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Analyzing the evolutionary game of subsidies' strategy in the digitization of marine ranch: a theoretical framework

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This study establishes a three-party evolutionary game model that includes marine ranch firms, consumers, and the government, with a focus on the digital transformation pattern of marine ranching. Subsequently, the researchers conduct gaming and simulation to analyze the government subsidy strategy in the digital transformation of marine ranching. The following findings are derived: (1) Government subsidies have the potential to facilitate the digital transformation of marine ranches, benefiting both the supply and demand sides. Government subsidies positively influence both the digital transformation of marine ranch firms and the involvement of consumers in this transformation process. (2) The findings from the evolutionary game system demonstrate that alterations in the cost–benefit dynamics of each participant lead to adjustments in the steady state, thereby prompting the government to adapt its optimal subsidy strategy. (3) More government subsidies are not always better. Excessive government subsidies will destroy the stability of the evolutionary game system, which is not conducive to the realization of the digitization of marine ranch. (4) Subsidizing consumers is more effective in driving the digital transformation of marine ranch than subsidizing marine ranch firms. Subsidies to marine ranch firms will destroy the stability of the evolutionary game system, whereas subsidizing consumers contributes positively to its stability.

KEYWORDS
digital transformation, subsidy strategy, marine ranch, government, game and simulation

1 Introduction

The majority of coastal countries possess extensive areas suitable for aquaculture, and their potential for development exceeds the space needed to meet anticipated seafood demand (Gentry et al., 2017). Since 1977, when the first marine ranch was built in Japan, marine ranch has been an important development direction for the mariculture industry (Purcell et al., 2012). The concept of marine ranch involves the intentional and organized stocking of fish, shrimp, shellfish, algae, and other marine biological resources through artificial release within a specific natural sea area. This process employs large-scale fisheries facilities and systematic management systems. Marine ranching provides a solution to the issues of improper marine resource utilization and seawater pollution commonly encountered in mariculture (Tan and Lou, 2021). Scholars examined the scale, nature, function, and spatial variation characteristics of China's national marine ranches, along with the factors influencing them (Qin et al., 2021), then validated the applicability of the supply chain sustainability assessment model for marine ranch (Wan et al., 2021b).

Resource and environmental carrying capacity is an important measure of the sustainable development of marine ranch. Scholars developed an energy-value ecological footprint approach that considers uncertainty, enabling the establishment of the resource and environmental carrying capacity of marine ranches (Du et al., 2022b), then formulated an evaluation index system to assess the status of resource and environmental carrying capacity for marine ranch firms in Yantai city (Du and Wang, 2021). Regarding resources, studies employed the Malmquist-DEA (data envelopment analysis) method to evaluate the technical efficiency and regional disparities of marine ranches in China. Additionally, they utilized a system dynamics model to simulate the evolutionary trajectory of technical efficiency in marine ranches under various strategy scenarios (Zhang et al., 2021). With a focus on the ecological environment, the composition and dynamics of bacterial and protist communities within Laoshan Bay Marine Ranch was investigated (Fang et al., 2021). Furthermore, certain studies have emphasized the significance of local governments offering specific subsidies for the blue carbon trading market in marine ranching (Wang et al., 2022). Marine ranches perform important ecological and economic functions, but also have various real problems and risks. Microplastics are present in 37.6% of fish in the marine ranch of Maan Islands (Wu et al., 2020), causing environmental risks and fish safety risks.

The issue of marine ranch management above is significantly influenced by digitization. The digitization of marine ranches not only addresses diverse management challenges in their development but also enhances the ecological functions and economic gains of marine ranches. Additionally, it amplifies the social benefits, thereby establishing it as a genuine digital operational model for the future mariculture industry (Wan et al., 2023). Digitization of marine ranch refers to the transformation and upgrading of marine ranch using information technology and digital tools, including the use of sensors to monitor the marine environment, data analysis to optimize the management of aquaculture, intelligent control of water quality and temperature, and the application of remote monitoring technology, so as to make the process of aquaculture in marine ranch smarter and more precise and, thus, to improve production efficiency, reduce costs, and enhance sustainability. New demands for aquaculture equipment have emerged in recent years due to the advancement of modern marine ranch development (Xu et al., 2022). Blockchain and other emerging technologies have accelerated the digitization process in various industries and improved the operational efficiency of firms (Su and Wang, 2022). However, the digitization construction of marine ranches cannot be completed through the firm itself. On one hand, the digital transformation of marine ranches necessitates substantial capital investment, a feat that proves challenging to accomplish solely with the firm's internal resources (Gao et al., 2022). On the other hand, the marine ranch construction investment is large, the cycle is long, and the return on investment is low (Wang and Zhang, 2021). Therefore, under the market mechanism, the willingness of social capital investment is low (Kumar et al., 2016). Consumers, government, and other external stakeholders are also important subjects that cannot be ignored (Wan et al., 2021a). Furthermore, considering that marine ranches are industrial models with considerable environmental and ecological impacts, the government assumes a crucial role as a driving force in their establishment (Wan et al., 2021c). In practice, countries have issued a large amount of government subsidies to promote national marine ranch construction demonstration areas. For the digital transformation of marine ranch, government subsidies remain an important driving force that cannot be ignored. Consequently, this paper's primary focus is centered on the government's subsidy strategy for the digital transformation of marine ranches.

The research most directly relevant to this paper is the digitization of fisheries, on which scholars have conducted a great deal of research. Within the framework of fisheries' digital transformation, the incorporation of digital technologies holds immense potential to significantly enhance fisheries operations and management practices. Rowan emphasized the necessity of harnessing and developing digital technologies like ICT, Internet of Things, cloud computing, artificial intelligence, machine learning, immersive technologies, and blockchain to facilitate the expansion of fisheries (Rowan, 2022). Presently, the availability of fisheries information concerning the high seas is insufficient. Scholars integrated descriptive vessel information and tracking data with species-specific catch reports to outline and characterize pelagic longline activity in the Pacific Ocean (Frawley et al., 2022), then designed a software system capable of processing digital underwater acoustic data to extract spatial and temporal distributions of fish density, fish abundance, and fish length (Michael Jech and Luo, 2000). Small-scale fisheries in the German Baltic Sea used a smartphone application to conduct fishing activities to demonstrate that no cod were caught in waters below 20 m depth (Meyer et al., 2022). Furthermore, scholars developed a Bayesian regression model utilizing climatic variables to predict the daily distribution of recreational boating traffic in Western Australia. This predictive model aims to support sustainable management practices for recreational fisheries (Afrifa-Yamoah et al., 2021). Building upon the foundation of fisheries digitization, the concept of smart fisheries can be advanced and further developed. Smart fishery involves the amalgamation of cutting-edge technologies such as the Internet, cloud computing, and the Internet of Things. It relies on the deployment of various sensors and wireless communication networks at fishery production sites to achieve intelligent sensing, warning systems, decision-making capabilities, data analysis, and expert online guidance for optimizing the fishery production environment. Based on this, scholars developed a web-based intelligent decision support system to promote sustainable fisheries development in Maluku, Southeast Indonesia. They utilized this system as a foundation for evaluating both current and past regional fisheries plans (Teniwut et al., 2022). Furthermore, suggestions have been put forth to progressively integrate information technology, data science, and artificial intelligence with fishing and fish farming techniques. This integration aims to attain increased productivity in aquaculture, ensure sustainable utilization of natural fishery resources, and enable mechanization and automation of related activities (Gladju et al., 2022). The following theoretical gaps exist in the above studies. First, owing to the complexity and uncertainty of the marine environment, the construction of marine ranch urgently needs to introduce digital technology. Nevertheless, current research predominantly centers on historical development, ecological and economic impacts, challenges, and corresponding response policies of marine ranch. Little attention has been given to the digital transformation of marine ranches and the establishment of intelligent marine ranches. Second, most of the research on digital transformation is focused on the digitization of fisheries; less research has been conducted on the digital transformation of marine ranches. Although those concepts, framework, and models about the digitization and intelligentization of the fishery industry can provide reference and assistance for the digital transformation of marine ranches, unlike the digitization of fisheries, the construction of marine ranches has a large investment, has a long cycle, and is generally managed as a firm operation. Therefore, the digital transformation of marine ranches is also the digital transformation of marine ranch firms. The existing research on digital transformation of firms is less involved in marine ranch firms.

Based on the above real issue and research gaps, we present a collaborative framework for the digital transformation of marine ranches and proceed with an examination of the government's digital subsidy strategy. Moreover, simulation analysis is performed using survey data regarding the quantity of government subsidy and its recipients. The findings can enrich the theory of government subsidies and offer guidance to advance the digital transformation of marine ranches. In contrast to existing research, this paper's marginal contributions are as follows: (1) Exploring the influence of external agents on the digital transformation of marine ranch firms. Most of the existing literature analyzes digital transformation within marine ranch firms based on the micro perspective of firm technology introduction, but the internal motivation of marine ranch firms themselves for digital transformation is insufficient. This paper extends the research perspective by investigating the impact of the government subsidy on the digital transformation of marine ranch firms. (2) Consumers are also an important factor influencing the digital transformation of firms but are often overlooked. In this paper, consumers are included in the analysis framework of digital transformation of marine ranches and consider the feasibility of facilitating the digital transformation of marine ranches from the consumer side. (3) Incorporating data from marine ranch firms, consumers, and relevant government departments from field surveys into the model parameter taking sources makes the simulation results more realistic and enhances the objectivity of the research findings.

2 Methodology

2.1 Realistic situation description of marine ranch digitization

Digitization is the basis of intelligence. The digital transformation of the marine ranch industry is mainly characterized by the digital form of processing all fishery elements, such as fishery resources, water ecology, fishing and breeding, the whole fishery production process and fishery management process, and other information. The application scenarios of digital technologies in fisheries management are as follows: Firstly, aquaculture activities encompass tasks such as monitoring and controlling the production environment, optimizing feed utilization, monitoring fish biomass, and implementing disease prevention measures. Secondly, fisheries management involves activities like resource assessment, fishing operations, monitoring catches, and implementing regulations. Lastly, environmental monitoring focuses on areas such as hydrology, primary production, and aquatic pollution (Gladju et al., 2022). In order to promote smart fisheries, there is an urgent need for digital transformation of marine ranches to involve data as an equally important factor of production as land, labor, capital, technology, etc. for allocation.

Firms are the core subjects of digital transformation of marine ranches, and they can choose to transform or not to transform according to their own cost–benefit analysis. However, the digital transformation of marine ranch has a large current investment, long payback period, and other characteristics; marine ranch firms undertaking digital transformation is not enough motivation and ability. The public benefits of marine ranching include enhancing the ecological environment and preserving biological resources. To bolster the digital transformation capabilities of marine ranch firms, government intervention through subsidies becomes essential. Consumers are the testers of the products of marine ranch firms. Along with the upgrade of consumption ability, consumers pay more attention to the quality and production process of seafood. Consumers' visualization of seafood production, supply, and marketing information will force the digital transformation of marine ranch firms. Therefore, in order to motivate consumers to participate in the digital transformation of marine ranches, the government can start from the consumer side and give subsidies to seafood consumers. As a result, marine ranch firms, consumers, and the government form the digital transformation pattern of marine ranch as shown in Figure 1.

2.2 Model construction of marine ranch digitization

2.2.1 Evolutionary game model construction

Based on an accurate depiction of the current circumstances, this study formulates a three-party evolutionary game model. In the behavioral decision of each participant of the pattern, marine ranch firms can choose whether to undertake digital transformation, consumers can choose whether to participate in digital transformation, and the government can choose whether to subsidize digital transformation. In this paper, we set the probability of marine ranch firms to undertake digital transformation as i, set the probability of consumers to participate in digital transformation as j, and set the government's probability of subsidizing digital transformation as k. Then, $i, j, k \in [0, 1]$. The cost of digital transformation for a marine ranch firm is

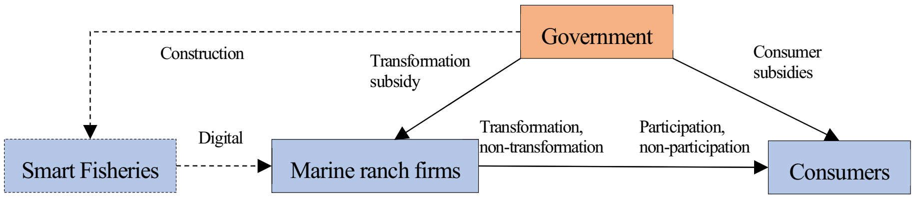

FIGURE 1
Digital transformation pattern of marine ranch.

assumed to be c_i and the benefit is s_i, the cost of not digitally transforming a marine ranch firm is c_{1-i}, and the corresponding benefit is s_{1-i}. The cost for consumers to participate in the digital transformation of marine ranches is c_j and the benefit is s_j, the cost for consumers not to participate in the digital transformation of marine ranches is c_{1-j}, and the benefit is s_{1-j}. b represents the quantity of government subsidies allocated for the digital transformation of marine ranches. w_i stands for the government subsidy coefficient designated for marine ranch firms. w_j denotes the government subsidy coefficient specifically designated for consumers. The utility gained by the government is s_k, and the utility gained by the government without subsidies is s_{1-k}. According to the conditions above, the three-party game's payoff matrix is shown in Appendix A1 Supplementary Table 1.

2.2.2 Building the numerical simulation model and assigning the parameters

The numerical simulation model is obtained in this paper based on the previously constructed evolutionary game model in Equation A13. The model parameters' values are mainly obtained from the field survey conducted by a research team on "digital transformation of marine ranches" in Yantai City in July and August 2022. Among all the national marine ranches in China, Yantai possesses the highest number, which underscores the urgency of conducting the digital transformation of marine ranches in the region. Therefore, Yantai city is a typical location for the survey. Appendix A2 Supplementary Table 2 displays the necessary parameter values for the numerical simulation model. This paper sets t = 200 as the time duration and sets 2023 as the base year. To provide a more intuitive representation, we perform numerical simulation analysis using the Ode45 function in MATLAB2019b software. The outcomes are illustrated in a two-dimensional graph using the Plot function. Subsequently, we utilize the Plot3 function to present the influence of the government subsidy amount in a three-dimensional graph for further visualization.

3 Results and analysis

3.1 Evolutionary game results and analysis

3.1.1 Marine ranch firms' stabilization strategy

Based on the benefit matrix of marine ranch digital transformation in Supplementary Table 1, as illustrated in Equations A1–A3, we can discern the anticipated benefits of marine ranch firms engaging in digital transformation, the anticipated benefits without digital transformation, and the average anticipated benefits of marine ranch firms. The replication dynamic equation of the marine ranch digital transformation strategy is shown in Equation A4. The analysis process is shown in Appendix B1.

The analysis result of Appendix B1 shows that the marine ranch firms' stable strategy is not to undertake digital transformation when the government subsidies' probability is low; the marine ranch firms' stable strategy is to undertake digital transformation when the government subsidies' probability is high. It indicates that the government subsidies' probability positively affects marine ranch firms to undertake digital transformation.

3.1.2 Consumers' stabilization strategy

In accordance with the benefit matrix of marine ranch digital transformation depicted in Supplementary Table 1, we can ascertain the anticipated benefits of consumers engaging in digital transformation, as well as the anticipated benefits of abstaining from digital transformation. Equations A5–A7 outline the average anticipated benefits of consumers. The replication dynamics equation of the consumers' participation in the digital transformation strategy is shown in Equation A8. The analysis process is shown in Appendix B2.

The analysis result of Appendix B2 shows that the consumers' stable strategy is not to participate in digital transformation when the government subsidies' probability is low; the consumers' stable strategy is to participate in digital transformation when the government subsidies' probability is high. It indicates that the government subsidies' probability positively affects the consumers' decision to participate in digital transformation.

3.1.3 Government's stabilization strategy

Based on the benefit matrix of marine ranch digital transformation presented in Supplementary Table 1, we can discern the anticipated payoffs for the government in providing subsidies for the digital transformation of marine ranches, as well as the anticipated payoffs for refraining from providing subsidies. Equations A9–A11 depict the average anticipated payoffs for the government. Equation A12 illustrates the dynamic equation replicating the government subsidy strategy. The analysis process is shown in Appendix B3.

First, the analysis result of Appendix B3 shows that when the marine ranch firms' probability to undertake digital transformation is low, the government's stabilization strategy involves offering subsidies. When marine ranch firms are highly likely to engage in digital transformation, the stabilization strategy of the government entails abstaining from offering subsidies. This implies that the government subsidy serves as a crucial motivating force encouraging marine ranch firms to undertake digital transformation. As digital transformation becomes an inherent market behavior for marine ranch firms, the government subsidy can be progressively phased out. Second, the analysis result of the data presented in Appendix B3 indicates that the government's stabilization strategy entails providing subsidies to consumers when their likelihood of participating in digital transformation is low. The government's stable strategy excludes the provision of consumer subsidies when consumers have a high likelihood of engaging in digital transformation.

This implies that government subsidy plays a vital role in motivating consumer participation in digital transformation. As consumers engage in digital transformation voluntarily, the government subsidy can be gradually phased out.

3.1.4 The evolutionary game system's stability analysis

We formulate the replicated dynamic system for the three-party game, which includes the government, marine ranch firms, and consumers. Subsequently, we examine the stabilization of the replicated dynamic system, with the analysis procedure detailed in Appendix B4.

In the situation of government providing subsidy, first, $E_2(1,0,0)$ is stable when the profit of the marine ranch firm undertaking digital transformation is more than the profit of not undertaking digital transformation, the utility of the consumer participating in digital transformation is more than the utility of not participating in digital transformation, and the net utility of the government subsidizing digital transformation is more than the amount of subsidy provided to the marine ranch firm. In this case, the final evolutionary strategy is that the marine ranch firm performs digital transformation, the consumer does not actively participate in digital transformation, and the government does not provide subsidies.

Second, $E_3(0,1,0)$ is stable when the profit of the marine ranch firm undertaking digital transformation is more than the profit of not undertaking digital transformation, the utility of the consumer participating in digital transformation is more than the utility of not participating in digital transformation, and the net utility of the government subsidizing digital transformation is more than the amount of subsidy provided to the consumer. In this case, the final evolutionary strategy is that the marine ranch firm does not actively undertake digital transformation, the consumer actively participates in digital transformation, and the government does not provide subsidies.

Third, $E_5(1,1,0)$ is stable when the profit of marine ranch firms undertaking digital transformation is more than the profit of not undertaking digital transformation, the benefit of consumers engaging in digital transformation surpasses the benefit of not participating in digital transformation, and the net utility of the government subsidizing digital transformation is less than the amount of subsidy paid. In this case, the final stable strategy is that marine ranch firms undertake digital transformation, consumers participate in digital transformation, and the government does not provide subsidy for digital transformation, which is the most ideal one, but may be difficult to achieve in reality.

In the situation where the government does not provide subsidy, first, $E_4(0,0,1)$ is stable when the sum of profits from digital transformation by marine ranch firms and subsidies received is less than the profits from not undertaking digital transformation, the sum of utility from consumers participating in digital transformation and subsidies received is less than the utility from not participating in digital transformation, and the utility of government subsidy is more than the utility of no subsidy. In this case, the final evolutionary strategy is that marine ranch firms do not undertake digital transformation, consumers do not participate in digital transformation, and the government provides subsidies, but this scenario does not occur in reality.

Second, $E_6(1,0,1)$ is stable when the sum of profits from digital transformation and subsidies received by marine ranch firms is more than the profits from not undertaking digital transformation, the sum of utility from consumers participating in digital transformation and subsidies received is less than the utility from not participating in digital transformation, and the net utility of the government subsidizing digital transformation is more than the cost paid by subsidizing marine ranch firms. In this case, marine ranch firms undertake digital transformation, consumers do not actively participate in digital transformation, and the government provides subsidies to marine ranch firms.

Third, $E_7(0,1,1)$ is stable when the sum of profits from digital transformation and subsidies received by marine ranch firms is less than the profits from not undertaking digital transformation, the sum of utility from consumers participating in digital transformation and subsidies received is more than the utility from not participating in digital transformation, and the net utility of the government subsidizing digital transformation is more than the cost paid by subsidizing consumers. In this case, marine ranch firms do not actively undertake digital transformation, consumers actively participate in digital transformation, and the government provides subsidy to consumers.

Fourth, $E_8(1,1,1)$ is stable when the sum of profits from digital transformation and subsidies received by marine ranch firms is more than the profits from not undertaking digital transformation, the sum of utility from consumers participating in digital transformation and subsidies received is more than the utility from not participating in digital transformation, and the net utility of the government subsidizing digital transformation is more than the amount of all subsidies paid. In this case, marine ranch firms initiate digital transformation, consumers actively participate in digital transformation, and the government provides subsidy for digital transformation. The current sustainable governance pattern lays the groundwork for the government to offer subsidies for digital transformation in marine ranches.

3.2 Numerical simulation results and analysis

3.2.1 Analysis of the impact of total government subsidies

According to the survey data of digital transformation of marine ranches in Supplementary Table 2, we derive the simulation results for the game strategy. We assume that the total government subsidy for marine ranching amounts to 1, 2, and 3, respectively, and the game strategy's evolution process and result of marine ranch firms, government, and consumers are shown in Appendix C1. Supplementary Figures 2, 3 illustrate that the game system evolves to the (1,1,1) equilibrium when the government subsidy amount is 1. In this case, marine ranch firms tend to undertake digital transformation, consumers tend to participate in digital transformation, and the government inclines towards providing subsidies for marine ranching. Upon increasing the government subsidy amount to 2, marine ranch firms undertake digital transformation, but the strategy of consumers and the government appears to be unstable, and at this point, the game system does not possess any stable equilibrium. When government subsidy amount increases to 3, the strategies of marine ranch firms and the government appear to fluctuate, and consumers do not participate in digital transformation. At this moment, the game system lacks any stable equilibrium.

This indicates that the desired evolutionary outcome of the game system is achieved when the government subsidy amount is minimal. The evolutionary game system will exhibit instability, as the amount of government subsidies increases. This phenomenon may arise because consumers and marine ranch firms respond proactively to the government's call, driven by economic rationality. When consumers and marine ranch firms participating in digital transformation increases gradually, the subsidy burden of the government increases, and the government gradually reduces subsidies until totally removing them, which, in turn, reduces the incentive of marine ranch firms and consumers for digital transformation.

3.2.2 Impact analysis of subsidies for marine ranch firms

Similarly, assuming that the subsidy coefficient of marine ranch firms is 0.1, 0.5, and 0.9 in the range of parameters according to Supplementary Table 2, we obtain the evolutionary process and outcome of the game strategy involving marine ranch firms, consumers, and the government, which is presented in Appendix C2. In Supplementary Figures 4, 5, when the subsidy coefficients of marine ranch firms are 0.1 and 0.5, the game system's evolution result is (1,1,1). In this case, marine ranch firms undertake digital transformation, consumers participate in digital transformation, and the government subsidizes digital transformation. The game system's evolution result is (1,0,1) when the subsidy coefficient of marine ranch firms increases to 0.9. In this case, the marine ranch firms' stable strategy is to undertake digital transformation, the government's stable strategy is to subsidize digital transformation, but the consumers' stable strategy is not to participate in digital transformation.

This suggests that the game system evolution presents an ideal state when the subsidies of the marine ranch firms are low. However, as the subsidies to marine ranch firms are raised, consumers gradually do not participate in digital transformation. This may be due to the fact that the marginal benefit of digital transformation for marine ranch firms is more than the marginal benefit of not undertaking digital transformation when the government subsidies provided to marine ranch firms is low. In this case, rational marine ranch firms' optimal decision is to undertake digital transformation. Since the government subsidy amount is fixed relatively, it crowds out the subsidy amount consumers received when the government provides higher subsidies to marine ranch firms. Thus, the consumer subsidy coefficient becomes smaller, and the subsidies received by consumers become lower. The marginal benefit of consumers participating in digital transformation is lower than the marginal benefit of not participating in digital transformation, and rational consumers choose not to participate in digital transformation.

3.2.3 Analysis of the consumer subsidy's impact

Similarly, the consumer's subsidy coefficient is assumed to be 0.1, 0.5, and 0.9, respectively, in the range of parameters according to Supplementary Table 2; in this case, the evolutionary process of the game strategy among the three parties is depicted in Appendix C3. Based on observations from Supplementary Figures 6, 7, it is evident that the game system's evolution result is (1,0,1) when the coefficient of consumer subsidy is 0.1. In this case, the marine ranch firms tend to undertake digital transformation, the government provides subsidies to marine ranch firms, but the consumers tend to not participate in digital transformation. When the subsidy coefficient of marine ranch firms increases to 0.5 and 0.9, the game system's evolution result is (1,1,1). In this case, marine ranch firms undertake digital transformation, consumers participate in digital transformation, and the government provides subsidies to marine ranch firms.

This suggests that consumers do not participate in digital transformation when consumer subsidies are low. As the amount of consumer subsidies increases, the game system evolves into an ideal state; in this situation, consumers participate in digital transformation. When consumer subsidies are low, they may perceive higher costs associated with the transformation and are therefore reluctant to participate. However, as consumer subsidies increase, what they receive enables them to gain more financial incentives and thus be willing to participate in digital transformation.

4 Discussion

This study focuses on the core question of subsidy strategy for digital transformation of marine ranches. The results indicate that government subsidies can enhance the likelihood of digital transformation among marine ranch firms and encourage consumer involvement in the digitization of marine ranches. There are differences in government subsidy strategies in seven different scenarios. In terms of subsidy amount, higher government subsidies are not always better. In terms of subsidy subject, subsidizing consumers is more effective than subsidizing marine ranch firms. These findings answer the research questions of this paper.

(1) Digital transformation involves utilizing digital technologies, including cloud computing, big data, artificial intelligence, the Internet of Things, and blockchain, as a means and approach to facilitate the restructuring of business ecosystems. Ingram et al. conducted a survey on digital transformation in agriculture and outlined seven essential research themes for digital agriculture in the UK. These themes encompass data

governance, encouraging the adoption of data and technology, comprehending the advantages and enhancing the performance of data and technology, examining the impact of digital agriculture, and exploring new collaborative arrangements (Ingram et al., 2022). Purcell and Neubauer performed a comprehensive review of existing literature on the digital twin in agriculture, aiming to identify current trends and unresolved matters that contribute to a deeper comprehension of the digital twin concept (Purcell and Neubauer, 2023). Porciello et al. conducted a comprehensive global evaluation of digital agricultural services and their influence. Their findings indicated that the majority of research has concentrated on delivering digital advice and extension services to farmers (Porciello et al., 2022). Lioutas et al. argued that the social, ethical, political, cultural, and environmental aspects related to digitization are more prominent (Lioutas et al., 2021). The above research lays a solid foundation for this paper, which focuses more on the function and role of digitization in the construction of marine ranch. This paper asserts that government financial support is crucial to fully leverage the active role of digitization in the domain of marine ranch.

Digitization of marine ranches has an important role to play. The digital transformation of agriculture significantly affects the agri-food systems, leading to fundamental changes in processes, products, and services (Zscheischler et al., 2022). The substantial influence of digital transformation and information technology on agriculture, rural areas, and farmers has resulted in enhanced quality development and green growth within China's agricultural sector (Shen et al., 2022). These studies demonstrate the significance of digital transformation and highlight the importance of this paper. Along with this, there are negative effects of digital transformation. Usai et al. contended that the influence of digital technologies on firms' innovation performance is minimal (Usai et al., 2021). Scholars pinpointed the potential adverse effects on food security resulting from the digital transformation of German agriculture, including data rights issues, value chain restructuring, altered knowledge prerequisites for farmers, and information asymmetries (Zscheischler et al., 2022). For marine ranch, these side effects may be less severe because the employees of marine ranch firms have a higher level of knowledge than the farmers, and the digital transformation of marine ranch is beneficial for food security and mitigating information asymmetry. With regard to the accuracy of digitization, Visser et al. discovered that concerning the accuracy of digitization in agriculture, it is often labeled as "precision inaccuracy". They observed that the extensive volume and granularity of big data are sometimes mistakenly associated with high accuracy, which can lead to the risk of falling into an "accuracy trap" (Visser et al., 2021). The lack of precision in improving information does not necessarily improve the accuracy of decision-making, a problem that may also exist in the digitization of marine ranch studied in this paper. Therefore, important decisions must be made with human involvement and digitization is only a tool to assist human decision-making.

(2) In order to support the construction of marine ranch, governments have issued a series of policy documents. Many scholars analyzed the evolution of marine ranch policies. Using a potential Dirichlet allocation model, Qin and Sun quantified the policy texts from a database of 25 marine ranches in Shandong province, aiming to identify the factors influencing the policy themes (Qin and Sun, 2021). Employing content analysis methods and ROSTCM software, Yu and Zhang conducted an empirical analysis of 92 policy documents. Their findings indicated that the policy system of marine ranching is progressively improving, yet there remains a deficiency in the coordination among various stakeholders and inadequate monitoring of the ecological effects on adjacent sea areas (Yu and Zhang, 2020). In terms of marine ranch policy adjustments, the future direction should revolve around prioritizing ecological considerations, emphasizing technological advancements, and aiming to achieve policy integration that aligns with the diverse needs of multiple industries (Qin et al., 2020). The enactment of these supportive policies provides the basis for the subsidy policy of marine ranch proposed in this paper. Regarding the number of subsidized amounts, Ba et al. found that there are role boundaries for government fishery subsidies and the incentive effect will decrease after the subsidy amount reaches a certain level (Ba et al., 2022). This paper similarly concludes that government subsidies for the digital transformation of marine pastures should adhere to the moderate principle. Regarding subsidized recipients, according to the study of Zheng and Yu, subsidies benefit both the production and consumption aspects (Zheng and Yu, 2022), which is consistent with the conclusions of this paper. However, they also suggested that subsidy tilted to the production side can obtain the best effect, which is contrary to the findings of this paper. This paper argues that subsidizing consumers can promote the digital transformation of marine ranch more than subsidizing producers.

There is a difference in the focus of support for sea ranching between the central government and local governments. Through content analysis, Yu and Wang encoded and examined marine ranch management policies, revealing substantial disparities between the objectives of the central government and those of local governments. The focus of local governments' goals mainly revolved around construction activities (Yu and Wang, 2020). A game model involving the central government, local governments, and marine ranch firms was established by Du et al. to investigate the policy instruments utilized by the central government to incentivize local governments and marine ranch firms in ensuring the ecological security of marine ranches (Du et al., 2022a). Currently, subsidies for marine ranch are mainly led by the central government, so this paper does not distinguish the difference in subsidy priorities between the central government and local governments.

Digital transformation involves a lot of aspects and issues, and not all of them can be solved by government subsidies. The proliferation of digital services in agriculture in sub-Saharan Africa is influenced by several key factors, including digital skills, technological infrastructure, service discoverability, service availability, service affordability, and the public policy environment (Kieti et al., 2022). The adoption of digital agriculture technologies is constrained by high investment costs and the presence of a digital divide among technology adopters. Moreover, the incentive to prevent food loss and waste does not frequently serve as a significant driver for technology adoption (Benyam et al., 2021). Except for the government subsidy strategy, in the future, further research should be conducted on other issues in the digital transformation of marine ranches. In addition to the external environment driving the digital transformation of marine ranch, what is more important is the internal transformation drive of marine ranch firms. The focus of this paper is solely on examining government subsidies in the digital transformation of marine ranch firms from the external perspective of the firms. How the digital transformation of marine ranch is realized from the internal perspective of firms has not been studied yet. In the future, the digitization of marine ranch can be further analyzed from the perspectives of human, financial, and resource inputs within the firms.

5 Conclusion and policy implications

5.1 Conclusion

This paper establishes a three-party evolutionary game model involving marine ranch firms, consumers, and the government, analyzing subsidy probability and optimal strategies, followed by numerical simulations to derive conclusions. (1) From the perspective of the role of government subsidies, government subsidies are capable of fostering the digital transformation of marine ranches. The likelihood of government subsidies positively affects both the digital transformation of marine ranch firms and the engagement of consumers in the digital transformation process. (2) In terms of the optimal government subsidy effect, the game system achieves seven different steady states according to the cost–benefit changes of marine ranch firms, consumers, and the government, and the ideal government subsidy strategy differs depending on the circumstances. (3) Based on the results of the system evolution concerning the subsidy amount, it is observed that the government subsidy amount negatively affects the stability. As the total amount of government subsidies increases, the optimal government strategy entails reducing the likelihood of digital subsidies and eventually phasing out subsidies for the digital transformation of marine ranches. (4) From the system evolution results of subsidy targets, subsidizing consumers is more effective in promoting digital transformation of marine ranches than subsidizing marine ranch firms. The subsidy amount allocated to marine ranch firms negatively influences the stability, whereas the subsidy amount given to consumers positively affects the stability.

5.2 Policy implications

According to the aforementioned findings, we present the following policy implications: (1) Establish dedicated subsidies for the digital transformation of marine ranches, utilizing these subsidies as a leverage to encourage active engagement from various stakeholders in the digital development of marine ranches. Furthermore, governments should choose the right time to subsidize according to the market situation, and adjust the amount and structure of subsidies at any time according to the effect of subsidies. (2) Reasonable allocation of subsidy funds maintains the principle of providing subsidies at a moderate level. On the basis of the issuance of special subsidies, governments should regularly assess the effectiveness of subsidies to prevent excessive financial subsidies' burden. In addition, the government should determine the financial situation of marine ranch firms for regular verification and to timely curb the possible existence of subsidy dependence. (3) Optimize the utilization of the limited financial subsidy funds to ensure a balanced allocation of subsidies between consumers and marine ranch firms. The subsidy amount should be moderately tilted to the consumer side, focusing on subsidizing seafood consumers to achieve the best subsidy effect.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

SZ: Writing – original draft, Writing – review & editing. YZ: Funding acquisition, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1376256/full#supplementary-material

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