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Multi-Player Evolutionary Game Theory in Cooperative Governance of Natural, Social, and Network Environments: A Review

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Abstract: In the context of rapid economic development, profound transformation of social structure and accelerated technological evolution, environmental governance issues are increasingly presented with cross-domain, multi-subject and dynamic complex characteristics. These challenges often involve strategic conflicts among governments, enterprises, and the public, making cooperation more uncertain and difficult to sustain. Traditional two-player game models are insufficient for capturing the evolving dynamics of such systems. In recent years, multi-player evolutionary game theory (EGT) has provided new perspectives for analyzing various environmental governance. This review explores the application of multi-player EGT in three major governance contexts: natural, social, and cyber environments, highlighting its effectiveness in modeling adaptive behaviors, feedback mechanisms, and policy outcomes under uncertainty, drawing on both theoretical frameworks and simulation-based studies. EGT offers a systematic analytical tool for understanding multi-agent interactions and optimizing governance mechanisms. Moreover, it provides theoretical guidance for public policy design and supports the stable development of collaborative governance. The review also discusses EGT's strong potential to make further contributions in more and more complex interdisciplinary fields in the future.

Keywords: Muti-player evolutionary game theory, Environmental governance, Cooperation

1. Introduction

Against the backdrop of rapid economic development, social restructuring, and the increasing penetration of digital technologies, human societies are facing increasingly complex challenges in environmental governance. These challenges extend beyond traditional ecological issues such as climate change, pollution control, and resource conservation [1–3], to include social concerns like public health, educational collaboration, and the allocation of social resources [4–6], as well as emerging topics in the digital economy such as data privacy, platform governance, and cybersecurity [7-9]. The above issues usually involve complex interactions among various groups—like governments, businesses, and the public—whose different goals can lead to selfish behaviour in different governance situations, making it hard to work together and resulting in unpredictable governance outcomes. [1, 10].

Evolutionary game theory (EGT) has gradually become an appropriate method to resolve this kind of issues. It originated from Smith & Price's concept of evolutionary stable strategies (ESS), which explains how populations evolve toward stable behavioral patterns[11]. This framework then was expanded by Nowak [12] through replicator dynamics and stochastic simulations, enabling analysis of multi-agent interactions. However, most traditional game models were still static and dyadic, failing to adequately reflect behavioral adjustments among multiple stakeholders under bounded rationality and dynamic learning. Later on, in recent years, multi-player evolutionary game theory (EGT) finally starts emerging as a valuable analytical tool in environmental governance and beyond, capable of simulating dynamic strategy evolution, behavioral stability, asymmetric payoffs, and the effects of incentive mechanisms [13]. The application of EGT in environmental governance has been extensively studied. Zhang et al. [14] outlined the current state of EGT in sustainable energy development, describing its use across areas such as traditional energy, carbon reduction, and electric vehicle policy to illustrate how strategic interactions in energy governance have been modeled and analyzed. Ahmad et al. [15] reviewed EGT's applications in the governance of urban road transport networks, categorizing existing studies into choice-based analysis, traffic management, routing operation, and transport safety, and highlighting EGT's advantages over classical models in handling dynamic and multi-agent interactions. Estalaki et al. [16] proposed EGT model to optimize environmental penalty functions for river pollution management, demonstrating its advantage in capturing realistic interactions between regulators and dischargers under limited monitoring conditions. This theoretical approach offers new perspectives for understanding cooperation mechanisms and governance logic behind complex decision-making environments.

This review explores recent developments in the application of multi-player EGT across three key environments: natural, social, and network cooperative governance. By examining theoretical models, strategic designs, and cooperative mechanisms, the review identifies common patterns and methodological insights across domains, and further discusses the potential of EGT to inform future research and optimize governance frameworks.

2. Advanced application of multi-player EGT in various environmental governance

2.1. Natural environmental governance

EGT has become pivotal in modeling policy dynamics in the field of natural environmental governance, particularly in areas such as pollution control, ecological compensation, and environmental taxation. These issues should involve multiple players—governments, enterprises, and the public—whose interests diverge and evolve over time, making cooperation both necessary and difficult to sustain. However, most earlier studies focus on two-player interactions, which may overlook the complexity of real-world governance.

Chen and Wang [17] initially constructed two separate models to analyze the strategic interaction between central and local governments as well as polluting firms under environmental taxation. But ultimately unified them into a coherent three-party framework, taking a step towards multi-player game models. Their findings emphasized that aligning fiscal incentives across government levels is critical to motivating local enforcement and guiding enterprise behavior, thus enhancing the overall effectiveness of environmental tax policy. Chen et al.[18] extended this to a tripartite evolutionary game model with replicator equations and system dynamics simulations to show that public participation can substitute government supervision, reducing enforcement costs. Liu et al.[19] introduced a multi-player model for coal-mine safety regulation, showing that dynamic penalty strategies can effectively reduce behavioral fluctuations and improve regulatory stability under bounded rationality. Chen et al.[20] analyzed tripartite cooperation in cascade hydropower systems, where two upstream operational stations and downstream under-construction stations negotiate compensation mechanisms under mixed development pressures.

Collectively, their researches demonstrate the versatility of evolutionary game models in revealing the mechanisms behind multi-party cooperation, regulatory adaptation, and behavioral convergence in complex natural environmental systems.

2.2. Social environmental cooperation

Cooperation among different parties in social environmental governance requires balancing conflicting interests through dynamic incentive structures that rely heavily on trust and institutional coordination [21]. In these settings, multi-player evolutionary game models offer valuable insights into how governments, enterprises, public, etc. adapt in response to shifting incentives and institutional constraints. For fields such as educational collaboration, social resource allocation, and public health governance, EGT contributes to more effective coordination and fosters a more equitable and resilient society.

Liu et al.[22] introduce governments into the regular schools-enterprises systems, analyzing the dynamic strategies and mutual incentives using replicator equations. The findings reveal that the stability of schools' and enterprises' strategies primarily depends on rewards from nongovernmental sources, while the government's action is more affected by the benefits derived from positive cooperation when schools and enterprises align. Their model is useful to simulate how different cooperation scenarios evolve over time in educational partnerships. Zhu et al. [23] applied EGT to urban food waste management, modeling conflicts among government departments, restaurants, and waste disposal companies. Yuan et al. [24] constructed a tripartite evolutionary game model involving the government, hospitals, and government-affiliated non-profit organizations (GNPOs) to optimize medical supply allocation during a public health emergency. The study demonstrated that well-designed reward and punishment mechanisms, combined with effective supervision, can significantly improve resource distribution efficiency and reduce conflict behaviors under crisis conditions. Wu et al. [25] explored three-party cooperation among upstream and downstream enterprises and consumers under a government subsidy policy. By building a payoff matrix and replicator dynamics, they revealed that regulatory incentive design has a direct impact on enterprise cooperation, while active consumer participation contributes to stable and sustainable market outcomes.

Together, these studies illustrate the growing utility of multi-player EGT frameworks in addressing complex cooperation problems in public services, especially when institutional trust, incentive asymmetry, and heterogeneous stakeholder interests must be reconciled.

2.3. Digital economy and cyber environment governance

The rise of the digital economy and cyber environment poses new challenges for governance, including algorithmic bias, data privacy risks, platform monopolies, and cybersecurity threats. These issues typically involve interactions among governments, digital platforms, consumers, and other actors, with diverse incentives and selfish interests. Traditional governance tools often fall short in addressing such decentralized, information-asymmetric systems. Multi-player EGT provides a useful analytical framework to capture the strategic adaptation and incentive-driven behaviors in these dynamic digital contexts.

Li et al. [26] modeled interactions among platforms, governments, and consumers through numerical simulation by introducing parameters such as the degree of discriminatory pricing, the degree of data property right confirmation, and the intensity of supervision. Results told that stricter supervision and defined data property rights reduce pricing discrimination. Li et al. [27] modeled tripartite interactions and payoff functions among data providers, users, and regulators in open data ecosystems. They simulated the evolution of the cooperation ratio as time progresses, revealing that dynamic reward-penalty mechanisms enhance long-term cooperation. User-side factors like data mining capabilities and acquisition costs critically influence strategy evolution under regulatory oversight. Similarly, Qiu et al. [28] modeled a game to examine regulatory credit mechanisms in e-commerce platforms. They analyzed how cost differentials for regulations, compensations, honest business, and complaints between merchants, consumers, and platforms affect e-commerce environment, enhancing long-term market sustainability. Tosh et al. [29] focused on cybersecurity collaboration through EGT, modeling an information sharing game among firms in a Cybersecurity Information Exchange (CYBEX) system. They presented a distributed learning heuristic to attain the evolutionary stable strategy (ESS) under various conditions; as well as showed how CYBEX can wisely vary its pricing for participation to increase sharing and its own revenue, eventually evolving toward a win-win situation. Their research contributes to protect against future cyber crimes through a collaborative effort from different types of agencies.

In short, the fitness of EGT in analyzing cooperative behavior in network environments is outstanding, where regulatory complexity, user heterogeneity, and information asymmetry frequently shape strategic interactions. EGT contributes to maintain a healthy network environment.

3. Future directions

Multi-player evolutionary game theory is expanding its role in governance research by integrating with fields such as behavioral science, complex systems modeling, data analytics, and artificial intelligence, enabling deeper analysis of strategic decision-making in diverse socio-environmental contexts [30]. This interdisciplinary approach allows for the incorporation of psychological and institutional variables, improving the realism and policy relevance of EGT models. By combining agent-based simulations, network theory, and real-time data streams, EGT is gaining potential to simulate large-scale systems, support collaborative planning, and optimize policy interventions across sectors such as climate governance, public health, and digital regulation. This integration advances the explanatory power of evolutionary dynamics, offering insights into long-term cooperation, adaptive behavior, and stakeholder alignment. Looking forward, EGT holds promise for contributing to inclusive, evidence-based policy design that bridges theory and practice. However, current research remains largely conceptual, and its practical application in real-world decision-making is still limited. Future efforts must address challenges such as model validation, data availability, and stakeholder engagement to ensure that EGT-based frameworks effectively inform policy innovation and promote sustainable cooperation in more and more complex interdisciplinary fields.

4. Conclusion

Environmental governance is crucial in addressing increasingly complex challenges across ecological, social, digital domains, and so on, requiring coordinated actions among multiple stakeholders. Traditional governance approaches often struggle to adapt to dynamic interests, institutional asymmetries, and evolving public expectations. In recent years, evolutionary game theory, particularly multi-player models, has emerged as a powerful tool to analyze strategic interactions in such complex systems. These models simulate adaptive behaviors among governments, enterprises, and the public, offering insights into cooperation mechanisms, incentive design, and policy effectiveness. By capturing the dynamics of player decision-making under uncertainty, EGT advances understanding of governance complexity and supports data-informed solutions. As the field continues to evolve, multi-player EGT holds strong potential to bridge theory and practice, enabling more inclusive, responsive, and sustainable governance outcomes.

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