between governmental layers in China, but has largely failed to model the strategic dynamics of environmental regulation and firm behavior that drive environmental quality outcomes. This study sets out to fill this gap using evolutionary-game-based learning theory (Samuelson, 2002; Shubik, 2002) and a series of quantitative simulation analyses. EGT is a promising tool with which to model social dilemmas grounded in problems of individual cooperation (Wu et al., 2017), allowing researchers to delineate and simulate mutually interactive outcomes among game players or groups whose strategic behaviors shape each other's payoffs.

This toolset is particularly well suited to the Chinese context. Here, regulatory mandates set by the CG are implemented at the LG level. The central government's decisions to set the stringency of its regulatory mandate and its willingness to enforce that mandate on its local agents shape - and are shaped - by the choices of the local regulator. At the firm level, managers decide the degree to which they will incur costs to mitigate pollution and so comply with local regulation. The LG regulator sits in the middle, balancing the pursuit of environmental quality in compliance with CG mandate with the economic payoffs of colluding with industry. The interaction between multi-agents is described in Fig. 1. Over time, each player may converge towards full enforcement/regulation/mitigation, respectively, a 1:1:1 outcome representing what an environmental fundamentalist might describe as an ideal state. By exploring the evolutionary stable strategy (ESS) of the different participants' behavior, EGT enables a robust, quantitative analysis of this iterative, interactive, three-player game and, in doing so, seeks insights to inform recommendations for reform.

This study seeks to address three primary research questions through the analysis of strategic interactions and outcomes in this three-player game. First, it seeks to understand the implications of the mezzanine position of LG regulators as "bridging architecture", linking together the mitigation decisions of firm managers with the mandate calculus of the central government. To this end, it seeks patterns by which differences in the initial values of the game translate into various equilibrium outcomes after multiple rounds. More specifically, the analysis seeks insights into ways in which variations in the relative influence of PEs and the CG on the payoffs of LG regulators shape outcomes. It also hopes to understand how differences in this "relative sensitivity" of the LG regulator shape the later-stage payoffs for the other players' strategic choices.

Second, this study sets out to understand how the first-round position ("choice proportion") of various agents (PE/LG/CG) influence the game evolution pathway and the speed of convergence towards the ideal state (1:1:1) in a stylized, ten-round game. In the marketplace - holding the behavior of CG constant — the studyis interested in the influence of LG's starting position on PE's game path (CG || LG_0 => $PE_{1\text{-}8}$) and vice versa (CG || PE_0 => $LG_{1\text{-}8}$). In the fiscally decentralized state - holding the behavior of PE constant — it investigates the influence of CG's starting position on LG's game path (PE || CG_0 => $LG_{1\text{-}8}$) and vice versa (PE || LG_0 => $CG_{1\text{-}8}$).

Third, this study seeks to uncover specific conditions that appear to encourage convergence towards the ideal state characterized by central enforcement, local implementation and corporate mitigation (1:1:1). It is particularly interested in the relative importance of costs and benefits for all three parties, the ways these relative "weightings" shape strategic interactions between counterparties, and the influence of changes in these weightings on rates of strategic convergence as the three actors make progress

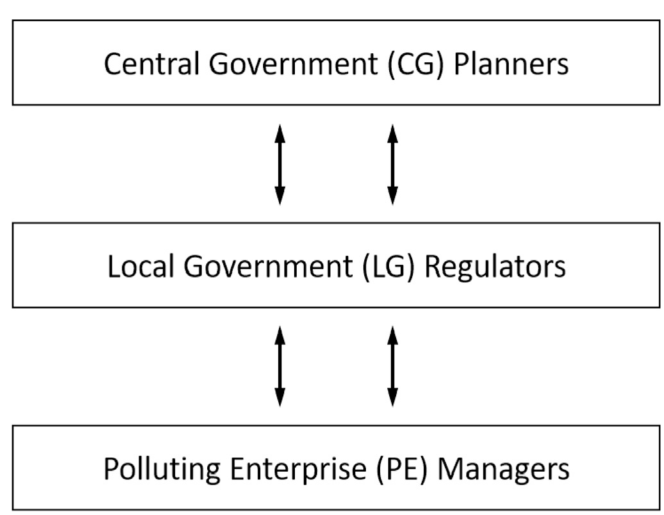


Fig. 1. Interaction between multi-agents.

through the simulation.

In answering these questions, this study makes three below contributions. This study first provides improved understanding of the fiscal decentralization system underlying current Chinese environmental policies. EGT analysis shows how the local regulators' political incentives shape the efficiency of environmental regulation and underscore recent advances in the environmental politics literature that emphasize the importance of politics in influencing policy outputs and market outcomes (Moore, 2014; Cao et al., 2016).

Second, this study deviates from mainstream EGT research focused primarily on two-player games of identical or different subjects (Dal Bó and Fréchette, 2011; Liu, 2015). By advancing the multi-agent matrix analysis, this study helps bridge a methodological gap between EGT applications and multi-level regulatory games such as might appear to prevail under Chinese fiscal decentralization policy. Multi-agent modeling returns insights with broader applicability to policymakers working in such environs. For example, the model reveals a series of strategic choices by which decision-makers may to improve the efficiency of environmental governance.

Third, in cross walking the simulation model to a real world case, the analysis verifies a dynamic process of constant adjustment and optimization and defining initial thresholds based on a real world example to sheds light on sufficient conditions that appear to promote more rapid convergence of the three-party game towards an ideal state. This study thus illustrates how reductions in regulatory costs at the CG level cascade to strengthen penalties for local violations and improve mitigation incentives that in turn spur converge towards the optimal end state of centrally-oriented, locally-promoted and enterprise-enacted pollution mitigation.

The remainder of this study progresses as follows. Section 2 reviews a selection of relevant literature informing the research questions and the design of the research approach. Section 3 details methods, including the establishment of game model as well as the replicator dynamic and ESS analysis of each agent. Section 4 then advances a numerical cased-based example, to verify the effectiveness of the proposed game-theoretic modeling. Section 5 summarizes major results and key points of discussion, and Section 6 provides summary conclusions and policy implications.

2. Literature review

2.1. Fiscal decentralization and environmental regulation

Scholars have investigated the influence of environmental regulation on economic growth in China by examining regulatory impacts on factors like foreign direct investment (FDI), industrial innovation and technological progress (Song et al., 2013; Chan et al., 2016; Yuan and Xiang, 2018). These studies broadly regard environmental pollution as an economic output and regulation as a lever of trade-off. Yet most have made little headway in uncovering the underlying drivers of effectiveness or efficiency for regulation itself. Indeed, relegating the phenomena of governance to a black box of government administration seems problematic, because it renders invisible so many important and dynamic sources of regulatory influence and constraint (Lin et al., 2014). Such oversight seems particularly untenable in China, as existing models drawn from outside contexts show only limited applicability to the Chinese case of fiscal decentralization.

For example, in the United States, scholars widely assert models of environmental federalism as credible maps with which to navigate and anticipate regulatory outcomes at different levels of government. These operationalize the observed roles of departments at various levels of government that work in tandem to design and implement a variety of environmental regulations. Early proponents of the environmental federalism model have argued that LGs possess efficiency and information advantages in providing local public goods (Tiebout, 1956; Musgrave, 1959; Oates, 1972) that inspire and sustain the institutional form. Later theorists have adapted the idea within a model of market-preserving federalism (Weingast, 1995), in which decentralized institutional arrangements provide incentives for LGs to ensure and facilitate a steady process of efficient marketization of public goods.

Yet these models may have only very limited transferability to China, where the central government takes a very limited role in enforcement, where critical central public goods are often absent, and where subnational authorities enjoy very few robust rights to preserve local assets from top-down interference or appropriation from the central state (Qian and Weingast, 1997). Unlike many developed countries, the administrative system in China possesses another important feature, fiscal decentralization, whereby LGs are responsible to higher authorities primarily for economic growth. Heightened responsiveness to economic mandates has been instrumental for mobilizing enthusiasm among LGs to pursue rapid industrialization. However, research also shows fiscal decentralization frequently proves inefficient in mobilizing LGs to provide public goods and services like environmental protection (Wang and Qin, 2008; Zhang et al., 2017).

The main reason for this shortfall is that the CG confers limited decision-making power and economic autonomy upon local governments in delegating authority over market actors. LGs are not only a representative of the CG for regulation, but also an agent for promoting local economic development, thereby indicating that there exists a complex principal-agent relationship between the two level governments (Yan and Wang, 2015). On the one hand, Chinese decentralization and performance evaluation system based on economic growth has led LGs to become hyper-competitive to attract inflows of external capital (Zhou et al., 2004). On the other, deregulation by LGs has led to a steady decline in environmental quality and resulted in a clear “race to the bottom” effect (Ding et al., 2016) in contradiction to CG mandates to ensure environmental quality.

Previous studies of the governance interplay in China (Li and Zhou, 2005; Li and Wu, 2017) have laid a solid foundation for this study. Under political centralization and fiscal decentralization, LGs possess dual characteristics as both “politicians” and “economic participants”. LGs thus balance decisions along two dimensions: first, to determine whether to work toward the provision of productive public goods under central supervision, and second, whether to seek to obtain greater profits from collusion with EPs (Yan and Wang, 2015). As result, the essence of environmental regulation strategy emerges as a dynamic, three party game process among relevant participants.

2.2. Application of EGT in environmental regulation

In contexts where players often cannot ascertain or obtain an optimized strategy by only one choice, they necessary default to strategies based in limited individual rationality (Binmore, 1988). Such cases proliferate in the real world economies, where outcomes are influenced by multiple factors such as the external environment, existing and emerging information, cognitive constrains, and scarce time resources for making and assessing decisions. To overcome the hypothesis of perfect rationality in the general game, Weibull (1997) develops the core precepts of EGT. The core idea of EGT is that interactions between individuals in a group shape a dynamic process of moves and counter-moves, nested with a constantly changing game environment. Based on the starting strategies and relative sensitivities of players' strategies to actions by other participating subjects, the game situation itself becomes interdependent with the behavior of the participants (Smith and Price, 1973). A process of dynamic strategy emerges which, through processes of learning, ultimately leads individuals to an equilibrium solution.

EGT has been increasingly employed in evolutionary economics and environmental policies (Faber and Frenken, 2009). In a novel application by Ji et al. (2015), EGT has proven useful in accounting forinter-firm dynamics in the recycling choices of different kinds of material waste producers and the cooperative tendencies of various stakeholders (buyer and suppliers) in an externality-producing value chain. EGT aids the author in determining pathways for the manufacturing industry to attain stable patterns of sustainable resource management, be revealing ways in which the recycling capability of various suppliers directly shapes downstream incentives across the supply chain. In other work, Zhao et al. (2016) use EGT to derive system dynamics from data on Chinese air conditioner firms to examine the impact of a carbon emission reduction labeling scheme on firm-level strategy, and find that subsidies and preferential taxes have complementary influence on the efficacy of the labeling policy to inspire clean-up. More recently, Wu et al. (2017) model low-carbon strategies in a complex network context to explore how companies compete and transform in the small-world network in ways that allow regulation to encourage firms to disseminate low-carbon practices, while Chen and Hu (2018) apply EGT to study manufacturers' strategies to deal with environmental regulation like carbon taxes and subsidies where abatement options prove expensive.

Additionally, scholars have begun to employ EGT to investigate the impact of third-party environmental regulatory policies. EGT has proven useful in anticipating pathways and patterns of persistence by which social groups push firms to comply with environmental laws and regulations (Post et al., 2011), public participation compensates for the shortcomings of “government intervention” and “market mechanism” (Huang, 2015; Song et al., 2018), and social media incentivizes signaling related to corporate sustainability (Tseng, 2017).

EGT has proved a promising tool for analyzing both corporate strategies under environmental supervision as well as the behavioral interactions between LGs. Nevertheless, studies of strategic interactions between multiple actors and the influence of those interactions on regulatory and market outcomes remains scarce. Under accelerating fiscal decentralization, LGs in China have acquired independent interests and behavioral capabilities leading to conflicts of interest and misaligned objectives in the implementation of environmental regulation. Given the resonance of the subjective rationality hypothesis under such conditions, this study employs EGT to consider the impact of changes in strategic behavior among different regulatory agents and market participants. Findings show relevance to the broader context of Chinese fiscal decentralization and inform policy prescriptions of practical benefit to the efficient implementation of China's environmental strategy.

3. Methods

3.1. Problem description and basic assumptions

Under “fiscal decentralization”, the CG develops a unified environmental policy, which LGs are responsible for implementing in their respective jurisdictions. Due to the excessive length of the information transfer chain between the central and lower government levels, local officials possess sufficient capacity to control “private information” and shape the “natural state” within their jurisdictions. This dynamic supports a strong opportunist tendency for LGs to underreport and generally deprioritize environmental problems. Two-level governments generally work to balance the relationship between environmental regulation and economic growth, such that when the CG intervenes to monitor and/or reform environmental policies by local governments, the CG confronts constraints of information asymmetry and limited central capacity. Conversely, LGs also possess only incomplete information regarding the payoffs of complying with central government regulations. These dynamics of administrative and economic decentralization form the foundation of a game relationship between the two levels of government in the enforcement of environmental regulation.

Meanwhile, LGs respond to the private interests of enterprises, which oftentimes provide opportunities for regulators to collude with businesses to forego enforcement in the interest of tax revenue and industrial growth. This results in derivative corruption and local regulation strategies based in purposeful, partial implementation. In other words, under such decentralized system, LGs act more like “operators of profit-seeking regimes”, concerned more with short-term economic development than environmental governance. Collusive incentives for both enterprises and local regulators further contribute to the formation of a game relationship between LGs and PEs, completing the game process in which LGs play a central, bridging role between the CG and PEs.

For functional simplicity, the evolutionary game model conceives of the CG, LGs and PEs as singular, limited rational economic persons. Informed by incomplete information, their behavioral strategy is suboptimal at the start of any game. With the passage of time, through learning and trial and error, gradually the players distill more suitable strategies. Strategic choices in each round are mutually independent and exclusive. Once a player selects a strategy, it receives payoffs based on its mutually independent payoff function. It then inspects the payoffs of the probable and respective strategies of its counterparties to decide whether to change its strategic choices in the next round of the game. Three basic assumptions describe the strategy set for the three players in anticipation of a game solution below.

Each LG proposed in this study has two pure strategic options: it may select to fully implement environmental regulation policies, such as regulating and reducing pollution emissions in its jurisdiction (Zhang and Cheng, 2009; Zheng et al., 2015), or elect to pursue partial implementation with a mix of collusion with PEs (Chen et al., 2014; Nie and Zhang, 2015; Jia and Nie, 2017). LGs select their enforcement level mindful of the previous and probable imminent choices of CG and PEs. The strategy set is {complete implementation, partial implementation}, denoted by $y \in [0,1]$ and $1 - y$, respectively.

Next, taking into account the previous and probable imminent choices of LGs, the central authority canperform fully enforced measures, such as inspecting regional energy consumption, setting carbon emissions targets (Liu et al., 2015; Chen et al., 2017) and imposing economic sanctions on penalties (fines, taxes or carbon charges) (Tanaka, 2011; Ouchida and Goto, 2014), or choose to partially enforcement. The strategy set is {complete enforcement, partial enforcement}. In the initial stage of each three game agent, if the proportion that the CG chooses the complete regulation strategy is $x \in [0,1]$, the proportion of partial regulation strategy, in accordance, becomes $1 - x$.

Last, taking into account the previous and probable imminent choices LG, the emissions of PEs are determined by their production scale, and for emission reductions under certain conditions, the selected strategy of PEs is generally affected by their capabilities, resources, and market forces (Tian et al., 2014), so that they can choose a higher level of pollution control inputs or a lower one. The strategy set is {completely mitigation, partially mitigation}, and the proportion of the above two strategy choices is expressed as $z \in [0,1]$ and $1 - z$, separately. Table 1 shows the basic variables symbol and definitions.

3.2. Evolutionary game model

When LGs implement the environmental regulation strategy entirely, its implementation costs are recorded as C_1, and the degree of implementation effort is denoted by $\lambda_1 \in (0,1)$. Under full implementation, local economic development will suffer a certain loss R_2. In contrast, environmental quality gains represent a profit R_1. When LGs do not fully implement, they also incur political losses R_3 from the local populace and further incur administrative penalties F, levied by the CG. Supposing LGs have an opportunity to solicit bribes from PEs within their jurisdiction; under partial implementation, LG may expect to receive a reasonable amount of collusive benefits E, but corresponding will bear a further element of expected losses L_1 to public goods including the trust of the population. To model the heterogenous nature of LGs, the model iterates using a series of descriptors to model the conditions of a given LG player relative to the national average. In specific, $\gamma_1 \in [0,1]$ represents the ratio of local environmental quality to the national environmental quality; $\gamma_2 \in [0,1]$ indicates the percentage of local economic development to mainland economic development; $\gamma_3 \in [0,1]$ expresses the influence coefficient of local political credibility to the total national political credibility.

Turning to the CG, the model anticipates first that LGs' economic development, environmental quality, and government credibility hold an equal value to the CG's payoff function as its own national interests.

When the CG regulates the LG's strategic behavior entirely, pays for the cost of regulatory action C_2, where the degree of enforcement effort is $\lambda_2 \in (0,1)$. Moreover, incomplete regulation causes a definite expected loss due to agency cost L_2. Further, if LGs do not fully implement their own regulatory strategy, this will force the CG to engage in remediation and pay a remedy cost G in compensatory governance.

For the PEs, lastly, abatement costs under complete emission reduction is C_3. The level of emission mitigation effort is recorded as $\lambda_3 \in (0,1)$. Let φ and q_1 represent the taxation and emission reductions, respectively, while discharges are expressed by q_2 under partial emission mitigation. D denotes the economic penalty incurred for illegal emissions that are detected by implementing LGs. LG may also allocate both a subsidy $C_3(1 - \sigma_1)$ and a form of tax relief $\varphi(1 - \sigma_2)(q_2 - q_1)$ to reward firms that cut emissions. The degree of subsidization and tax deduction are σ_1 and σ_2, respectively. The probability that PEs who do not completely cut emissions are detected and punished by LGs is m. The implementation effort and regulatory capacity of LGs thus serve as "inputs" to PEs strategic calculus, while "outputs" include the probability of being detected and punished by upper governments where PEs discharge illegal emissions. A Cobb-Douglas production function (Meeusen and van Den Broeck, 1977) informs the ready deduction of $m = e{\lambda_1}^{\alpha}k^{\beta}$. Here, $e$reflects LG's environmental management capability while k captures LGs' proficiency in applying regulatory techniques. For simplicity, this study assumes that $\alpha = \beta = 1$.

Table 1
Variables symbol descriptions.

Variables	Descriptions
x	Probability that CG adopts an *enforcement* strategy ($0 \le x \le 1$)
y	Probability that LGs adopt an *implementation* strategy ($0 \le y \le 1$)
z	Probability that PEs adopt a *mitigation* strategy ($0 \le z \le 1$)

The interactive strategic behavior among the tripartite mainstay is thus shown in Fig. 2. Relevant notation and definitions are further described in Table 2.

Based on the foregoing analysis, a payoff matrix of eight strategies among three game agents is established, as shown in Table 3. The full range of interactive, strategic combinations is expressed below.

$$\left(\prod_{cg1}, \prod_{lg1}, \prod_{pe1}\right) = (-C_2 + \gamma_1 R_1 - \gamma_2 R_2, -C_1 + R_1 - R_2 - \sigma_1 C_3 + \varphi(1 - \sigma_2)(q_2 - q_1), -C_3(1 - \sigma_1) - \varphi(1 - \sigma_2)(q_2 - q_1))$$

$$\left(\prod_{cg2}, \prod_{lg2}, \prod_{pe2}\right) = (-C_2 + \gamma_1 R_1 - \gamma_2 R_2, -C_1 + R_1 - R_2 + \varphi(q_2 - \lambda_3 q_1) + kD, -\lambda_3 C_3 - \varphi(q_2 - \lambda_3 q_1) - kD)$$

$$\left(\prod_{cg3}, \prod_{lg3}, \prod_{pe3}\right) = (-C_2 - \lambda_1 \gamma_3 R_3 - G + F, -\lambda_1 C_1 - \lambda_1 R_3 + (1 - \lambda_1)(E - L_1) - F + \varphi(q_2 - q_1), -C_3 - \varphi(q_2 - q_1))$$

$$\left(\prod_{cg4}, \prod_{lg4}, \prod_{pe4}\right) = (-C_2 - \lambda_1 \gamma_3 R_3 - G + F, -\lambda_1 C_1 - \lambda_1 R_3 + (1 - \lambda_1)(E - L_1) - F + \varphi(q_2 - \lambda_3 q_1) + e\lambda_1 kD, -\lambda_3 C_3 - \varphi(q_2 - \lambda_3 q_1) - e\lambda_1 kD)$$

$$\left(\prod_{cg5}, \prod_{lg5}, \prod_{pe5}\right) = (-\lambda_2 C_2 + \gamma_1 R_1 - \gamma_2 R_2 - L_2(1 - \lambda_2), -C_1 + R_1 - R_2 - \sigma_1 C_3 + \varphi(1 - \sigma_2)(q_2 - q_1), -C_3(1 - \sigma_1) - \varphi(1 - \sigma_2)(q_2 - q_1))$$

$$\left(\prod_{cg6}, \prod_{lg6}, \prod_{pe6}\right) = (-\lambda_2 C_2 + \gamma_1 R_1 - \gamma_2 R_2 - L_2(1 - \lambda_2), -C_1 + R_1 - R_2 + \varphi(q_2 - \lambda_3 q_1) + kD, -\lambda_3 C_3 - \varphi(q_2 - \lambda_3 q_1) - kD\Big)$$

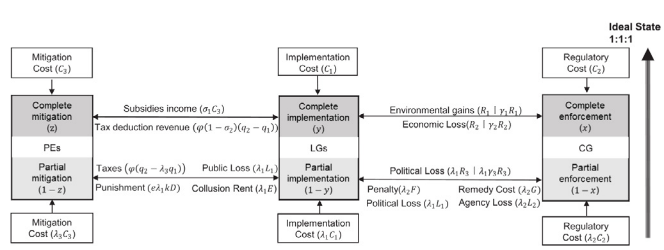


Fig. 2. Interactive strategic behavior framework among multi-agents.

Table 2
Parameters symbol descriptions.

Parameters	Descriptions
C_h	Cost of different agent ($h = 1,2,3$)
λ_h	Effort degree of different agents ($0<\lambda_h<1$)
q_1	Total emission reductions
q_2	Total amount of discharges
φ	Emission tax rate
E	Expected collusive benefits for LGs when $0<\lambda_1<1$
L_1	Expected public losses of LGs when $0<\lambda_1<1$
L_2	Expected agencies losses of the CG when $0<\lambda_2<1$
R_1	Expected environmental profits of LGs with full implementation
R_2	Expected economy losses of LGs with full implementation
R_3	Expected political losses of LGs with partial implementation
γ_1	The ratio of local environmental quality to national level
γ_2	The ratio of local economic level to national level
γ_3	The influence coefficient of local political credibility on national level
G	Central environmental remedy cost with partial implementation of LGs
F	Central penalties with partial implementation of LGs
σ_1	Subsidy payment proportion from LG to PE as reward for $z = 1$
σ_2	Tax deduction proportion from LG to PE as reward for $z = 1$
m	Probability of being penalized from LGs with partial emission reductions of PEs
e	Environmental management capability of LGs
k	Regulatory proficiency of LGs
D	Economic penalties from LGs with partial emission reductions of PEs

Table 3
Game payoff matrix among each game agent.

	Complete Enforcement ($x = 1$)		Partial Enforcement ($0\le x<1$)	
	Complete Implementation ($y = 1$)	Partial Implementation ($0\le y<1$)	Complete Implementation ($y = 1$)	Partial Implementation ($0\le y<1$)
Complete Mitigation ($z = 1$)	$(\prod_{cg1}, \prod_{lg1}, \prod_{pe1})$	$(\prod_{cg3}, \prod_{lg3}, \prod_{pe3})$	$(\prod_{cg5}, \prod_{lg5}, \prod_{pe5})$	$(\prod_{cg7}, \prod_{lg7}, \prod_{pe7})$
Partial Mitigation ($0\le z<1$)	$(\prod_{cg2}, \prod_{lg2}, \prod_{pe2})$	$(\prod_{cg4}, \prod_{lg4}, \prod_{pe4})$	$(\prod_{cg6}, \prod_{lg6}, \prod_{pe6})$	$(\prod_{cg8}, \prod_{lg8}, \prod_{pe8})$

$$\left(\prod_{cg7}, \prod_{lg7}, \prod_{pe7}\right) = (-\lambda_2 C_2 - \lambda_1\gamma_3 R_3 - L_2(1-\lambda_2) - \lambda_2 G + \lambda_2 F, -\lambda_1 C_1 - \lambda_1 R_3 + (1-\lambda_1)(E - L_1) - \lambda_2 F + \varphi(q_2 - q_1), -C_3 - \varphi(q_2 - q_1))$$

$$\left(\prod_{cg8}, \prod_{lg8}, \prod_{pe8}\right) = (-\lambda_2 C_2 - \lambda_1\gamma_3 R_3 - L_2(1-\lambda_2) - \lambda_2 G + \lambda_2 F, -\lambda_1 C_1 - \lambda_1 R_3 + (1-\lambda_1)(E - L_1) - \lambda_2 F + \varphi(q_2 - \lambda_3 q_1) + e\lambda_1 kD, -\lambda_3 C_3 - \varphi(q_2 - \lambda_3 q_1) - e\lambda_1 kD)$$

3.3. Replicator dynamic analysis of each agent

In deriving the utility functions based on these matrixes, let U_1 and U_2 indicate the expected payoffs of the CG who adopts various regulation strategies, i.e., completely or partial regulated. The expected utility of the CG becomes $\overline{U}_{12}$, giving:

$$U_1 = yz\prod_{cg1} + y(1-z)\prod_{cg2} + z(1-y)\prod_{cg3} + (1-y-z)\prod_{cg4} \tag{1}$$

$$U_2 = yz\prod_{cg5} + y(1-z)\prod_{cg6} + z(1-y)\prod_{cg7} + (1-y-z)\prod_{cg8} \tag{2}$$

$$\overline{U}_{12} = xU_1 + (1-x)U_2 \tag{3}$$

Based on the Malthusian dynamic equation, when the income of a strategy in one group is higher than the average earnings of other strategies in a given round issue, that strategy can possess strong resistance to prevent the invasion of the mutation strategy (Friedman, 1991) and thus drive the adaptation of the group evolutionary process. The consequent replicator dynamics equation of $x$becomes:

$$F(x) = \frac{dx}{dt} = x(U_1 - \overline{U}_{12}) = x(1-x)[y(1-\lambda_2)(G-F) - (1-\lambda_2)(C_2 - L_2 + G - F)] \tag{4}$$

Moreover, according to the stability theorem of differential equations and the property of ESS, the ESS point must be robust to minor disturbance. In specifically, when the value of x becomes smaller than x^*, $F(x)$ must be greater than zero. While when the value of x becomes larger than x^*, $F(x)$must be smaller than zero. As a consequence, to achieve ESS, $F(x) = 0$ and $F'(x) < 0$ are required, similar for $F(y)$ and $F(z)$. On this theoretical basis, the following proposition is figured out at first.

Proposition 1.

(1) When $y = y^* = (1-\lambda_2)(C_2 - L_2 + G - F)/(1-\lambda_2)(G-F)$, $F(x) = 0$, all game strategies are at a steady state.
(2) When $y \neq y^*$, supposing $F(x) = 0$, then $x = 0$and $x = 1$are two stable points of x.

Proof 1. The derivative of the replicator dynamics equation of $x$can be further calculated below:

$$F'(x) = \frac{dF(x)}{dx} = (1-2x)[y(1-\lambda_2)(G-F)-(1-\lambda_2)(C_2-L_2+G-F)] \tag{5}$$

Then, two circumstances are discussed separately according to Eq. (5):

(i) If $C_2 - L_2 + G - F > G - F$, under the restraints of $0 < x < 1$, $0 < y < 1$ and $0 < z < 1$, it can be deduced that $y(1-\lambda_2)(G-F)-(1-\lambda_2)(C_2-L_2+G-F) < 0$ holds, $F'(x)|x = 0 < 0$ and $F'(x)|x = 1 > 0$.

Thus, $x = 0$ is the ESS, as shown in Fig. 3(a1).

(ii) If $C_2 - L_2 + G - F < G - F$, then:
①When $y > y*$, $F'(x)|x = 0 > 0$ and $F'(x)|x = 1 < 0$. Thus, $x = 1$ is the ESS, as shown in Fig. 3(a2).
②When $y < y*$, $F'(x)|x = 0 < 0$ and $F'(x)|x = 1 > 0$. Thus, $x = 0$ is the ESS, as shown in Fig. 3(a2).

Utilizing U_3 and U_4 to denote the expected payoffs of LGs that select different implementation strategies, i.e., completely or partial implemented. $\overline{U}_{34}$ represents the expected utility of LGs that adopt the former two strategies, then:

$$U_3 = xz\prod\nolimits_{lg1} + x(1-z)\prod\nolimits_{lg2} + z(1-x)\prod\nolimits_{lg5} + (1-x-z)\prod\nolimits_{lg6} \tag{6}$$

$$U_4 = xz\prod\nolimits_{lg3} + x(1-z)\prod\nolimits_{lg4} + z(1-x)\prod\nolimits_{lg7} + (1-x-z)\prod\nolimits_{lg8} \tag{7}$$

$$\overline{U}_{34} = yU_3 + (1-y)U_4 \tag{8}$$

Therefore, the replicator dynamics equation of $y$is:

$$F(y) = \frac{dy}{dt} = y(U_3 - \overline{U}_{34}) = y(1-y)\{xF(1-\lambda_2) - z[\sigma_1 C_3 + \sigma_2\varphi(q_2-q_1) + kD(1-e\lambda_1)] - C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E-L_1) + kD(1-e\lambda_1)\} \tag{9}$$

Proposition2.

(1) When $z = z^\circ = \frac{xF(1-\lambda_2)-C_1(1-\lambda_1)+R_1-R_2+\lambda_1R_3+\lambda_2F-(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)}{\sigma_1C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)}$ $F(y) = 0$, all game strategies are at a steady state.

(2) When $z \neq z^\circ$, supposing $F(y) = 0$, then $y = 0$ and $y = 1$ are two stable points of y.

Proof 2. The derivative of the replicator dynamics equation of y can be calculated as below:

$$F'(y) = \frac{dF(y)}{dy} = (1-2y)\Big\{xF(1-\lambda_2) - z[\sigma_1 C_3 + \sigma_2\varphi(q_2-q_1) + kD(1-e\lambda_1)] - C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E-L_1) + kD(1-e\lambda_1)\Big\} \tag{10}$$

Then, two circumstances can be discussed separately according to Eq. (10):

(i) If $-C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E-L_1) + kD(1-e\lambda_1) > F(1-\lambda_2) - [\sigma_1 C_3 + \sigma_2\varphi(q_2-q_1) + kD(1-e\lambda_1)]$, with $0 < x < 1$, $0 < y < 1$ and $0 < z < 1$ constraints, it can be further inferred that $xF(1-\lambda_2) - z[\sigma_1 C_3 + \sigma_2\varphi(q_2-q_1) + kD(1-a\lambda_1)] - C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E-L_1) + kD(1-e\lambda_1) < 0$ is constant, $F'(y)|y = 0 < 0$ and $F'(y)|y = 1 > 0$. Thus, $y = 0$ is the ESS, as shown in Fig. 4(b1).

(ii) If $-C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E-L_1) + kD(1-a\lambda_1) < F(1-\lambda_2) - [\sigma_1 C_3 + \sigma_2\varphi(q_2-q_1) + kD(1-e\lambda_1)]$, then:
①When $z > z^\circ$, $F'(y)|y = 0 < 0$ and $F'(y)|y = 1 > 0$. Thus, $y = 0$ is the ESS, as shown in Fig. 4(b2).
②When $z < z^\circ$, $F'(y)|y = 0 > 0$ and $F'(y)|y = 1 < 0$. Thus, $y = 1$ is the ESS, as shown in Fig. 4(b2).

Supposing that U_5 and U_6 refer to the expected payoffs of PEs that select different emission-reduction strategies, i.e., completely or partial reduced emissions. $\overline{U}_{56}$ can be interpreted as the expected utility of PEs that adopt the former two strategies, then:

$$U_5 = xy\prod\nolimits_{pe1} + x(1-y)\prod\nolimits_{pe3} + y(1-x)\prod\nolimits_{pe5} + (1-x-y)\prod\nolimits_{pe7} \tag{11}$$

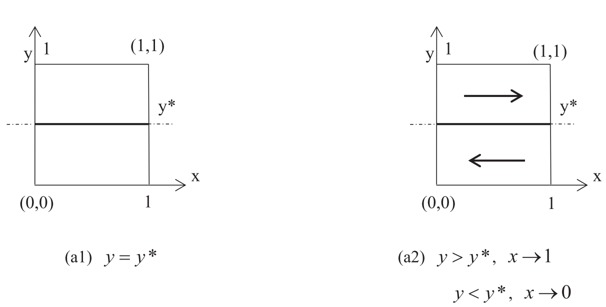


Fig. 3. Replicator dynamic phase diagram of the CG.

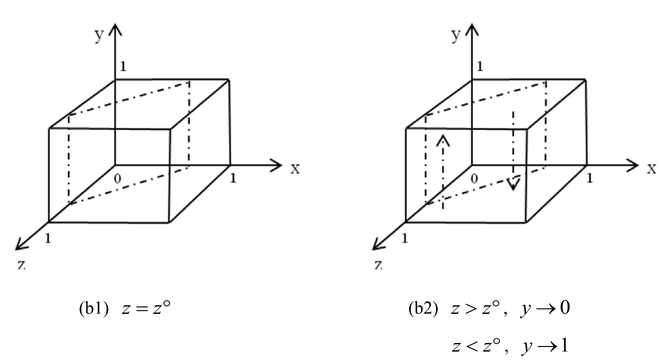


Fig. 4. Replicator dynamic phase diagram of LGs.

$$U_6 = xy\prod_{pe2} + x(1-y)\prod_{pe4} + y(1-x)\prod_{pe6} + (1-x-y)\prod_{pe8} \tag{12}$$

$$\overline{U}_{56} = zU_5 + (1-z)U_6 \tag{13}$$

Therefore, the replicator dynamics equation of z is:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(U_5 - \overline{U}_{56}) \\ &= z(1-z)\{y[\sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)] \\ &\quad -[(1-\lambda_3)(C_3 - \varphi q_1) - e\lambda_1 kD]\} \end{aligned} \tag{14}$$

Proposition3.

(1) When $y = y^{\circ} = \frac{(1-\lambda_3)(C_3-\varphi q_1)-e\lambda_1 kD}{\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)}$, $F(z) = 0$, all game strategies are at a steady state.

(2) When $y \neq y^{\circ}$, supposing $F(z) = 0$, then $z = 0$ and $z = 1$ are two stable points of z.

Proof 3. Similarly, the derivative of the replicator dynamics equation of z can be calculated as below:

$$\begin{aligned} F'(z) = \frac{dF(z)}{dz} &= (1-2z)\{y[\sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)] \\ &\quad - [(1-\lambda_3)(C_3 - \varphi q_1) - e\lambda_1 kD]\} \end{aligned} \tag{15}$$

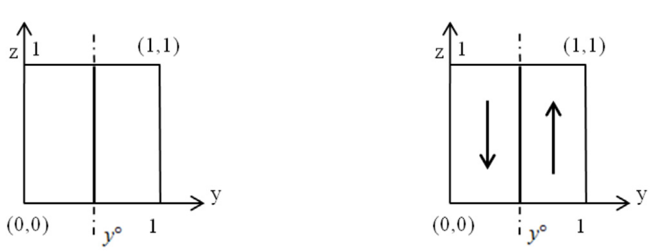
Accordingly, two circumstances are discussed separately according to Eq. (15):

(i) If $(1-\lambda_3)(C_3 - \varphi q_1) - e\lambda_1 kD > \sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)$, under the conditions of $0<x<1$, $0<y<1$ and $0<z<1$, $y[\sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)] - [(1-\lambda_3)(C_3 - \varphi q_1) - e\lambda_1 kD] < 0$ can be further demonstrated constant, $F'(z)|z = 0 < 0$ and $F'(z)|z = 1 > 0$. Thus, $z = 0$ is the ESS, as shown in Fig. 5(c1).

(ii) If $(1-\lambda_3)(C_3 - \varphi q_1) - e\lambda_1 kD < \sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)$, then:
①When $y > y^{\circ}$, $F'(z)|z = 0 > 0$ and $F'(z)|z = 1 < 0$. Thus, $z = 1$ is the ESS, as shown in Fig. 5(c2).
②When $y < y^{\circ}$, $F'(z)|z = 0 < 0$ and $F'(z)|z = 1 > 0$. Thus, $z = 0$ is the ESS, as shown in Fig. 5(c2).

3.4. ESS analysis of two replicator dynamic systems

From the replicator dynamics analysis of three agents above-mentioned, it is guaranteed that, in the game model, changes in the strategic behavior of the CG (x) depend heavily on the strategic selection of LGs (y), that is, x and y are correlated. Likewise, the changes in the strategic behavior of PEs (z) are closely related to y, that is, z and y are correlated. In this study, it is feasible to analyze the strategic action step-by-step between the two-level governments first. As such, z can be considered a constant first, and then investigating the selected strategy between LGs and PEs, x can be regarded as the constant that moment.



(c1) $y = y^{\circ}$

(c2) $y > y^{\circ}$, $z \to 1$
$y < y^{\circ}$, $z \to 0$

Fig. 5. Replicator dynamic phase diagram of PEs.

According to the EGT, the replicator dynamic equation reflects the direction and speed of learning of a participant in this game. When the replicator dynamic equation is zero, the stable states can be determined by the equilibrium point involved. Let the replicated dynamic system (I) is treated as the combining of Eq. (4) and Eq. (9), i.e., the strategies of two-level governments is regarded as a replicated dynamic system, then Proposition 4 is obtained below.

Proposition4. Five replicated dynamic equilibrium points exist in the plane $P = \{(x,y)|0 \le x, y \le 1\}$ of the replicated dynamic system I, which are (0,0), (1,0), (1,1), (0,1), and (x^*, y^*), if and only if the desired condition $x^* \in [0,1]$ and $y^* \in [0,1]$ is established).

where $x^* = z[\sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) + kD(1 - e\lambda_1)]$

$$\frac{+C_1(1-\lambda_1) - R_1 + R_2 - \lambda_1 R_3 - \lambda_2 F + (1-\lambda_1)(E - L_1) - kD(1 - e\lambda_1)}{F(1-\lambda_2)}$$

and $y^* = \frac{(1-\lambda_2)(C_2-L_2+G-F)}{(1-\lambda_2)(G-F)}$

Proof 4. Let each of the equation in the replicated dynamic system I equal to zero, i.e., $F(x) = 0$ and $F(y) = 0$ are satisfied, separately. Subsequently, five replicated dynamic equilibrium points are obtained.□

It is worth noting that the equilibrium point is not all ESS, since ESS must also possess the ability to resist the error or deviation caused by bounded rationality, i.e., the ability to recover to a stable point after disturbance. As such, Friedman (1998) pointed out that the local asymptotic stability method can be used for Jacobian matrix to ascertain whether the evolutionary system's equilibrium point is stable. Taking the derivative with respect to x and y using the replicator dynamic equation in Eq. (5) and Eq. (10) to determine the final ESS in the game, then the $Jacobian1(J_1)$ matrix can be obtained as follows:

$$J_1 = \begin{pmatrix} \partial X/\partial x & \partial X/\partial y \\ \partial Y/\partial x & \partial Y/\partial y \end{pmatrix} = \begin{pmatrix} \pi_1 & \pi_2 \\ \pi_3 & \pi_4 \end{pmatrix} \tag{16}$$

then,

$$\pi_1 = (1-2x)[y(1-\lambda_2)(G-F) + (1-\lambda_2)(-C_2 + L_2 - G + F)] \tag{17}$$

$$\pi_2 = x(1-x)(1-\lambda_2)(G-F) \tag{18}$$

$$\pi_3 = y(1-y)F(1-\lambda_2) \tag{19}$$

$$\begin{aligned} \pi_4 = (1-2y)\{&xF(1-\lambda_2) - z[\sigma_1 C_3 + \sigma_2\varphi(q_2 - q_1) \\ &+kD(1 - e\lambda_1)] - C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F \\ &-(1-\lambda_1)(E - L_1) + kD(1 - e\lambda_1)\} \end{aligned} \tag{20}$$

The determinant (det) and trace (tr) of J_1 are as follows:

$$detJ_1 = \pi_1\pi_4 - \pi_2\pi_3 \tag{21}$$

$$trJ_1 = \pi_1 + \pi_4 \tag{22}$$

When $detJ_1 > 0$ and $trJ_1 < 0$ are satisfied, it is considered that the fixed point of the locally asymptotically stable method corresponds to the ESS. Meanwhile, a disturbance resisting ability must exist when the evolution strategy reaches a steady state, that is, $dx/dt<0$ and $dy/dt>0$. Thus, according to the different range of parameters, the stability of the evolutionary equilibrium between two level governments can be further studied. In order to facilitate the observation of the calculation results, $\omega_1 = (1-\lambda_2)(-C_2+L_2-G+F)$, $\omega_2 = (1-\lambda_2)(-C_2+L_2)$, $\omega_3 = F-z[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)]-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3-(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)$ and $\omega_4 = -z[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)]-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3+\lambda_2 F-(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)$ are hypothesized, respectively, which meet $\omega_3>\omega_4$, as shown in Table 4.

From Figs. 3 and 4 and Table 4, the dynamic evolution diagram of two level government strategiescan be further drawn, as shown in Fig. 6.

Let the replicated dynamic system (II) is treated as the combining of Eq. (9) and Eq. (14), i.e., the strategies of LGs and PEs are regarded as a replicated dynamic system, then Proposition 5 is obtained below.

Proposition5. The equilibrium points of replicated dynamic system (II) that exist in the plane $Q=\{(y,z)|0\le y,z\le 1\}$ among LGs and PEs, which are (0,0), (1,0), (1,1), (0,1), and (y°, z°), if and only if the desired condition $y^\circ\in[0,1]$and $z^\circ\in[0,1]$ is established.

where. $y^\circ = \frac{(1-\lambda_3)(C_3-\varphi q_1)-e\lambda_1 kD}{\sigma 1C3+\sigma 2\varphi(q_2-q_1)+kD(1-e\lambda_1)}$ and $z^\circ = \frac{xF(1-\lambda_2)-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3+\lambda_2 F-(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)}{\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)}$.

Proof 5. For the replicated dynamic system (II) be $F(y)=0$ and $F(z)=0$, then five equilibrium points that meet above conditions, including (0,0), (1,0), (1,1), (0,1) and (y°, z°).

Further, $Jacobian2(J_2)$ matrix can also be acquired by derivative with respect to y and z, from the replicator dynamic equation in Eq. (10) and Eq. (15), respectively.

$$J_2 = \begin{pmatrix} \partial Y/\partial y & \partial Y/\partial z \\ \partial Z/\partial y & \partial Z/\partial z \end{pmatrix} = \begin{pmatrix} \pi_5 & \pi_6 \\ \pi_7 & \pi_8 \end{pmatrix} \tag{23}$$

where

$$\pi_5 = (1-2y)\{xF(1-\lambda_2)-z[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1) +kD(1-e\lambda_1)]-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3+\lambda_2 F -(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)\} \tag{24}$$

$$\pi_6 = y(y-1)[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)] \tag{25}$$

$$\pi_7 = z(1-z)[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)] \tag{26}$$

$$\pi_8 = (1-2z)\{y[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD(1-e\lambda_1)]-(1-\lambda_3)(C_3-\varphi q_1)+e\lambda_1 kD\} \tag{27}$$

The determinant (det) and trace (tr) of J_2 are as follows:

$$detJ_2 = \pi_5\pi_8-\pi_6\pi_7 \tag{28}$$

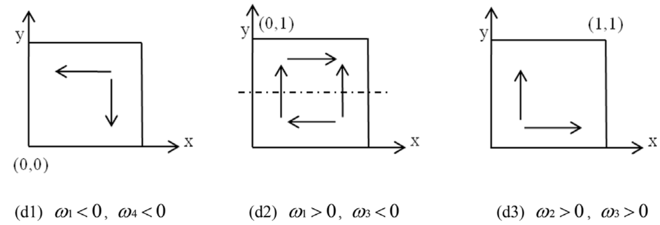


Fig. 6. Dynamic evolution diagram of strategies between two level government.

$$trJ_2 = \pi_5+\pi_8 \tag{29}$$

When $detJ_2>0$ and $trJ_2<0$ are satisfied, the fixed point of the locally asymptotically stable will correspond to ESS and meets $dy/dt<0$ and $dz/dt>0$. Likewise, according to the different values of relevant parameters, the stability of the evolutionary equilibrium between LGs and PEs can be further analyzed. Suppose that $\omega_7 = xF(1-\lambda_2)-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3+\lambda_2 F-(1-\lambda_1)(E-L_1)+kD(1-e\lambda_1)$, $\omega_8 = \sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD-(1-\lambda_3)(C_3-\varphi q_1)$ and $\omega_9 = -(1-\lambda_3)(C_3-\varphi q_1)+e\lambda_1 kD$, separately, and meet $\omega_6<\omega_7$ and $\omega_8<\omega_9$, see Table 5.

From Figs. 4 and 5 and Table 5, the dynamic evolution diagram of strategies between LGs and PEs can be depicted, as shown in Fig. 7.

From the evolutionary stability conditions of the above stepwise analysis, it can be concluded that the evolutionary equilibrium regulatory decisions between x and y varies with the proportion of z reduction strategies in the evolution process. Similarly, the evolutionary equilibrium regulatory between y and decisions z changes with the proportion of x. It is worth mentioning that the values of z and x vary with changes in the evolutionary process, while the equilibrium state of the game system does not possess the robustness to handle the small perturbations between z and x. Therefore, it is unable to drive the tripartite mainstay to the expected steady state by only adjusting the initial parameters. This study aims to promote the three game agents ultimately evolved into the research that proposed to form a low-carbon operation mode with a central-oriented, local-positive response, with enterprise-emission reduction (Bao et al., 2008), the ideal decision state namely x=1, y=1, z=1. Here, combined with Eq. (4) and Fig. 6(d3), it is concluded that the condition $(1-\lambda_2)(L_2-C_2)>0$ can keep x increasing monotonically and trending toward to x=1. Thus, by defining the initial threshold of $\tilde{x}$, it can maintain the evolutionary conditions of $xF(1-\lambda_2)-[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)]-C_1(1-\lambda_1)+R_1-R_2+\lambda_1 R_3+\lambda_2 F-(1-\lambda_1)(E-L_1)>0$and $\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD-(1-\lambda_3)(C_3-\varphi q_1)>0$, so that the tripartite game agents finally evolve into x=1, y=1, z=1.

4. Numerical example

4.1. Case description and parameter settings

The results presented thus far entirely analytical but on constructs. A numerical example may thus serve to illustrate how

Table 4
Stability analysis between the CG and LGs.

Equilibrium point (x,y)	Determinant symbol of J_1	Trace symbol of J_1	Results	Stability condition
(0, 0)	+	-	ESS	$\omega_1<0$, $\omega_4<0$
(0, 1)	+	-	Unstable	Any condition is not stable
(1, 0)	+	-	ESS	$\omega_1>0$, $\omega_3<0$
(1, 1)	+	+	ESS	$\omega_2>0$, $\omega_3>0$
(x^*, y^*)	0	0	Saddle point	0, 0

Table 5
Stability analysis between LGs and PEs.

Equilibrium point (y,z)	Determinant symbol of J_2	Trace symbol of J_2	Results	Stability condition
(0, 0)	+	-	ESS	$\omega_7 < 0, \omega_9 < 0$
(0, 1)	+	+	Unstable	Any condition is not stable
(1, 0)	+	-	ESS	$\omega_7 > 0, \omega_8 < 0$
(1, 1)	+	+	ESS	$\omega_6 > 0, \omega_8 > 0$
(y°, z°)	0	0	Saddle point	0, 0

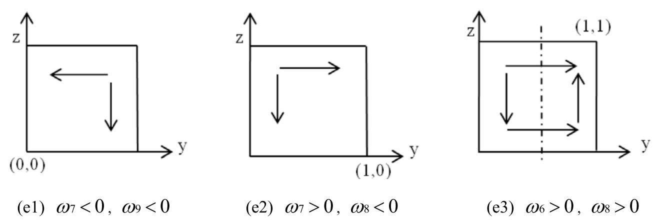


Fig. 7. Dynamic evolution diagram of strategies between LGs and PEs.

related parameter values affect the evolutionarily stable strategy and convergence trends for multi-agents in an empirical setting. In order to obtain higher profits and reduce manufacturing waste, a growing number of enterprises in China are realizing the importance of emission reductions. In response to the central government's call for “accelerating the development of ecological civilization” in the 13th five-year plan outline of China, the Hunan Province LG has identified the Xiangjiang River as its “No. 1 Project” for advancing environmental protection and governance.

As the largest steel and iron manufacturing enterprise in Hunan Province, V Enterprise has actively participated in the provincial government's “No.1 Project”. Tightly coupled mitigation action by V Enterprises and the local regulator have led to the achievement of near complete recovery of wastewater pollution from blast furnace converters. Industrial clean-up has led to significant improvement in regional environmental quality. In recognition of its private sector leadership, V Enterprise was certified as a National Leader in Energy Saving Emission Reductions in 2017.

Based on in-person investigations in Hunan Province, including on-the ground interviews the relevant government department and V Enterprise, the regulatory and abatement costs are denoted as $C_1 = 3$ and $C_3 = 5$, respectively. Observed levels for regulatory effort and emission reduction meet the condition $\lambda_1 = 0.29$ and $\lambda_3 = 0.31$. To simulate game with these parameters that evolves into an ideal state - in which all three players select the 1:1:1 strategy, the following constellation of parameters values are kept as a benchmark: $C_2 = 2$, $R_1 = 2$, $R_2 = 1$, $R_3 = 3$, $F = 5$, $E = 3$, $D = 2$, $L_1 = 4$, $L_2 = 5$, $q_1 = 3$, $q_2 = 5$, $\lambda_2 = 0.35$, $\sigma_1 = 0.4$, $\sigma_2 = 0.3$, $\varphi = 0.6$, $e = 0.68$, $k = 0.47$, $\tilde{x}$=0.2. The foregoing initial parameter settings satisfy the following evolution conditions: $(1-\lambda_2)(L_2 - C_2) > 0$,

$$xF(1-\lambda_2) - [\sigma_1 C_3 + \sigma_2 \varphi(q_2 - q_1)] - C_1(1-\lambda_1) + R_1 - R_2 + \lambda_1 R_3 + \lambda_2 F - (1-\lambda_1)(E - L_1) > 0$$

and $\sigma_1 C_3 + \sigma_2 \varphi(q_2 - q_1) + kD - (1-\lambda_3)(C_3 - \varphi q_1) > 0$.

4.2. The impact of selecting an initial change of strategy on evolutionary results

Under the conditions of the above initial setting, when the initial value of y and z are fixed, the initial value of x is randomly selected within the threshold $\tilde{x}$ as the lower limit to verify the effect of the initial value of $x$on its own evolutionary trend, as illustrated in Fig. 8(f1) (f2) (f3). Under the premises that meet the above-mentioned evolutionary conditions and if x is greater than the threshold $\tilde{x}$, $x$shows a monotonically increasing trend with the changing of t, and the convergence direction of x is related to velocity of y and z. That is, under the condition of fixed y, the larger z is, the slightly slower x converges but with little change, finally evolving into the ideal steady state. In the fixed condition of z, the greater is y, the sooner x converges to the ideal state. The initial value of y and z has little effect on the velocity change of x but eventually approaching to the extreme value 1 after a period of evolution. This means that the rate of central regulation will continue to rise with $t$and the CG will eventually take initiative regulatory decisions.

Simultaneously, with the premise of $x > \tilde{x}$, the initial value of x and z are randomly selected to verify their impact on y, as illustrated in Fig. 8(g1) (g2) (g3). Under the condition of fixed x, the larger z is, the slower y converges to the ideal state. On the contrary, in the fixed condition of z, the greater the x, the faster y approaches 1 but appears in a downward trend at one stage, which may relate to the supervision level of the CG, resulting in LGs carrying out negative regulation strategy and colluding with PEs. However, under the initial conditions, y will take a full implementation strategy eventually with the change of t.

Moreover, under the premise of greater than the threshold $\tilde{x}$, the initial value of x and y can be randomly chosen to measure their influence on z. Specific results are illustrated in Fig. 8(h1) (h2) (h3). Under the condition of fixed x, the larger y is, the faster z approaches 1 but appears in a downward trend at one stage, which led their own do not fit the property of monotonically increasing. This may be closely related to the level of administrative decision execution of their superior government, resulting in a large number of enterprises retreating to the traditional mode of production. Retrenchment is a common economic phenomenon.

In summary, it can be seen from Fig. 8 that the evolutionary results and the convergence rate among these three agents are affected by the initial proportion of each subject's choice. Furthermore, each is influenced by the initial probabilities by which the other two players choose the equilibrium state strategy. This is to say that the strategy evolution path between each agent has a reliable degree of interdependence.

4.3. The impact of selecting a parameter change of strategy on evolutionary results

Under the premise that the benchmark parameters of the example remain unchanged, an isolate increase in the subsidy reward for pollution reduction σ_2 will not change the direction in which the PEs finally converges to the equilibrium state, as shown in Fig. 9. However, higher subsidies significantly slow the pace of convergence of both PEs and LGs towards the ideal state, as higher subsidies inhibit the expected income of LGs. In effect, higher reliance on subsidies appears to diminish the enthusiasm of regulatory forces. Due to the fall in the expected earnings of local agencies, the scale of enterprises within their jurisdiction will be further reduced, so as to the profit of PEs.

In the next panel, Fig. 10 explores a case where the LG does not actively regulate pollution within its jurisdiction despite an

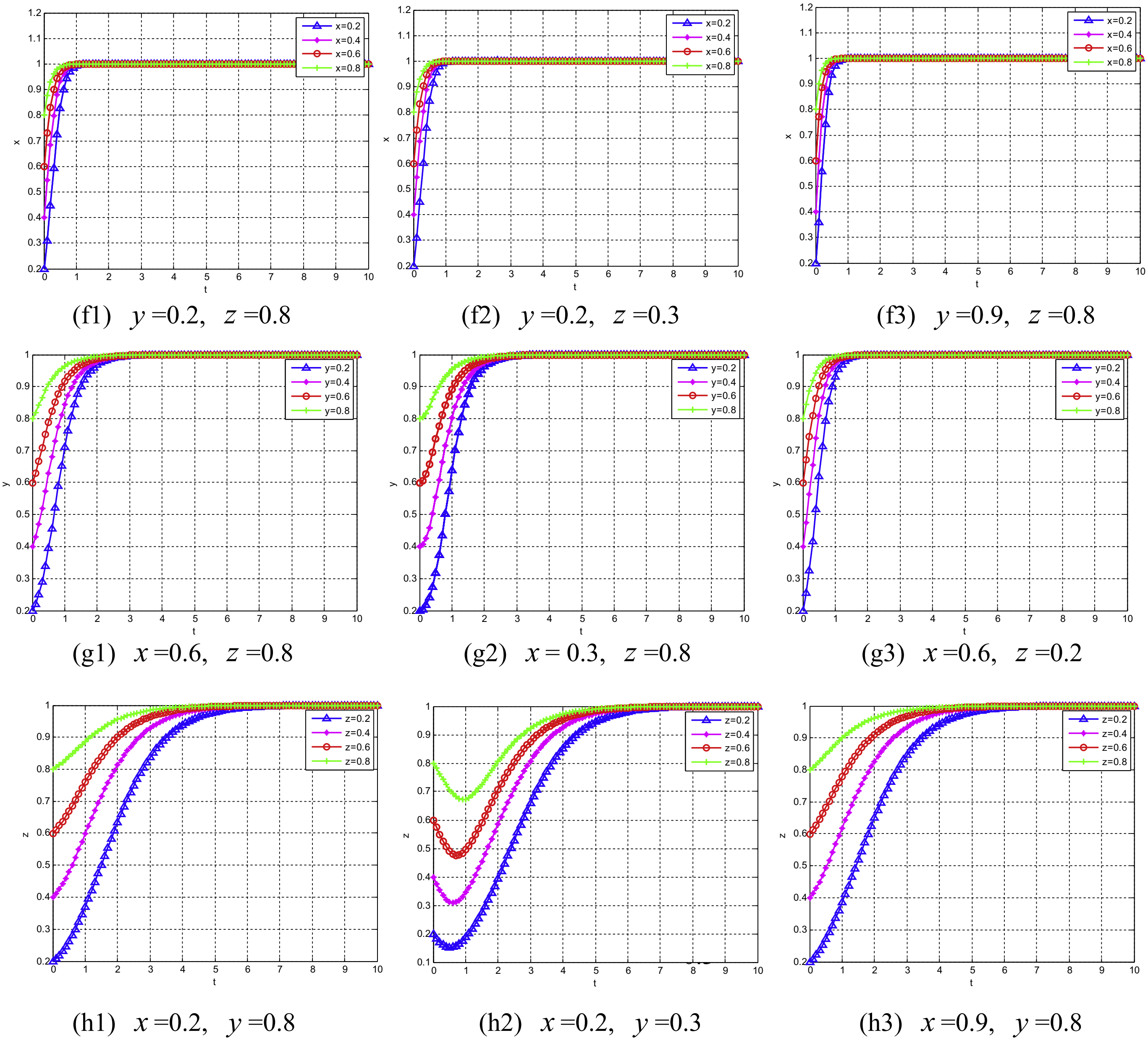


Fig. 8. The impact of selecting an initial change of strategy on the evolutionary results.

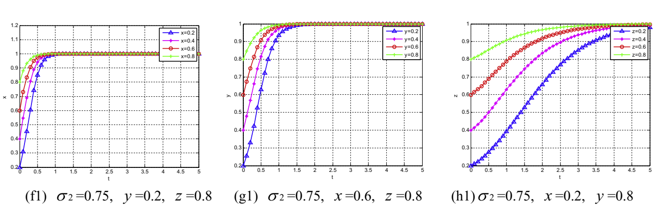


Fig. 9. The impact of σ_2 on evolutionary results.

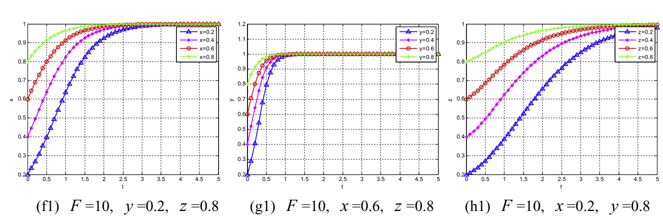


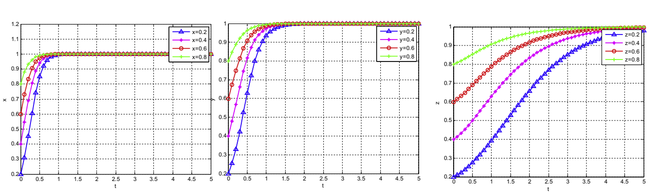
Fig. 10. The impact of F on evolutionary results.

increase in penalties imposed by the central administration F, holding all other parameters unchanged. A comparison with Fig. 8 indicates that the CG may do well to increase the degree of punishment when LGs do not undertake initiative to implement emissions control. However, while increased penalties do not change the direction of LG convergence, they do appear to slow the game's evolution towards the desired equilibrium state. This is may be due to short-term dynamics by which local agencies compensate for penalty losses by reducing environmental implementation costs and increasing rent-seeking. These potentially perverse outcomes in local environmental governance in turn cause the CG to incur increased environmental management costs. As such, the central administration may increase its utility through an initial and sustained focus on using legal policy to restrict LGs' behavioral decision-making.

When LGs intensifies their enforcement, i.e., only increasing the value of parameter λ_1, other parameters are the same as Fig. 8, it does not change the path of PEs away from eventually converging into the equilibrium state, as shown in Fig. 11. Rather, intensified enforcement appears to slow the evolution of the game towards the ideal state. It appears that periods of extensive growth may increase the "chips" for the political promotion of local officials. However, from a long-term perspective, environmental governance represents an investment in "soft" public goods whose longer cycles and consumer characteristics less directly affect the production function of officials' jurisdiction. This explains the slowing in the rate of convergence. Only when the environmental performance of the CG in terms of achievements in the appraisal system really affects the interests of LGs will regulators see stronger incentives to ramp up implementation.

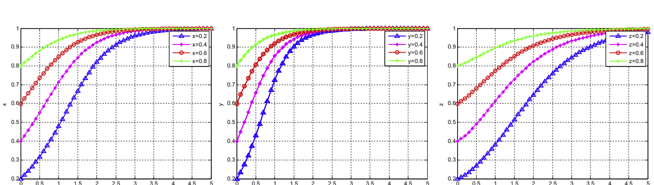
As the environmental regulation effort of the CG λ_2 increases, it does not change the direction of LGs, which eventually converges into the equilibrium state, but will delay the speed of their evolution to the equilibrium state, and the evolution rate of the CG itself also becomes slower simultaneously, as shown in Fig. 12. Considering the Chinese fiscal decentralization, the two-class governments possess obvious characteristics of information asymmetry, which in turn leads to the central cannot intuitively monitor the extent of local implementation. In particular, the independent decision-making behavior between two-level governments leads to the supervision falling into the plight of individual rationality and collective rational conflict, which makes it impossible for regulation to achieve common optimization at the same time.

In the case of the benchmark parameters of the example, only increasing the abatement intensity of PEs λ_3 will not change the direction of the game state that eventually converges to the balanced state. However, it accelerates the speed of their evolution to the equilibrium state, while the evolution of the local government remains relatively slow, as shown in Fig. 13. In the face of the Chinese financial decentralization, emission-cutting work is still dominated by administrative means, which merely relies on energy-saving and emission reduction targets to counteract the constraints of LG and corporate behavior. It has not yet transformed completely into the enterprises' conscious action, nor the formation of effective market behavior. Eventually, great differences still exist between the goal of reducing emissions and regional



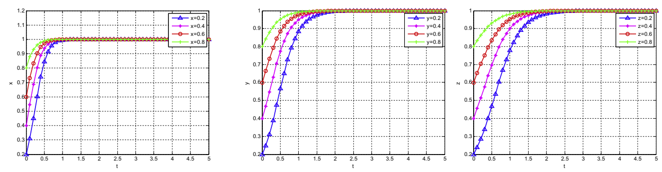
(f1) λ_1=0.92, y=0.2, z=0.8 (g1) λ_1=0.92, x=0.6, z=0.8 (h1) λ_1=0.92, x=0.2, y=0.8

Fig. 11. The impact of λ_1 on evolutionary results.



(f1) λ_2=0.87, y=0.2, z=0.8 (g1) λ_2=0.87, x=0.6, z=0.8 (h1) λ_2=0.87, x=0.2, y=0.8

Fig. 12. The impact of λ_2 on evolutionary results.



(f1) λ_3=0.85, y=0.2, z=0.8 (g1) λ_3=0.85, x=0.6, z=0.8 (h1) λ_3=0.85, x=0.2, y=0.8

Fig. 13. The impact of λ_3 on evolutionary results.

economic development.

5. Results and discussion

The results derived from the comprehensive simulation analysis, including various factors faced by the three game agents, have reference value for the practical application of the CG, LGs and PEs. First, the analysis reveals the importance of the probabilities describing the likelihoods the various agents will pursue their respective strategies to the equilibrium outcome and convergence speed of the game. Analyzing the game's dynamic equilibrium reveal show differences in the initial points and values of the game system produce various counter-balancing patterns effects that shape the players' commitments to environmental action. From a long-term perspective, the selection of regulatory strategies proves a dynamic process of mutual adjustment and change based in constant adjustment. Optimization hinge on the shifts in internal and external factors including degrees of reward and punishment, cross-scale competition strategies, decision-making styles, and organization capacities to reduce emissions and modify counterparties' incentives.

Second, this study shows that the evolution and the convergence of strategies among agents exhibits a reliable degree of interdependence. When fixing the emission-reductions of PEs, this study work shows that greater levels of LG commitment to implementation accelerate the convergence of CG strategy towards the ideal state of full supervision. Conversely, the higher the level of CG enforcement, the faster LGs strategy converges towards full implementation. Lastly, when fixing the level of CG enforcement, greater commitment to implementation on the part of LGs speeds the evolution of PE strategy towards the pursuit of more robust emission reductions.

Third, defining initial thresholds sheds light on sufficient conditions that appear to promote more rapid convergence of the three-party game towards an ideal state. The specific evolutionary requirements are $(1-\lambda_2)(L_2-C_2)>0$,

$$xF(1-\lambda_2)-[\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)]-C_1(1-\lambda_1)+R_1-R_2 \\ +\lambda_1 R_3+\lambda_2 F-(1-\lambda_1)(E-L_1)>0$$

and $\sigma_1 C_3+\sigma_2\varphi(q_2-q_1)+kD-(1-\lambda_3)(C_3-\varphi q_1)>0$. When these constraints are met, the expected loss of the CG's supervisory negligence outweighs its enforcement costs, the fines for LGs are higher than the combination of cost inputs and subsidies when regulatory policy is completely enforced, and firms' rewards (net of fines) outweigh the costs of investing in cleaner production. Under these conditions, the three game players evolve reliably towards the ideal state of central enforcement, local implementation and corporate mitigation.

Forth, under any initial condition, $x=0$, $y=0$ or $y=0$, $z=1$ is not the ultimate stable state of evolution. Specifically, combining Eq. (5), Eq. (10), Eq. (15) and a local stability analysis of the evolutionary strategy makes clear that many factors exist that affect the interaction among the three agents. A change in a random factor will cause one of the other parties to alter their selection strategy, changing the tripartite strategy choice, and leading the model to evolve towards an unstable strategy.

6. Conclusions and policy implications

6.1. Conclusions

This study takes China's fiscal decentralization system as an entry point, and constructs an asymmetric dynamic game model of the CG, LGs and PEs to explore the implementation process of multi-agent environmental regulation strategies. According to the replicator dynamic equations, the evolution of different participants' behavior and their ESS are separately discussed. The relative commitments of different agents to their respective enforcement strategies prove the central factor influencing the outcome of the interdependent strategic game. Further, the strategy evolution path and convergence speed between the three players exhibits a consistent degree of interdependence.

Then, a numerical example based on observed conditions in Hunan Province serves to verify the theoretical results. By defining initial thresholds based on real-world observations of an ideal case, sufficient conditions can be obtained to promote the evolution of the three-party game to the long-term ideal state. In the context of fiscal decentralization, it appears impossible for LGs to persist in a “race to the bottom” in the absence of minimal central regulation, or for polluting enterprises to sustain a strategy of unchecked emissions for a protracted period of time.

6.2. Implications

To advance the efficient implementation of environmental regulation in China and encourage a more benign transformation of economic growth towards social performance, several policy implications based on the findings appear clear and straightforward. First, the strategic choice of the CG hinges on setting levels of enforcement supervision and fines. Meanwhile, the excessively high cost of full enforcement by the CG makes it difficult to comprehensively supervise the implementation behavior of local officials increases information asymmetry between the two-level governments. Therefore, additional third-party regulatory mechanisms, such as the general public, media, and wide range of non-governmental organizations may prove useful to supplement state-driven environmental monitoring, reduce the central governments enforcement costs, and so enhance society's overall regulatory efficiency.

Second, from a policy-making perspective, while penalties for local government failures to implement environmental regulation appear ripe for strengthening, it appears necessary to first improve environmental laws and regulations. Improving norms to celebrate the enforcement of the rule of law and the moral value of foregoing collusive behavior on the part of civil servants, LGs will more readily execute regulatory policies. Restrictions on opportunistic forms of government-enterprise cooperation will enhance environmental outcomes and accelerate societal shifts towards a cleaner economy.

Third, given that the strategic choices of LGs are shaped by political losses, management capability, bribes, and the degree of regulatory efforts, it is essential to reform the current regime for local government performance appraisal. A more scientific framework for assessing environmental performance that leverages indicators such as pollutant emission intensity, environmental quality changes, total pollutant discharge, and public satisfaction should be incorporated into the evaluation system to increase the political costs of non-implementation of environmental laws. The weighting coefficient of environmental quality index in the performance evaluation system should be increased accordingly, and the CG should place greater emphasis on assessing environmental quality in assessing the tenure of local officers.

Fourth, increasing rewards for LGs that earnestly implement environmental regulations alongside greater punishments for officials who prove tolerant of corporate pollution will correct the mindset that GDP is the only standard with which to measure development and government performance. Financial approaches including subsidies, fiscal transfers, and grants to offset costs of regulatory implementation should prove effective tools to nudge LGs towards a strategic equilibrium favoring environmental protection. In general, the central government's strategy towards provincial governments might do best to employ a “carrots first, sticks second” approach to obtain the most rapid and efficient change to a complex regulatory equilibrium.

Fifth, firm-level strategies appear consistently influenced by emission tax rates, penalties, and the signaling of a credible commitment by the local regulator to enforce environmental laws. Therefore, from a marketing perspective, governmental sectors with higher position and greater power should continue to signal the imminent establishment of a robust emission trading system and science-based standards for industrial and municipal effluent. Trading systems in particular show promise for facilitating efficient balancing of penalties, incentives, and market transactions so as to raise the efficiency of emission reduction within the overarching political economy of industrial pollution.

Finally, governmental departments should consider active experimentation with localized, market-driven mechanisms to promote a transition from environmental regulation costs “external negative effect” to an “internal positive effect” of profit-sharing between firms and local officials in the transition to a cleaner economy. Subsidy rewards should be focused accordingly to reward firm-level leadership in emission reductions based particularly on ecological R&D, so as to maximize enthusiasm for low-emission innovation and weaken incentives for “free-riding” on vanguard reductions among corporate competitors.

6.3. Limitations

This study contends with several limitations. When the game model converges on the ideal state, this study reveals only the sufficient — though potentially non-essential - stability conditions. The current work remains unable to complete summarize the stable equilibrium conditions for the general three-dimensional evolutionary game model. In the long term, the realistic choice of environmental regulation strategy is likely to prove a more dynamic change process over time, marked by persistent adjustment and mutual optimization according to the transformation of internal and external factors including changing reward and punishment levels, local competitive strategies, official decision-making style, and shifts in corporate capacities. Such problems will provide ample challenge for forthcoming studies.

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