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Strategic interactions and market equilibrium in China's agricultural catastrophic insurance

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Abstract: In China's agricultural catastrophe insurance market, issues of non-equilibrium are prominent. To understand the causes of non-equilibrium in agricultural catastrophe insurance and to develop prevention strategies, this study employs an Evolutionary Game Model, incorporating disaster and insurance data for three types of cereal crops in Henan Province to analyse the Evolutionarily Stable Strategies in the agricultural catastrophe insurance market. The research also considers government policies and disaster reinsurance as implicit participants in the model. The findings reveal significant differences in the impact of non-equilibrium in the agricultural catastrophe insurance market and the choice of game strategies, dependent on the scale of farm operations, the type of crops cultivated, and regional variations. Significantly, decision-making evolutionary paths vary between small and medium-scale farmers, with rice growers emphasising income insurance more. In regions prone to frequent catastrophes, the insurance rates for agricultural catastrophe insurance exhibit greater flexibility. By scientifically delineating agricultural catastrophe risk zones, appropriately expanding the scale of cultivation, reducing insurance rates, and adjusting agricultural catastrophe insurance products, a balanced development in the agricultural catastrophe insurance market can be promoted.

Keywords: agricultural insurance; evolutionary game theory; non-equilibrium problem; numerical simulation analysis; time sequence dynamics

Climate change has notably increased agricultural calamities (Ahmed et al. 2022; WMO 2023). These occurrences have had a significant effect on farmers' income and have propelled them back into poverty. Research indicates that in 2020, the area of crops in China subjected to disasters amounted to 19 957.7 thousand ha, of which 2 706.1 thousand ha were utterly devastated. This resulted in a staggering economic loss of 51.13 billion USD (Zhang et al. 2019; National Bureau of Statistics of China 2021).

Nevertheless, the compensation disbursed by agricultural insurance, totalling only 8.52 billion USD, was insufficient to cover the incurred losses (China Statistical Press 2021). Despite the rapid growth of agricultural insurance during China's 13$^{\text{th}}$ Five-Year Plan for Economic and Social Development, the disproportionate ratio between agricultural disaster insurance and direct disaster losses and affected areas, inadequate compensation and protection, an incomplete mechanism for market concentration in the agricultural dis-

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aster insurance market, and the unbalanced development of supply and demand in the market al. remain (Yu and Yu 2021).

As such, it has become imperative to fully exploit agricultural disaster insurance to mitigate the impact of disasters on the farmers' income, maximise the protection of their interests, and reinforce the achievements of poverty alleviation in rural areas (Gu and Wang 2020). To this end, the central government's 'No. 1 central document' for 2022 emphasises the need to effectively prevent and respond to major agricultural disasters and actively develop agricultural insurance and reinsurance.

Due to the distinctive characteristics of agricultural catastrophes, which differ significantly from general natural disasters, the losses incurred from such calamities exhibit a 'low-frequency, high-damage' tail distribution, accompanied by significant 'fat-tail' features. These peculiarities present formidable challenges in risk diversification, ultimately leading to a singularity trap (Ibragimov et al. 2009). These factors have significantly impeded the growth of China's agricultural catastrophe insurance market over time. Moreover, specific issues such as imprecise premium and coverage determination (Zhang and Wang 2021) and the limited range of available agricultural catastrophe insurance products suggest an underdeveloped market, lack of risk pricing basis (Tu et al. 2014), homogeneity of agricultural catastrophe insurance products that fail to reflect the differentiated demand, and inadequate government involvement are contributing factors to the sluggish development. Insurance companies frequently eschew offering this type of insurance to mitigate their risks. When such policies are provided, they are typically accompanied by elevated premium standards (Kramer et al. 2022). Consequently, the high demand for agricultural catastrophe insurance versus the low supply of agricultural insurance in China, the high claims ratio of agricultural insurance versus its low premium income, and the quasi-public nature of agricultural catastrophe insurance versus insufficient government support has led to contradictions (Tang et al. 2021; Song et al. 2022).

A comprehensive literature review has identified the critical limitations in the research on China's agricultural catastrophe insurance. The market remains immature, with most insurance products still in the experimental or promotional phase. This results in a lack of empirical evidence and a heavy reliance on numerical simulations for research. Additionally, existing game theory studies often overlook the influence of government policies and reinsurance, which are critical to understanding the whole dynamics of the market. Moreover, while the government's involvement is recognized, its dualistic role alongside insurance companies in agricultural catastrophic insurance has not been fully explored. Current models have reduced the government participation to binary decisions regarding subsidies, thus neglecting the policy-driven and semi-public nature of agricultural insurance.

The application of evolutionary game theory to China's agricultural insurance market is both innovative and essential, given the dynamic nature of the agricultural sector, which is significantly influenced by unpredictable environmental factors and diverse stakeholder interests. Traditional analytical models are insufficient for capturing the complex and adaptive behaviours among farmers, insurers, and policymakers, highlighting the need for a more nuanced understanding of the market dynamics that evolutionary game theory provides. This study improves this approach by employing three methodological improvements: First, it utilises the theory formulated by Smith and Price (1973) to integrate market evolutionary and long-term equilibria with an equilibrium level in the agricultural catastrophic insurance market. Second, a model based on Taylor and Jonker (1978) and Duncan and Myers (2000) dynamically analyses sequential decision-making for market groups, guaranteeing that the 'replicating dynamic equation system' accurately reflects the actual market conditions. Lastly, agricultural reinsurance and government policies are indirect factors in the model that explicitly address the insurance needs of China's three main grain crops. Through MATLAB simulations, this research examines decision-making and non-equilibrium issues to provide deeper insight into the market equilibrium factors and decision-making processes of agricultural insurance entities. By clarifying the decision-making progression in these settings, the study offers a valuable theoretical basis for developing and adapting agricultural insurance and reinsurance products to suit the evolving market conditions better. This is a critical need in China, where agricultural policies and risk management strategies continually evolve. This approach enables the prediction and simulation of various policy scenarios and their impacts, thus enhancing our understanding of strategic interactions under conditions of uncertainty and limited information, which are common in agricultural settings.

Theoretical analysis based on the literature review

Non-equilibrium issues in the agricultural catastrophe insurance market. Borch (1962) applied

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the general equilibrium theory to investigate the uncertainty in reinsurance markets, treating uncertainty as a commodity. This approach led him to conclude that the reinsurance market achieves Pareto exchange optimality (Borch 1968). He effectively demonstrated how insurance markets, characterised by risk aggregation, achieve general financial risk diversification mechanisms. Subsequent research on the equilibrium in the agricultural catastrophe insurance market has focused on information asymmetry (Arrow 2009), farmer's ambivalent attitudes towards catastrophic risk (Klibanoff et al. 2005), individual agricultural catastrophe loss correlations (Raykov 2015), and studies from the perspective of behavioural and experimental economics (Yu et al. 2019). The fundamental finding of this research is that uncertainty in agricultural catastrophe risk is the root cause of the agricultural catastrophe insurance market's imperfection. Although information asymmetry can undermine the insurance risk management function, it does not significantly impact the equilibrium of the agricultural catastrophe insurance market. Farmers' aversion to the ambiguity of catastrophic risk and the extensive essential risk associated with 'weather index insurance' may lead to a low demand for agricultural catastrophe insurance (Miranda and Glauber 1997; Lichtenberg and Iglesias 2022).

China's agricultural catastrophe insurance market exhibits incomplete competition (Xu and Chen 2021), which results in a shortage of market suppliers. The presence of information asymmetries between insurance companies and farmers, insurance companies and various levels of government, and village committees and farmers significantly curtail this market's effective demand and supply to varying degrees (Cheng 2010). Moreover, the predominance of small farmers in China significantly exacerbates transaction and operating costs for agricultural insurance institutions (Tu and Zhu 2014). In contrast, the systemic risk associated with agricultural catastrophes further limits the market's supply and demand scale. The non-equilibrium state of China's agricultural catastrophe insurance market arises from several factors, including subsidy methods, the subsidy scope, the market mechanism, and the competition mode. Additionally, the non-equilibrium levels of policy agricultural catastrophe insurance markets differ significantly across provinces, where an inadequate supply and demand persists (Wei et al. 2021).

Behavioural bounded rationality and evolutionary theory in the participation of agricultural catastrophe insurance. In the agricultural catastrophe insurance market, participants reach equilibrium through continuous gameplay. The participants' understanding of catastrophic losses and agricultural insurance is ongoing, with decision-making evolving from rationality to limited rationality (Hazell and Varangis 2020). It highlights the challenge of achieving long-term equilibrium due to the quasi-public nature of agricultural insurance and the bounded rationality required for Nash equilibrium. Participants achieve equilibrium in the agricultural catastrophe insurance market through continuous learning, adjustment, and improvement rather than a one-time choice (Liao et al. 2020). The study posits that the market equilibrium is dynamic, with participant strategies continuously evolving in response to others, analogous to biological evolution (Xu et al. 2019).

Maynard Smith and Price's (1973) work on evolutionary game theory integrates Darwinian concepts into game strategy, with Friedman (1991) expanding this by linking Nash equilibrium with evolutionary stability. This theory extends classical game theory by incorporating bounded rationality and strategy evolution, offering a novel perspective on analysing game situations, especially in addressing the market's non-equilibrium issues (Liao et al. 2021; Fu et al. 2022).

The research also explores the development of rationality levels among the participants within agricultural insurance, emphasising the dynamics of strategy evolution in specific market scenarios.

Issues surrounding agricultural catastrophe insurance market challenges and their associated evolutionary game models. The development of game models to simulate equilibrium strategy choices and the learning evolution process of participants in the agricultural catastrophe insurance market game is a crucial aspect of evolutionary game analysis. The game features two primary participants in this market: farmers and insurance companies. Farmers, influenced by their cultural background, traditional habits, and inherited experience in decision-making, tend to exhibit 'herd behaviour' during the initial decision-making stages. Such herd behaviours exemplify the low rationality game party described by evolutionary game theory, where decision-making is primarily based on imitating the crowd (Smith and Price 1973).

In the agricultural catastrophe insurance market, individuals with lower rationality often adjust their strategy choices for the next stage based on the decisions of others in the same game group and the benefits they have obtained in the current game. This process involves strategy replication within the group, eventu-

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ally leading to interference, known as the Evolutionarily Stable Strategy (ESS) (Smith 1982).

Through strategy choices, participants aim to secure a predictable, expected return during the evolutionary game (Xu et al. 2019). The degree of consistency between the expected return and actual return reflects the alignment between the strategy choice and benefit in the game, also known as the expected fitness (Smith and Price 1973). As individuals in the groups of farmers and insurance companies adopt different strategies, they achieve varying fitness levels. Over time, changes in the expected fitness will influence the proportion of strategies within the group, ultimately establishing a dynamic evolution rule known as the replication dynamics rule for strategy proportions (Smith and Price 1973; Taylor and Jonker 1978; Smith 1982; Friedman 1991).

MATERIAL AND METHODS

Selection of the model

This research explores decision-making in the agricultural catastrophe insurance market to provide a theoretical basis for designing insurance and reinsurance products. It employs evolutionary game theory for dynamic analysis, addressing the current research gaps in the field and focusing on equilibrium strategy and attaining long-term equilibrium amid variable decision-making processes.

The application of evolutionary game theory is particularly beneficial for examining participant strategy, as it encompasses learning dynamics in the decision-making. It utilises concepts such as limited rationality, strategy replication dynamics, and evolutionarily stable strategies, which are well-suited for analysing the dynamic selection behaviour in the agricultural insurance market.

The study uses MATLAB simulations to investigate the decision-making processes, market equilibrium, and factors influencing strategy choices, elucidating how decision-making evolves among farmers and insurance companies. The findings contribute to crafting a reference for the agricultural insurance product design and highlight the value of evolutionary game theory in strategic studies.

Construction of theoretical evolutionary game models in the agricultural catastrophic insurance market

This study models China's agricultural catastrophe insurance market using Maynard Smith's evolutionary game theory to reflect the interactions between the supply and demand (Mahini et al. 2021). The model incorporates insurance and reinsurance companies, farmers of various scales, and government bodies, with the latter two categories acting as 'implicit participants'. It presupposes that the market participants are risk-averse with limited rationality, continuously striving to make optimal decisions through a learning process that involves trial and error.

Fundamental assumptions of the model. Assumption 1: Strategic choices in the agricultural catastrophe insurance market are part of a dynamic learning process where transaction costs are initially disregarded.

In some regions of China, agricultural catastrophe insurance remains experimental. Understanding of local agricultural insurance policies among the market agents continues to evolve. Variables are in flux, including the frequency and intensity of catastrophes, the magnitude of losses, compensation levels, and participant knowledge and experience. Consequently, during these initial stages, agents with limited rationality encounter challenges in determining the best course of action (Briggeman and Akers 2010).

To facilitate the establishment of the model, let k represent the game participant group, where $k = 1$ represents the insurance company group, $k = 2$ represents the farmer group, and let i represent the strategy choice of participants. For the insurance company, $i = 1$ indicates providing insurance, $i = 2$ indicates not providing insurance. Similarly, for the farmers, $i = 1$ indicates purchasing insurance, and $i = 2$ indicates not purchasing insurance. Let s represent the decision-making space. When the strategy is simplified to one dimension, $s = [(s_1^1, s_2^1), (s_1^2, s_2^2)]$. If we let $s_1^1 = x$, $s_1^2 = y$, then $s_2^1 = 1 - x$, $s_2^2 = 1 - y$. Consequently, the decision-making space can be described by the points within the square $[0,1] \times [0,1]$.

Assumption 2: We assume that the harmful repercussions suffered by farmers are limited to tangible financial losses and are entirely contingent upon happenstance.

The agricultural output is dependent on the availability of arable land and water infrastructure. Natural disasters impact the crop yield, expected income, infrastructure, and soil fertility. However, due to the challenges in measuring the soil fertility and infrastructure damage and because insurance policies typically do not cover these aspects, it is practical for models to focus solely on direct financial losses.

Assuming an agricultural insurance market encompassing N farmers, each cultivating an area of h and with a projected revenue of M, the likelihood of a catastrophic event is p. Consequently, farmers incur a direct monetary loss of L, resulting in a random income of $M - L$.

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Assumption 3: In the agricultural catastrophe insurance market, the risk borne by farmers during catastrophic events is associated with the level of insurance coverage (φ), the cost per unit area of coverage (w), and the number of agricultural catastrophe insurance contracts (n) held by each insurance company.

Assumption 4: Agricultural insurance enterprises can mitigate risk through reinsurance, diversifying their portfolio.

Due to limited theoretical and practical knowledge, China's agricultural insurance system currently lacks an effective mechanism for managing large-scale agricultural risks, especially in developing agricultural catastrophe reinsurance. In a functional market, agricultural insurance firms, reinsurance companies, and capital markets play critical roles in dispersing significant catastrophic and social risks. This paper suggests that agricultural insurance companies can mitigate the risk of catastrophe claims from the insured through reinsurance.

Assuming that an insurance company disburses a fraction of its premium, represented by α, $\alpha \in [0,1]$, to a reinsurance company, the latter pledges to cover a specific proportion of the reinsurance claim, indicated by δ, $\delta \in [0,1-\alpha]$, in the event of an agricultural calamity (Table 1).

Evolutionary game model of agricultural insurance

Profit analysis of insurance companies. The stochastic nature of agricultural catastrophes makes them inherently unpredictable. This unpredictability significantly impacts the strategic approaches of insurance companies. Consequently, the outcomes of these strategies can vary widely, underscoring the necessity for robust adaptive mechanisms within the insurance sector.

Within the evolutionary paradigm, the efficacy of these adaptive mechanisms is critically analysed. This analysis helps to articulate the expected effectiveness of strategies over time, offering insights into how companies can better align their practices with the dynamic nature of risk they face.

The formula for the projected revenue within this model is designed to integrate several key factors that influence the financial outcomes for insurance companies in the face of agricultural catastrophes. It is expressed as:

Table 1. Main parameters and their description

Parameter		Description
Agricultural catastrophic risk	p	probability of a catastrophic agricultural loss is assigned 0.7 for high, 0.3 for medium, and 0.1 for low-risk levels
	L	agricultural disaster losses faced by farmers.
Agricultural insurance company	w	insurance premium per unit area; $w > 0$
	φ	insurability or coverage level $0 \le \phi \le 1$: specifies the fraction of losses covered by insurance.
	n	number of agricultural insurance contracts; $n > 0$
	b	operating cost of agricultural insurance for insurance companies; the comprehensive expense ratio is 23% of premium income
Farmers	M	net agricultural income of farmers, $M > 0$
	N	total number of households purchasing agricultural insurance, $N > 0$
	h	operational land area of farmers, $h > 0$
Reinsurance company	α	proportion of insurance policies allocated to reinsurance companies per unit by the insurance company, $0 \le \alpha \le 1$
	δ	reinsurance company's compensation proportion, $0 \le \delta \le 1 - \alpha$
Government	g	government premium subsidy proportions: directly materialized 72.5% for cost insurance and 80% for full insurance.
Proportion of the groups	x	proportion of insurance companies in group t; choosing the 'provide insurance' strategy, $0 \le x \le 1$
	y	proportion of households choosing the 'purchase insurance' strategy, $0 \le y \le 1$

Source: catastrophic agricultural loss was collected from the Henan Province Statistical Yearbook (2020); comprehensive expense ratio data was sourced from the State Council Policy Briefing (2021); proportion of government premium subsidy was sourced from the Henan Provincial Rural Revitalization Financial Product Manual. (2023) for the years 2021–2022, the probability of agricultural catastrophes is calculated using the ratio of disaster-stricken areas to sown areas as documented in the Henan Statistical Yearbook (2020)

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$$E_1\ (x = 1, y = 1) = n\phi(1 - \alpha)w(1 - b) - \\ - \phi(1 - \alpha - \delta)\sum_{i=1}^{n} pL_i \quad (1)$$

$$E_1\ (x = 0, y = 1) = E_1\ (x = 0, y = 0) = \\ = E_1\ (x = 1, y = 0) = 0 \quad (2)$$

where: E_1 – expected revenue of insurance companies; $E2$ – expected income or loss of farmers; n – number of agricultural insurance contracts, which influences the scale of premium income for the insurance companies; ϕ – coverage level of the agricultural catastrophe insurance; w – insurance premium per unit area, which represents the price that farmers pay for each unit of land they insure; p – probability of the occurrence of a catastrophic event; L – total potential loss.

Analysis of farmers' income. As deduced from assumption 2, the expected loss due to agricultural disasters can be mathematically formulated as follows:

$$p \times L + (1 - p) \times 0 = pL \quad (3)$$

The anticipated earnings of farmers adopting varying strategies are represented mathematically, as indicated in the subsequent equations:

$$E_2\ (y = 1, x = 1) = M - wh(1 - g) - (1 - \phi)pL \quad (4)$$

$$E_2\ (y = 0, x = 1) = E_2\ (y = 1, x = 0) = \\ = E_2\ (y = 0, x = 0) = M - pL \quad (5)$$

Conclusively, the payment matrix for the evolutionary game of the agricultural catastrophe insurance market is obtained and depicted in Table 2. This matrix visually represents the outcomes for various strategic interactions between participants, namely farmers and insurance companies, based on their chosen strategies within the defined parameters of the game.

Sequential dynamic analysis of the evolutionary game model in the agricultural catastrophe insurance market

Construction of a replicator dynamic system in the agricultural catastrophe insurance market. In line with Friedman's investigative framework (Friedman 1991), this section explores the construction of a replicator dynamic system. Replicator dynamics are used to model changes in the strategies' populations over time within evolutionary games, offering valuable insights into which strategies might persist, spread, or diminish.

Assuming a bilinear fitness function allows for modelling the fitness (or payoff) that insurance companies derive from different strategic decisions within the agricultural insurance market. This approach facilitates the analysis of the strategy stability and potential shifts in strategic choices based on their fitness outcomes.

The fitness values for insurance companies choosing to provide insurance or not, which are assumed to be independent of the proportion of companies choosing a particular strategy (denoted by x) can be expressed as follows:

$$f^1\ (e^1, s) = y[n\phi(1 - \alpha)w(1 - b) - \\ - \phi(1 - \alpha - \delta)\sum_{i=1}^{n} pL_i\ ] + (1 - y) \times 0 \quad (6)$$

$$f^1\ (e^2, s) = 0 \quad (7)$$

Similarly, to the approach taken for insurance companies, the fitness values of households choosing

Table 2. Payoff matrix of agricultural catastrophic insurance market game

Agricultural insurance company	Farmer: buying insurance	Farmer: not buying insurance
Providing insurance	$n\phi\ (1 - \alpha)w(1 - b) - \phi\ (1 - \alpha - \delta)\sum_{i=1}^{n} pL_i$, $M - wh(1 - g) - (1 - \phi)pL$	0, $M - pL$
Not providing insurance	0, $M - pL$	0, $M - pL$

n – number of agricultural insurance contracts issued by insurance companies; ϕ – coverage level of agricultural catastrophe insurance; w – insurance premium per unit area; b – operating cost of agricultural insurance for insurance companies; α – proportion of insurance policies allocated to reinsurance companies; δ – compensation proportion paid by the reinsurance companies in the event of a loss; p – probability of an agricultural catastrophe occurring; L – potential agricultural disaster loss faced by farmers in case of a catastrophe; M – net agricultural income of farmers; g – government premium subsidy proportion
Source: Author's estimation

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whether to procure insurance can also be systematically formulated. These values represent the perceived benefits or drawbacks of the insurance decision, independently of the proportion y of households opting for insurance, which can be expressed as follows:

$$f^2(e^1, s) = x[M - wh(1 - g) - (1 - \phi)pL] + (1 - x) \times (M - pL) \tag{8}$$

$$f^2(e^2, s) = x(M - pL) + (1 - x) \times (M - pL) \tag{9}$$

Based on the principles proposed by Malthus (1798), Malthus's dynamics suggest that a population's growth rate (or strategy in game theory) is proportional to its current size and relative fitness within a given environment. In the context of evolutionary game theory, this translates to the idea that an individual's expansion rate is directly linked to its comparative fitness—essentially, how well it performs relative to other strategies in the population. The mathematical expression of Malthusian dynamics within an evolutionary game setting is typically modelled by the replicator equation, which describes how the proportion of individuals adopting a given strategy changes over time. This can be formulated as:

$$(\ln x) = \dot{x} / x = f^1(e^1, s) - f^1(x, s) \tag{10}$$

$$f^1(x, s) = xf^1(e^1, s) + (1 - x) f^1(e^2, s) \tag{11}$$

Within the group of insurance companies, the mean fitness of a particular strategy, such as 'providing insurance', is denoted as $f^1(x, s)$. This function represents the average payoff or success of this strategy within the specified market conditions and market parameters, where x is the proportion of insurance companies choosing to provide insurance and represents other variables affecting this decision, such as the market conditions or policy changes.

The replication dynamic equation describes how the proportion of insurance companies that choose to provide insurance changes over time based on the fitness of that strategy compared to the others. It can be mathematically expressed as follows:

$$F(x) = \dot{x} = xy(1 - x)[n\phi(1 - \alpha)w(1 - b) - \phi(1 - \alpha - \delta)\sum_{i=1}^{n} pL_i] \tag{12}$$

Analogous to the dynamics discussed for insurance companies, the evolutionary approach can also be applied to understand the farmers' decision-making process regarding purchasing insurance. This involves modelling the change in the proportion of farmers who purchase insurance based on the strategy's fitness relative to the alternatives.

The replication dynamics governing the farmers' 'purchasing insurance' strategy can be mathematically expressed with a similar formulation to those used for insurance companies. This is represented as:

$$F(y) = \dot{y} = xy(1 - y)[\phi pL - wh(1 - g)] \tag{13}$$

Building on the foundational equations discussed above, namely Equations (12) and (13), which govern the strategies of providing and purchasing insurance, we can derive the comprehensive dynamic system that models the entire agricultural catastrophe insurance market. This system encapsulates the interactive dynamics between insurance companies and farmers, each adapting their strategies based on their payoffs and the overall market conditions.

The dynamic system for replicating strategies within the agricultural catastrophe insurance market integrates the individual dynamics of insurance companies and farmers. This integration can be formally expressed as follows:

$$\begin{cases} F(x) = \dot{x} = xy(1-x) \times \\ \qquad \times \left[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n} pL_i \right] \\ F(y) = \dot{y} = xy(1-y)\left[\phi pL - wh(1-g)\right] \end{cases} \tag{14}$$

Stability analysis of the replicator dynamic system. Building on Equation (14), which establishes the replicated dynamic system, it becomes evident that it comprises a set of interconnected differential equations. These equations describe how the proportions of insurance providers offering insurance and farmers purchasing insurance evolve over time within the market.

Following the principles laid out by Friedman (1991), the Jacobian matrix of this system can be deduced. The Jacobian matrix is crucial for analysing the stability of equilibrium points within the system. It is computed by deriving the first partial derivatives of each equation's right-hand side to each variable involved. For our system, the Jacobian matrix can be represented as stated in Equation (15):

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$$J=\begin{pmatrix} y(1-2x)\left[n\phi(1-\alpha)w(1-b)-\phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i\right] & x(1-x)\left[n\phi(1-\alpha)w(1-b)-\phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i\right] \\ y(1-y)\left[\phi pL-wh(1-g)\right] & x(1-2y)\left[\phi pL-wh(1-g)\right] \end{pmatrix} \quad (15)$$

By using the Jacobian matrix, the determinant of matrix J can be obtained:

$$\det(J) = xy(3xy - x - y)[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i][\phi pL - wh(1-g)] \quad (16)$$

The trace of matrix J is:

$$trJ = y(1-2x)[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i] + x(1-2y)[\phi pL - wh(1-g)] \quad (17)$$

When the values of the replication dynamic equations within the replicator dynamic system [as specified in Equation (14)] are set to zero, the system reveals four fixed points within the square [0,1] × [0,1]. These points represent the states of the system and are defined as follows: e_1^* (0,0), e_2^* (0,1), e_3^* (1,0), e_4^* (1,1).

These points correspond to the four pure strategy equilibria where participants (insurance companies and farmers) either fully adopt or completely reject the insurance strategies, reflecting the outcomes of the individual pairwise antagonistic strategy games within the system. The Lyapunov indirect method is employed to assess these equilibrium points' stability. This approach involves analysing the system's behaviour near these points by substituting their values into the Jacobian matrix derived from Equations (16) and (17). The stability criteria are typically based on the signs of the eigenvalues of the Jacobian matrix evaluated at each equilibrium point: it is stable if all the eigenvalues have negative real parts and is unstable if any of the eigenvalues have a positive real part.

Table 3 details the specifics of the Jacobian matrix and its eigenvalues. It presents the mathematical formulations for deriving these values and the resultant stability conditions for each equilibrium point.

Concurrently, as per Equation (14), the replicator dynamic equation $F(x)$ of the agricultural insurance company group is such that if $y = 0$, $F(x)$ remains at 0, indicating that any level of insurance purchase by the farmer group in the agricultural catastrophe insurance market is a stable state. However, if $y \neq 0$ (where y must be greater than 0), $x^* = 1$ and $x^* = 0$ represent two stable states, with $x^* = 1$ being an ESS. This evolutionary trajectory is delineated in Figure 1.

Table 3. The numerical expressions of the four steady-state equilibrium points of the replicator dynamic system

Steady-state	Jacobian determinant and trace	Numerical expressions of matrices and determinants
e_1^* (0,0)	det(J)	0
	tr(J)	0
e_2^* (0,1)	det(J)	0
	tr(J)	$n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i$
e_3^* (1,0)	det(J)	0
	tr(J)	$\phi pL - wh(1-g)$
e_4^* (1,1)	det(J)	$[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i] \times [\phi pL - wh(1-g)]$
	tr(J)	$-[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n}pL_i + \phi pL - wh(1-g)]$

e – equilibrium; det – determinant; tr – trace; J – Jacobian; n – number of agricultural insurance contracts issued by insurance companies; ϕ – coverage level of agricultural catastrophe insurance; w – insurance premium per unit area; b – operating cost of agricultural insurance for insurance companies; α – proportion of insurance policies allocated to reinsurance companies; δ – compensation proportion paid by the reinsurance companies in the event of a loss; p – probability of an agricultural catastrophe occurring; L – potential agricultural disaster loss faced by farmers in case of a catastrophe; h – operational land of farmers; g – government premium subsidy proportion

Source: Author's estimation

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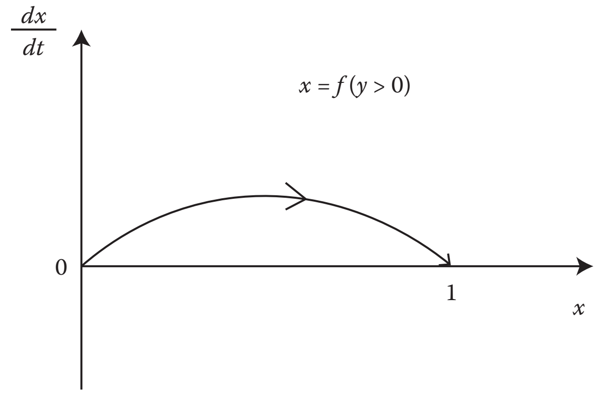

Figure 1. Dynamic replication of the agricultural insurance company

x – proportion of insurance companies choosing a particular strategy; y – proportion of farmers opting to purchase insurance; t – time
Source: Author's estimation based on analysis

In the replicator dynamic equation $F(y)$ of the farmer group, $F(y)$ is always 0 when $x = 0$, indicating that any degree of insurance provision by the insurance company group in the agricultural catastrophe insurance market is a stable state. However, when $x \neq 0$ (where x must be greater than 0), $y^* = 0$ and $y^* = 1$ represent two stable states, with $y = 1$ being an ESS. The specific evolutionary path is depicted in Figure 2.

Utilising an analysis of four stable states and the dynamic equations of single population replication, the agricultural catastrophe insurance market's dynamic replication relationship between two population types is conveyed via dots in a square [0,1] × [0,1], illustrated in Figure 3.

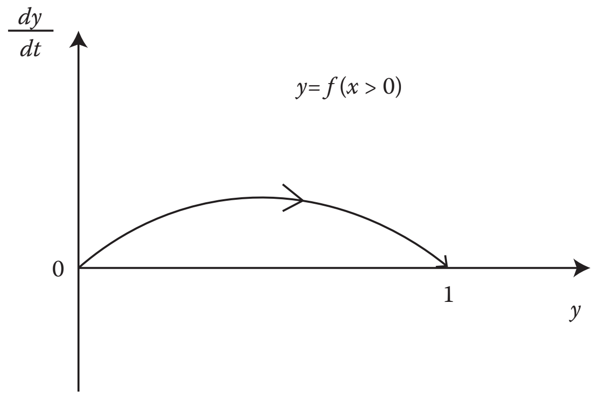

Figure 2. Dynamic replication of the farmer

x – proportion of insurance companies adopting the 'provide insurance' strategy; y – proportion of farmers opting for the 'purchase insurance' strategy; t – time
Source: Author's estimation based on an analysis

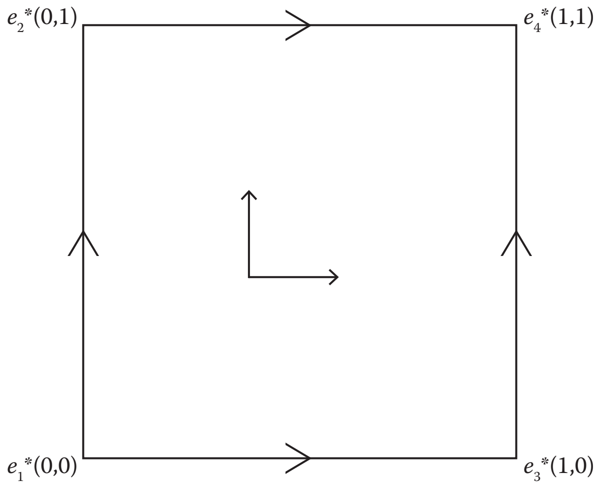

Figure 3. Evolutionary stable strategy dynamic phase diagram

e – equilibrium points
Source: Author's estimation based on analysis

The arrows' direction in the figure depicts the temporal evolution process of the two populations' strategy choices. Ultimately, Table 3 and Figure 3 demonstrate the instability of e_1^* (0,0), e_2^* (0,1), and e_3^* (1,0) points. Upon Equation (18) satisfying certain conditions, e_4^* (1,1) achieves ESS status. At this point, farmers' and insurance companies' equilibrium strategies are respectively to 'purchase insurance' and 'provide insurance' in the agricultural insurance market. This simultaneous strategy ensures the insurance company's break-even operation and positive expected return for farmers in catastrophic events, satisfying Equation (19).

$$\begin{cases} \left[n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n} pL_i \right] \times \\ \quad \times \left[\phi pL - wh(1-g) \right] > 0 \\ -\begin{bmatrix} n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n} pL_i + \\ + \phi pL - wh(1-g) \end{bmatrix} < 0 \end{cases} \tag{18}$$

$$\begin{cases} n\phi(1-\alpha)w(1-b) - \phi(1-\alpha-\delta)\sum_{i=1}^{n} pL_i > 0 \\ \phi pL - wh(1-g) > 0 \end{cases} \tag{19}$$

The study examines the dynamics of the strategy selection in the agricultural insurance market and the influence of various parameters on the equilibrium [Equation (14)]. The analysis based on Table 4 indicates that the insurance premium per unit coverage w and

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Table 4. Analysis of the parameter effects on the strategy selection of game participants

Parameters	Effect on *F(x)*	Effect on *F(y)*
p	/	+
L	–	+
w	+	–
ϕ	–	+
b	–	/
δ	+	/
g	/	+

p – probability of an agricultural catastrophe occurring; *L* – agricultural disaster losses faced by farmers; *w* – insurance premium per unit area; ϕ – coverage level of agricultural catastrophe insurance; *b* – operating cost of agricultural insurance for insurance companies; δ – compensation proportion paid by the reinsurance companies in the event of a loss; *g* – government premium subsidy proportion; / – no effect; + – positive effect; – – negative effect

Source: Author's elaboration

reinsurance compensation per unit δ are positively related to the propensity of insurance companies to adopt insurance strategies *x*. In contrast, farmers' catastrophic losses *L*, insurance coverage level ϕ, and insurance operating costs *b* negatively impact *x*. The probability of catastrophic events *p*, the proportion of the farmers' losses L_i, coverage level ϕ, and premium subsidy rate *g* have a positive relationship with the farmers' insurance purchasing decisions *y*.

RESULTS

MATLAB numerical simulation and case study analysis

We conducted numerical simulations using MATLAB to analyse the decision-making dynamics of farmers and insurance companies within the agricultural catastrophe insurance market, particularly under non-equilibrium conditions. These simulations aimed to model the responses of market participants to varying risk levels and policy changes across different scenarios.

The numerical simulations relied on diverse and authoritative data sources, as stated in Henan Provincial Rural Revitalization Financial Product Manual. (2023). The comprehensive insurance cost rate was determined to be 23% by a policy briefing from the State Council dated July 6, 2021. Additionally, data on agricultural insurance subsidy rates were compiled from central and provincial government financial statements. Information regarding the operational scale of farms, specifically medium-scale operations defined as family farms over 0.033 km^2, cooperatives, and similar organisations, was obtained from the official website of the Henan Provincial Government. This information was meticulously organised into a parameter table in Table 5 to support our case analysis, ensuring that each dataset contributed to a robust simulation environment.

Evolutionary game analysis of fully cost insurance for wheat planting. The Ministry of Finance's 2021 guidelines characterize agricultural catastrophe insurance as a hybrid model, providing a middle ground between fully materialized insurance, which covers only direct physical damages, and total cost insurance, which encompasses all associated costs. Henan Province's 2021 policy, for instance, covers all production costs for wheat, rice, and corn, including material, land, and labour. In 2022, Xinxiang City's finance department allocated 2.54 million USD for subsidies on full-cost insurance, supporting 3 630.95 km^2 for wheat and securing a risk protection amount of 718 million USD.

The study explores the strategic evolutionary process within Xinxiang City's agricultural catastrophe insurance market, utilising various initial strategy configurations for the market participants. Initial values for MATLAB simulations were established across seven pairings from (0.1,0.6) to (0.8,0.5), incorporated into the market's replicator dynamics [Equation (14)] and analysed with a Jacobian matrix [Equation (15)]. The

Table 5. Evolutionary game parameters for each type of agricultural insurance

Parameter	Wheat cost insurance	Rice income insurance	Corn agricultural catastrophe insurance
p	0.30	0.40	0.50
w	10.00	20.00	10.00
ϕ	0.80	0.80	0.65
b	0.23	0.23	0.23
h_{i1}	5.00	10.00	—
h_{i2}	100.00	100.00	200.00
α	0.10	0.10	0.10
δ	0.50	0.50	0.50
g	0.80	0.70	0.60

p – probability of a catastrophic event occurring; *w* – insurance premium per unit area; ϕ – coverage level of agricultural insurance; *b* – operating cost of insurance; h_{i1} – initial operational land area for farmers in lower-risk areas; h_{i2} – initial operational land area for farmers in higher-risk areas; α – proportion of insurance policies allocated to reinsurance companies; δ – reinsurance company's compensation proportion; *g* – government premium subsidy proportion

Source: Henan Provincial Rural Revitalization Financial Product Manual. (2023)

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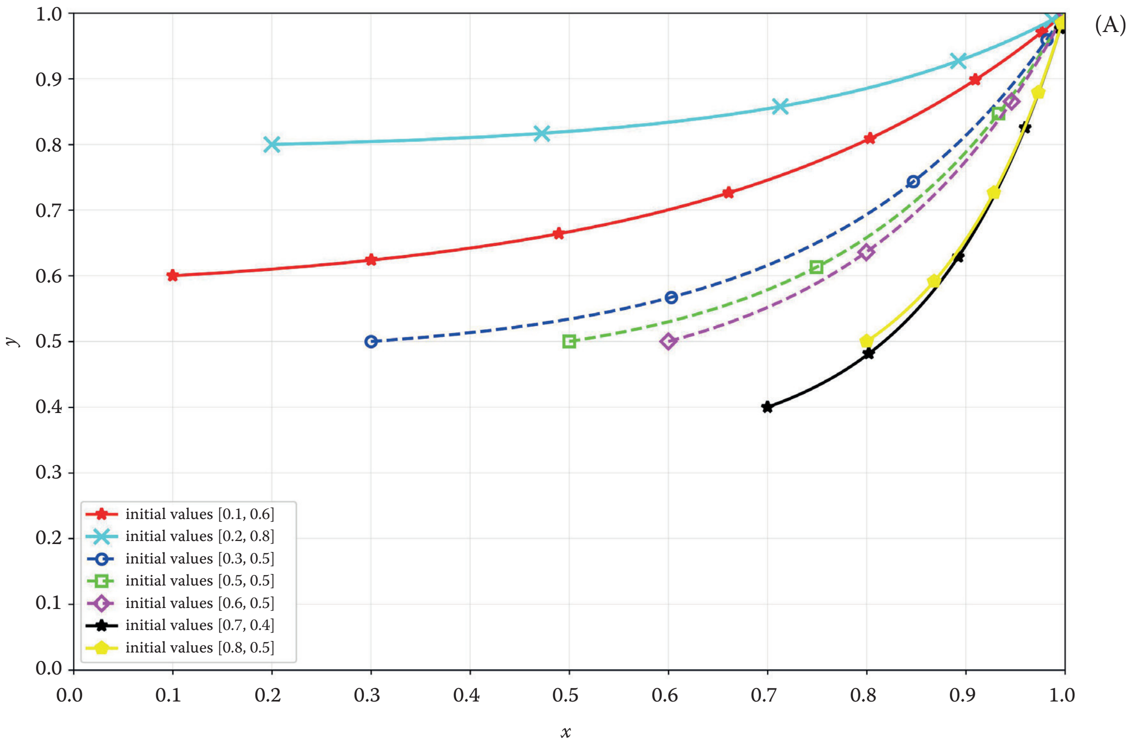
outcomes demonstrate the strategic evolution of small and moderate-scale farmers and insurance companies, as depicted in Figure 4A and 4B.

Figure 4A shows that farmers with lower initial adoption rates of insurance strategies experience slower convergence toward an ESS. Conversely, a higher initial



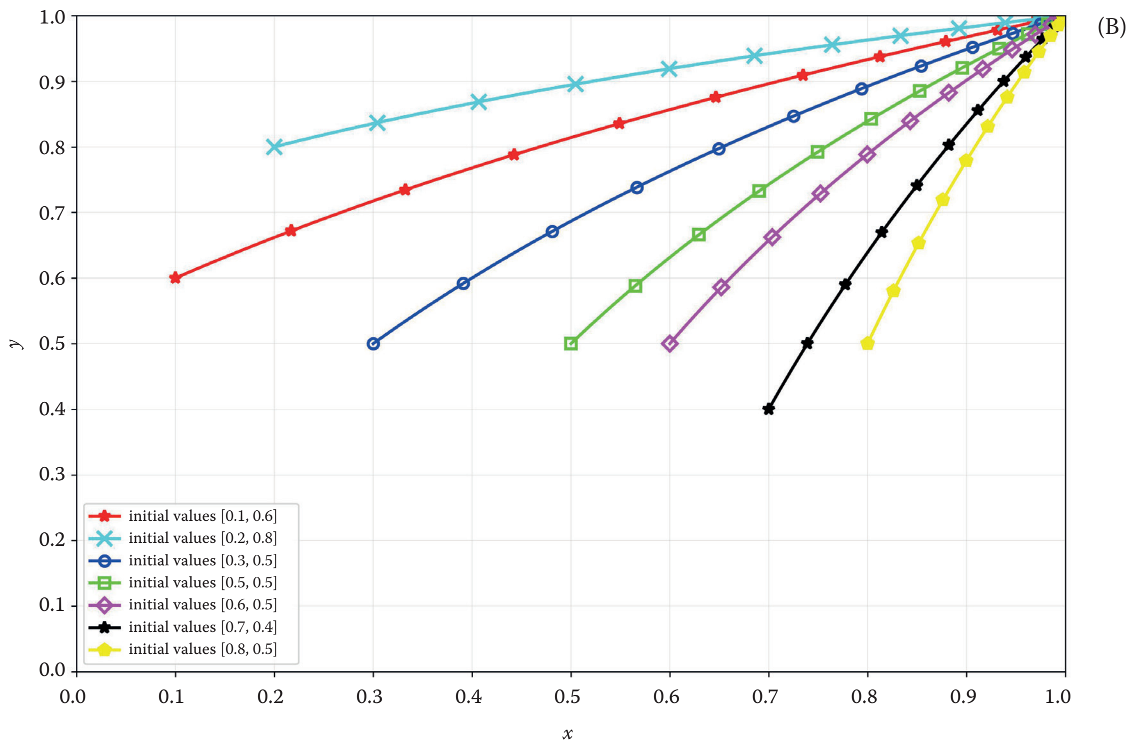


Figure 4. Dynamic evolution diagram of (A) small farmers' dynamic decision-making under full cost insurance; (B) moderate-scale management subject's dynamic decision under full-cost insurance

Source: Author's calculation

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adoption rate markedly accelerates this convergence. The pattern observed among moderate-scale managers mirrors that of farmers, though with a faster transition towards ESS. Figure 4B indicates that moderate-scale managers reach ESS more swiftly, implying that full-cost insurance policies promote smoother coverage adoption.

Additionally, the local government's subsidy policy for agricultural insurance has positively impacted the market. These figures enhance our understanding of market dynamics, demonstrating the varied responses of farm owners of different scales to policy changes and environmental challenges. The analyses of Figures 4A and 4B illustrate how farmers and managers adapt to market shifts under various initial conditions and highlight the pivotal role of government policies in shaping market behaviours. Through this detailed dynamic analysis, we are better equipped to predict the impacts of diverse policy scenarios on farmer behaviour and market stability, providing a theoretical foundation for policymakers and insurers to refine agricultural insurance products and strategies.

Evolutionary game analysis of agricultural catastrophe insurance for corn planting. Henan Province, a leading maize producer in China, typically observes maize planting following the winter wheat harvest, with maize consistently occupying over three-quarters of the autumn grain planting area. However, the severe '7.20' torrential rains in 2021 primarily affected the maize, causing extensive crop damage, with a 10.4% drop in the output and a 12.4% decrease in the maize production. The absence of governmental subsidies for maise insurance since a policy change in 2017 has diminished the farmers' motivation to purchase insurance, leading to minimal risk-sharing for the disaster (Tan et al. 2022).

In 2021, catastrophe insurance for major food crops was introduced on a pilot basis in just 50 agricultural counties in Henan, targeting entities with over 0.033 km^2 of land and covering only direct costs. A study of the strategic decisions of moderate-scale entities in purchasing catastrophe insurance for maize incorporated model parameters from Table 5 into an evolutionary game model, utilising replicator dynamics [Equation (14)] and the Jacobian matrix [Equation (15)], resulting in the temporal strategic evolution diagram depicted in Figure 5.

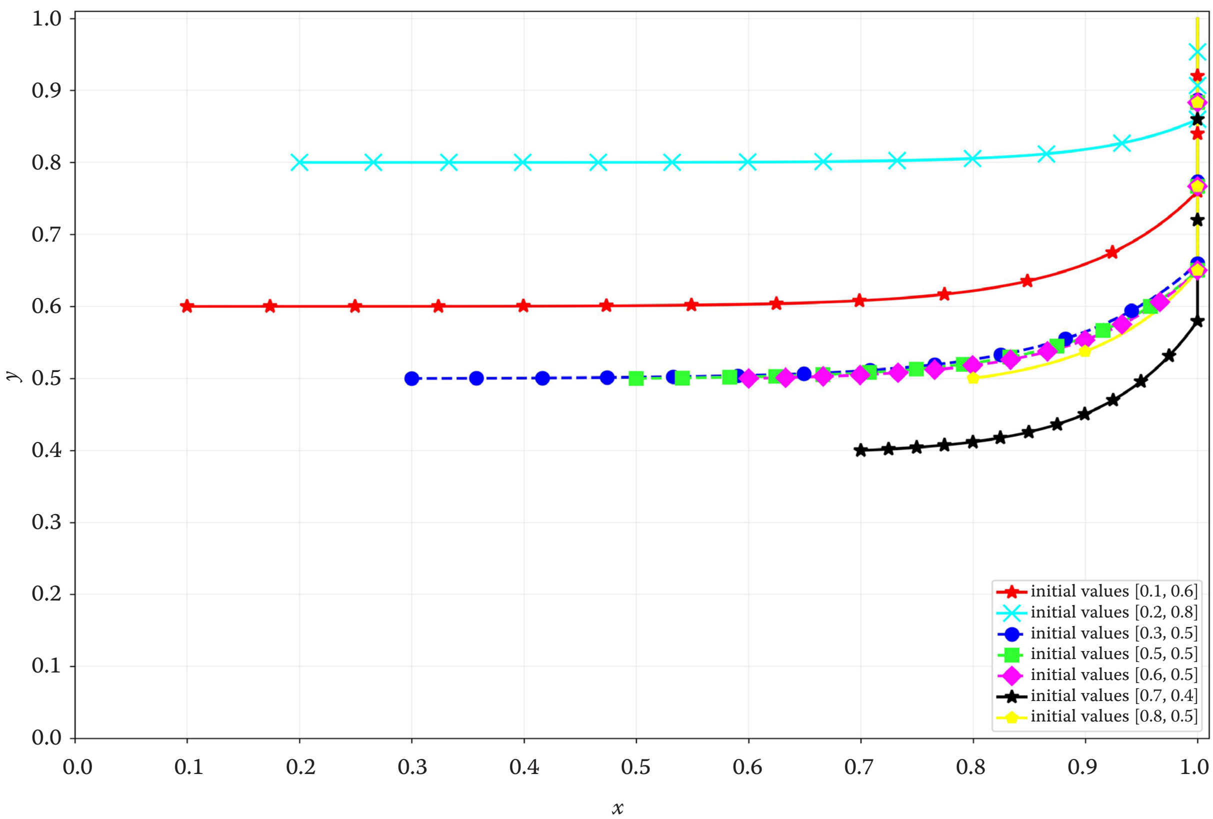

Figure 5. Evolutionary sequence diagram of game subject strategy selection for agricultural catastrophic insurance

Source: Author's calculation

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The figure demonstrates that full-cost insurance, with its comprehensive coverage, is more effective at encouraging scale management entities to purchase insurance than agricultural catastrophe insurance, which offers lower coverage levels. This leads to a slower adoption of strategies within the ESS region for agricultural catastrophic insurance compared to full-cost insurance.

In summary, the analysis of the agricultural insurance strategies reveals that decision-making evolution paths vary between small farmers and larger-scale management entities, with the latter reaching evolutionary equilibrium more quickly as time progresses. Furthermore, given the current subsidies and insurance rates, the market participants are trending towards a stable evolution strategy of providing and purchasing insurance. This suggests that all the available agricultural insurance is moderately effective in mitigating the risk of agricultural catastrophes. Full-cost insurance, by covering all the production costs, achieves a higher coverage level per unit area of crop output, thereby accelerating the formation of ESS for farmers, particularly larger-scale entities, and consequently shortening the time required to reach evolutionary game equilibrium. This underscores the positive impact of the insurance coverage level on the decision-making dynamics in the agricultural catastrophe insurance market.

Evolutionary game analysis of rice planting income insurance. The study transitioned from examining cost-based to income-based agricultural insurance, specifically targeting larger-scale rice producers. The income insurance model compensates farmers when earnings fall below a contractually established benchmark. Using MATLAB, the parameter values for the rice income insurance in Xinyang were established (Table 5), and simulations were conducted using the replicator dynamics system [Equation (14)] and the Jacobian matrix [Equation (15)]. The results in Figure 6 illustrate the strategic evolution of the insurance decisions among rice farmers in Xinyang.

The simulations demonstrate that moderate-scale entities invariably reach the same pure strategy equilibrium in the evolutionary game, denoted as e^*_4 (1,1),

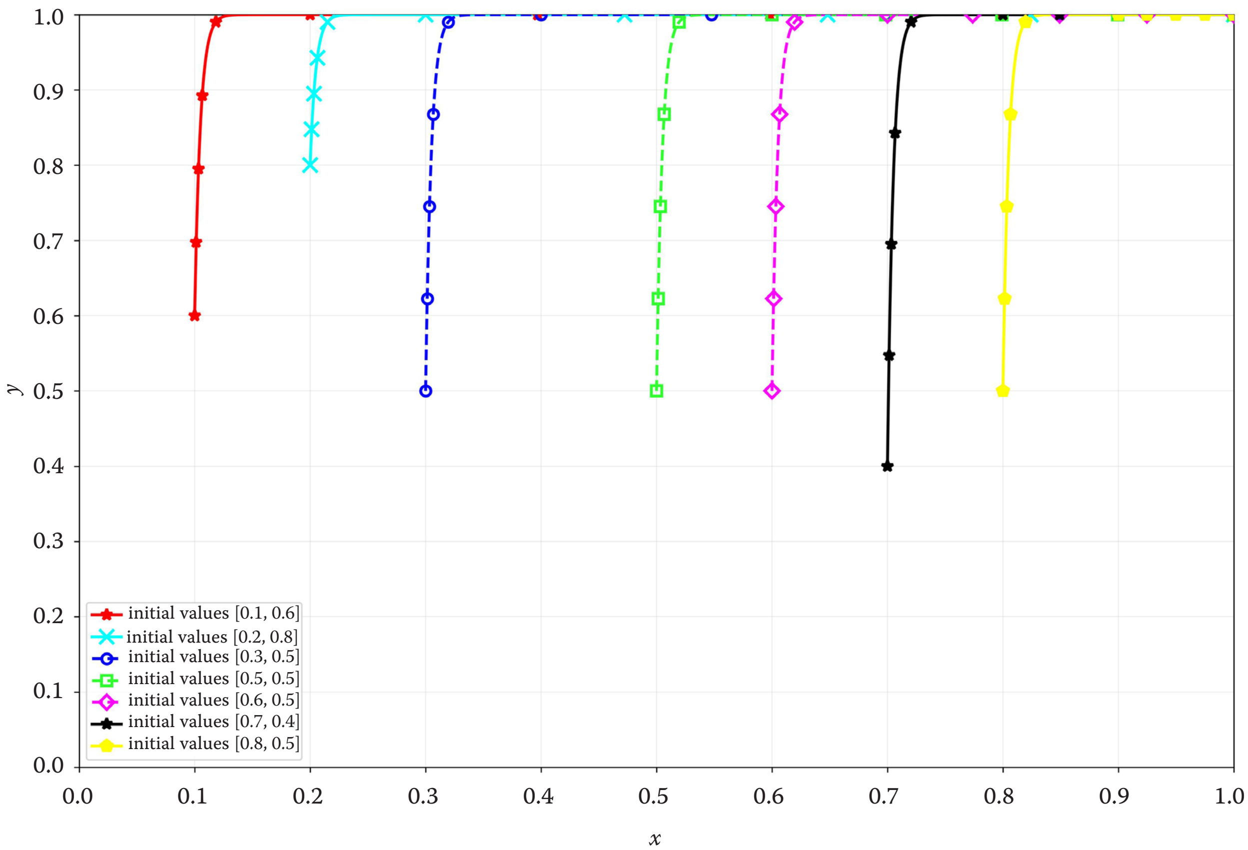

Figure 6. Dynamic evolution of dynamic decision-making of moderately scaled business entities for rice planting income insurance

Source: Author's calculation

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irrespective of their initial strategic position (x, y). This outcome underscores the principle that evolutionary equilibrium is invariant to initial conditions and applies to small and large farm management groups.

Conversely, farmers prefer rice income insurance over wheat cost insurance. The findings from Figure 5 indicate that the strategic choice of moderate-scale managers to purchase rice income insurance converges rapidly to ESS, suggesting a preference for income over cost protection in agricultural insurance.

Numerical simulation analysis of the game participation subject based on the agricultural insurance premium rates and the agricultural land management scale. This study employs numerical simulation to analyse how agricultural insurance premium rates and the land management scale influence participant behaviour in China's agricultural catastrophe insurance market. The study uses real-world market data and references from Table 4 to identify the comprehensive cost ratio of agricultural insurance as a critical performance metric. The lower cost ratio increases the attractiveness of agricultural insurance to the potential purchasers. Additionally, the scale of the land management significantly influences the farmers' decisions to purchase insurance.

We apply Equation (19) to investigate this phenomenon and integrate relevant data on corn planting in Henan Province. The parameter settings are defined as follows: $\{b, h_1\}$= {0.23, 200}, {0.22, 250}, {0.21, 300}, {0.20, 350}. Through numerical simulations, we generate results concerning the participation of the game subjects relative to the agricultural insurance rates and the scale of agricultural land operation, as illustrated in Figure 7.

The trends depicted in Figure 7 demonstrate that reducing the comprehensive insurance cost ratio and increasing the scale of land management accelerate the adoption of the evolved strategic behaviours by the insurance market participants. These trends suggest that both reducing the insurance costs and adopting

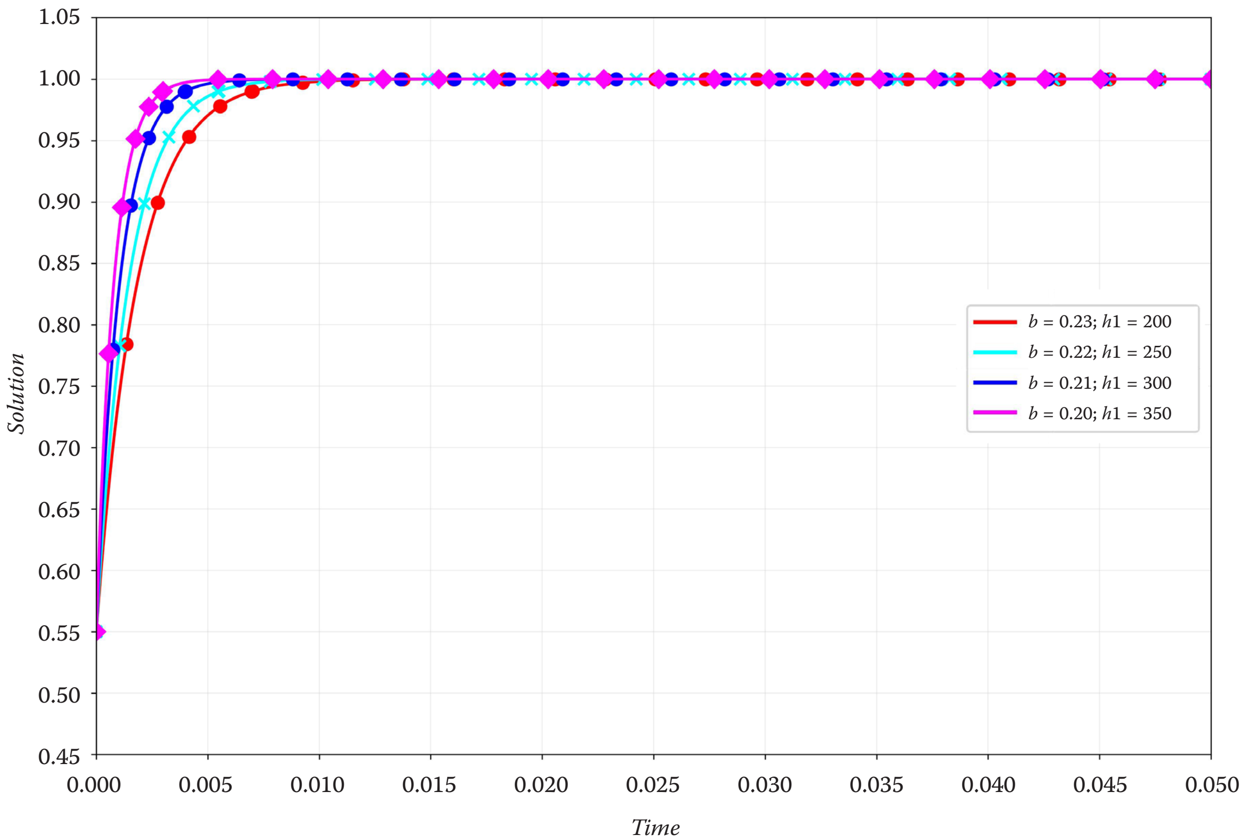

Figure 7. Influence of agricultural insurance comprehensive expense ratio and agricultural land management scale on the dynamic evolution of game participants

b – comprehensive expense ratio of agricultural insurance; h – agricultural land management scale
Source: Author's calculation

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moderate scales of land management positively influence the evolutionary dynamic of decision-making among the market participants.

DISCUSSION

This study deepens our understanding of the decision-making dynamics within the agricultural catastrophe insurance market, mainly focusing on Henan Province, China. The research findings advance beyond previous studies (Gao et al. 2021; Tan et al. 2022), providing new insights into the behaviours of farmers and insurers under various conditions. The study corroborates previous findings that the farm size significantly impacts the rate at which agricultural entities reach evolutionary equilibrium, supporting Schurle's (1996) research that larger farms benefit from lower crop insurance premiums due to business-risk advantages. Similarly, Ehiakpor et al. (2021) found that the farm size influences the adoption of sustainable practices among Ghanaian smallholders. However, contrasting the findings by Agbenyo et al. (2022), which show regional variations and the overriding impact of the financial access on the insurance adoption, highlighting the complex interplay between the farm size, financial accessibility, and local conditions in determining the insurance uptake. Furthermore, the study demonstrates that full-cost insurance significantly promotes the adoption of ESS among farmers, highlighting the critical role of comprehensive coverage in fostering stable agricultural practices (Gao et al. 2021). This aligns with the findings by Dick and Wang (2010), who note the importance of robust insurance frameworks in ensuring financial stability and facilitating access to credit in agriculture. On the contrary, Burns and Prager (2018) suggest that while insurance enhances stability, it does not necessarily drive farm expansion. Supporting this, Kajwang (2022) argues that insurance mitigates operational risks and fosters stable environments, which is crucial for sustainable agricultural growth. Collectively, these insights underscore the pivotal role of comprehensive insurance in sustaining agricultural operations and enhancing resilience.

Additionally, the study reveals medium-scale managers' preferences for income-focused agricultural insurance, aligning with findings by Pérez-Blanco et al. (2016), who reported a higher willingness to pay for such insurance than existing premiums suggest. This indicates an untapped market potential for tailored insurance products. Additionally, Tan et al. (2022) found that agricultural insurance positively impacts the income and fosters technological advancement in areas with dense insurance coverage, underscoring the broader benefits of aligning insurance products with the farmers' specific preferences and needs, especially those focused on income security.

Lastly, the research indicates that lowering the comprehensive insurance expense ratio and adopting moderate-scale land management strategies can positively affect strategic decision-making within the insurance market (Tan et al. 2022). These findings have significant policy implications, suggesting that making agricultural insurance more affordable and tailoring it to various scales of farm operations can enhance the insurance adoption more broadly.

CONCLUSION

This study aims to innovatively address the limitations of the current research on agricultural catastrophe insurance in China, which includes an underdeveloped market, scarce empirical evidence, and incomplete game models. This study employs evolutionary game theory to investigate the market's equilibrium strategy and long-term equilibrium, construct a dynamic model that accurately represents individual decision-making, and incorporate government policies and reinsurance as implicit participants in the game model. By focusing on promoting agricultural insurance for China's three significant grains, the authors utilise MATLAB simulation analysis to examine the decision-making choices and non-equilibrium issues f of the farmers and insurance companies in the agricultural catastrophe insurance market. The objective is to identify the factors affecting the market equilibrium and elucidate the sequential evolution process of decision-making among agricultural insurance companies and farmers. Ultimately, this research offers a theoretical framework for designing agricultural insurance and reinsurance products.

The decision-making process in the agricultural catastrophe insurance market is characterised as an evolutionary game involving continuous learning and strategy improvement, exhibiting characteristics similar to those of biological population evolution. Applying evolutionary game theory, we analyse the evolutionary process of decision-making and the factors influencing the market equilibrium in the agricultural catastrophe insurance market, leading to the following conclusions:

Firstly, a pure strategy equilibrium exists in the Chinese agricultural insurance market, characterised by both parties adopting the strategy of e^*_4 (1,1), which involves

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both providing insurance and purchasing insurance. The agricultural insurance premium per unit coverage and reinsurance compensation per unit insurance positively correlate with the proportion of insurance companies adopting the insurance strategy. Conversely, factors such as significant losses of farmers, the probability of agricultural catastrophes, the underwriting or coverage level of agricultural catastrophe insurance, and the proportion of agricultural catastrophe insurance premium subsidies, are positively correlated with the proportion of farmers that adopt the strategy of purchasing insurance. Secondly, compared to cost insurance, farmers – particularly those with moderately sized farms – are more responsive to income insurance and can rapidly achieve the evolutionary equilibrium strategy. Lastly, by reducing the comprehensive cost rate of agricultural insurance and suitably increasing the area of the agricultural land operation, the agricultural catastrophe insurance market can achieve effective equilibrium, thereby exerting positive effects.

Policy recommendations. First, agricultural catastrophe risk zoning and pricing standards: Implement risk zoning and establish pricing standards for agricultural insurance premiums, considering the country's vast geographical differences and varying levels of agricultural risk, natural conditions, and land rent. Advanced analytics, big data, and cloud computing should be utilised to devise region-specific insurance models and policies, which would help mitigate any adverse selection and moral hazard issues through scientifically based pricing standards.

Second, performance orientation of subsidy funds: There is a need to enhance the performance orientation of agricultural insurance premium subsidy funds and direct the collective efforts of agricultural insurance companies toward improving the quality and efficiency of services. Currently, the claims settlement process in China's agricultural catastrophe insurance market lacks standardisation, which is evident in 'large losses with small compensation' and 'small losses with large compensation'. The primary drivers of these concerns include the underdevelopment of the agricultural catastrophe insurance market and its associated regulatory systems, coupled with inadequate performance orientation. Consequently, at all levels of government, institutional arrangements should be established to stipulate scientifically and rationally sound performance appraisal targets for premium subsidy funds. Additionally, enhanced supervision penalties and rewards for agricultural disaster insurance should be implemented to encourage insurance companies to expand the coverage of agricultural catastrophe insurance, improve the quality and efficiency of claims processing, stimulate the farmers' demand for participation, and promote the balanced development of the market.

Third, advancing the enterprise-based operation of land transfer and scale-based agricultural planting management is imperative to foster a balanced development of the agricultural catastrophe insurance market. Promoting scale-based agricultural management attains equilibrium among moderately scaled entities, offering an effective strategy for farmers to expand their operating scales appropriately. Through this approach, economies of scale can be harnessed to transform the agricultural catastrophe insurance market from an imbalanced state to one of equilibrium.

The contractual management of land production has significantly enhanced the farmers' productivity, though at the expense of small-scale and decentralised agricultural planting management. Despite the issuance of the 'Opinions on Guiding the Orderly Transfer of Rural Land Management Rights and Developing Moderately Scaled Agricultural Management' by the General Office of the Communist Party of China Central Committee and the General Office of the State Council in 2014, aimed at promoting scale-based rural land management, the goal's full nationwide realisation remains unachieved. Given this context, promoting enterprise-based land transfer operations and adopting scale-based operations in the planting industry is necessary to foster the balanced development of the agricultural insurance market.

Fourth, it is crucial to intensify the publicity of agricultural insurance policies to enhance the farmers' participation in agricultural insurance. Although agricultural insurance remains the most influential risk diversification tool for most farmers, the lack of understanding about agricultural insurance, attributed to the low cultural literacy levels among farmers in China, has hindered the balanced development of the agricultural catastrophe insurance market. Consequently, it is vital to strategically utilise both traditional media and emerging self-media channels to promote agricultural insurance's critical role to farmers actively. This strategy will increase awareness of the timely reporting of agricultural disasters among farmers and boost their enthusiasm for insurance coverage, thereby enhancing the scale effect of agricultural insurance.

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