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Cultural rice fields in the wave of climate change: a multilateral evolutionary game framework for adaptive management of agricultural heritage systems

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Abstract

Agricultural Heritage Systems (AHS) are pivotal in preserving rich agricultural production experience and traditional culture, as well as in maintaining biodiversity and promoting sustainable development in agriculture and rural economies. However, climate change poses significant threats to these systems, such as ecological degradation, biodiversity loss, and shifts in agricultural production patterns. This study, grounded in theories of information asymmetry and bounded rationality, constructs evolutionary game models for adaptive management of AHS under market mechanisms and government guidance. By employing stability analysis and numerical simulation with Delay Differential Equations (DDE) that consider historical delays, and through sensitivity analysis, this research delves into the strategic evolutionary outcomes of stakeholders under various scenarios. It aims to provide theoretical insights and policy recommendations for the dynamic protection and adaptive management of AHS in the face of climate change. The findings indicate that the public goods nature of AHS, alongside externalities and information asymmetry, leads to market failure. Sole reliance on autonomous actions by farmers and meteorological departments is insufficient for optimal resource allocation and effective protection. Government intervention, through regulatory and incentive measures, can effectively mitigate market failures and steer adaptive management of AHS towards efficiency and sustainability. Moreover, the study identifies key factors for adaptive management, such as enhancing stakeholders' initial willingness to participate, reducing the costs of adapting to climate change, optimizing cooperative benefit distribution mechanisms, and increasing the profitability of resource cooperation. Sensitivity analysis of government subsidies and penalty mechanisms further reveals the complex and critical role these policy tools play in fostering stakeholder engagement. Based on these findings, the study recommends enhancing initial participation willingness, controlling transformation costs to alleviate economic burdens, optimizing benefit distribution mechanisms to boost cooperative resource profitability, and establishing dynamic subsidy and penalty mechanisms for optimal resource allocation. The theoretical and practical contributions of this research lie in applying theories of information asymmetry and bounded rationality to the adaptive management of AHS under climate change, enriching the theoretical framework in this field, and providing scientific decision-making support for policymakers. By demonstrating an effective path for AHS protection through combined government and market mechanisms in the context of global climate change, this research holds significant theoretical and practical implications for enhancing the efficiency of adaptive management of AHS, protecting, and inheriting valuable agricultural cultural heritage.

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Introduction

In the context of global warming, rising sea levels, and increasing frequency of extreme weather events, climate change has become a key factor affecting socio-economic growth, societal welfare, and the sustainable development of ecological environments. Thus, at the 28th United Nations Climate Change Conference (COP28) held in the United Arab Emirates in November 2023, the international community was challenged to adopt bold and effective measures to address the climate crisis. Agriculture, being one of the industries most sensitive to climate change, exhibits a complex interplay with climatic conditions. Climate change, by increasing the frequency and intensity of extreme weather events such as droughts and floods, directly impacts the growth cycles, yield, and quality of crops, thereby reducing the production efficiency and income of farmers. Consequently, Agricultural Heritage Systems (AHS) are particularly vulnerable to climate impacts [1]. In response, the Food and Agriculture Organization (FAO) launched a Global Important Agricultural Heritage Systems (GIAHS) protection project in 2002, with support from the Global Environment Facility (GEF). The project aims to establish protection systems for AHS, landscapes, biodiversity, and culture, to raise awareness and knowledge among farmers about the conservation of traditional agricultural culture, and to utilize this knowledge to face developmental challenges, thereby promoting sustainable agricultural development. Specifically, the project seeks to dynamically protect and adaptively manage traditional agricultural systems that meet certain criteria on a global scale. However, the dynamic protection and adaptive management of AHS is a complex systemic project. Its core lies in balancing traditional and modern farming techniques to ensure that AHS can continue to adapt and develop in the face of external pressures such as climate change. Active participation from relevant stakeholders is crucial for the conservation of cultural heritage [2]. The process of dynamic protection and adaptive management of AHS is a typical evolutionary game, where the behavior and decisions of participating entities are driven not only by their own interests but also by the actions of others and environmental changes. Therefore, how to effectively utilize evolutionary game theory to clarify the behavioral strategy choices and evolutionary processes of stakeholders involved in AHS protection under climate change, and to promote dynamic protection and adaptive management of AHS on a fair and cooperative basis, remains a pressing issue to be addressed.

In the context of globalization and climate change, the protection of Agricultural Heritage Systems (AHS) is emerging as a distinct and significant branch of research within the social sciences. Current studies on the protection of AHS provide a solid theoretical foundation for this paper. The concept of agricultural heritage, initially defined by Prentice [3], encompasses a range of agricultural activities including farming, dairying, agricultural museums, vineyards, fishing, and mining. In 2002, the Food and Agriculture Organization (FAO) defined AHS as unique land-use systems and agricultural landscapes formed through long-term co-evolution and dynamic adaptation with their rural environments. These systems and landscapes, characterized by rich biodiversity, meet local socio-economic and cultural development needs and foster regional sustainable development. Since 2005, the FAO has identified 67 Globally Important Agricultural Heritage Systems (GIAHS) across 22 countries, with China, Japan, and South Korea establishing their own AHS protection systems [4–7]. AHS have become a focal point of research, and their protection is recognized as a crucial pathway to promoting sustainable agricultural development. These systems, with their longstanding land-use patterns and production methods, are highly adapted to local natural environments, forming unique ecosystem services. For instance, the rice-fish ecosystem in Qingtian, China, has developed a distinctive carp population through long-standing practices of rice field fish farming, enhancing genetic biodiversity. The interaction between fish and rice, where fish excrements serve as fertilizer for rice, improves soil fertility, reduces pests and diseases, thereby promoting rice growth and effectively reducing greenhouse gas emissions [8–12]. The Hani terraced fields in China rely more on irrigation systems for water regulation to enhance soil productivity and possess a certain resilience against extreme droughts [13–16]. However, despite the numerous benefits of AHS, current climate change poses significant risks to their protection, and most countries lack a comprehensive dynamic protection mechanism and adaptive management framework for AHS under the backdrop of climate change. This deficiency makes many valuable AHS vulnerable to extinction due to extreme weather events [17–21].

To summarize, extensive research has been conducted on AHS, laying a solid foundation for subsequent studies in this field. However, the process of protecting AHS under the context of climate change involves not only the AHS themselves but also the complex interplay of interests among farmers, climate services department, and governments. To date, no study has explored an adaptive management framework for the protection of AHS under climate change using evolutionary game theory to coordinate the complex decision-making behaviors among stakeholders. In light of this, our paper constructs an evolutionary game framework for the dynamic protection and adaptive management of AHS under climate change. By conducting an in-depth analysis of the complex decision-making interactions among stakeholders involved in AHS protection, this paper explores how adaptive management mechanisms can be designed under different policy and market conditions to incentivize stakeholders to protect AHS while ensuring their own interests.This paper employs evolutionary game theory to analyze the interactions and strategic evolution among farmers, climate services department, and governments in the adaptive management process of AHS under climate change. Unlike traditional evolutionary game approaches that use Ordinary Differential Equations (ODE) for numerical simulation, this paper introduces Delay Differential Equations (DDE) to simulate decision-making, considering the influence of previous decisions. This approach more accurately models real-world decision-making processes, allowing for a more precise exploration of the dynamics within this game system. Consequently, this facilitates the design of policy tools that guide stakeholders towards positive interactions, collectively enhancing the protection of AHS and promoting sustainable agricultural development.

Materials and methods

Evolutionary game model of "farmer vs. CSD" under market mechanisms

Fundamental assumptions of the model

In this section, we will provide a brief overview of evolutionary game theory and delay differential equations to enhance readers' understanding of these concepts and make them more accessible to a broader audience.

Evolutionary Game Theory: Evolutionary game theory is a mathematical framework that studies how strategic behaviors evolve within a population over time. It integrates game theory and dynamic systems theory to analyze how individuals or groups adjust their behaviors in response to various choices and environmental conditions. In the context of agricultural heritage systems, evolutionary game theory aids in understanding the decision-making processes and strategy selections of different stakeholders, as well as how these choices influence the evolution of the entire system.

Delay Differential Equations: Delay differential equations are a specialized class of differential equations where the current state of the system is influenced not only by present variables but also by past states. These equations are particularly useful for describing systems with time-delay effects. In agricultural systems, policy implementation, environmental changes, and other factors can result in delayed behaviors or outcomes, making delay differential equations highly relevant in such studies.

By combining evolutionary game theory and delay differential equations, we can more accurately simulate and predict the complex dynamics of agricultural heritage systems. This approach allows us to consider the evolution of decision-making behaviors and the time-delay effects within the system, providing an effective method for analyzing and guiding system behavior over long time scales.

This paper establishes a two-party evolutionary game model between farmers and Climate Service Departments (CSD) under market mechanisms to explore whether the adaptive management of Agricultural Heritage Systems (AHS) necessitates government participation.

Assumption 1: In the evolutionary game model of adaptive management for Agricultural Heritage Systems (AHS) under market mechanisms, two main types of participants are involved: farmers and Climate Service Departments (CSD).Farmers may choose to actively respond to climate change by adopting diverse planting strategies and effective irrigation management plans, or they may opt not to take any measures. Concurrently, CSD can decide whether to enhance the precision and diversity of their meteorological services.CSD play a critical role in providing climate-related scientific data, information, and solutions. Their core functions include monitoring and data collection, climate prediction and early warning, research and development, information dissemination, and policy advising. The structure and responsibilities of CSD may vary by country due to differing national needs, resources, and policy environments. In some countries, dedicated CSD may not exist, and their functions may be dispersed across various governmental departments, such as meteorological bureaus, environmental agencies, and disaster management organizations. Regardless of their form, the aim of CSD is to facilitate better adaptation and response to climate change. When both farmers and CSD actively engage in addressing climate change, they can collaborate to integrate resources, providing precise climate forecasting services tailored to AHS regions. Linking climate service

Table 1 Parameters of the Evolutionary Game Model under Market Mechanisms

Variables	Meaning of the variables	Notes
X	Willingness of Farmer to participate	$0 \le X \le 1$
Y	Willingness of CSD to participate	$0 \le Y \le 1$
R^F	The intrinsic income of a farmer	–
R^C	The intrinsic income of CSD	–
H^F	Resources expended by farmers to address climate change	–
H^C	Resources for CSD to improve precise weather services	–
$W(\varphi^F,t)$	The value coefficient of Farmer resources	$0 < W(\varphi^F,t) < 1$
$W(\varphi^C,t)$	The value coefficient of CSD resources	$0 < W(\varphi^C,t) < 1$
$C(\varphi^F,t)$	The intrinsic costs of a Farmer	–
$C(\varphi^C,t)$	The intrinsic costs of a CSD	–
$L(\varphi^F,t)$	The risk coefficient of Farmer facing climate disasters	$1 < L(\varphi^F,t)$
$L(\varphi^C,t)$	The risk coefficient of CSD facing climate disasters	$1 < L(\varphi^C,t)$
α	Benefit distributing coefficient	$0 < \alpha < 1$
β	The ability to convert resources into profit	$0 < \beta < 1$

products with AHS-related tourism projects—such as certifying climate-themed products and recommending optimal visiting periods—can significantly enhance the visitor experience, thereby generating higher economic returns. This collaborative model not only contributes to the sustainable development of AHS but also fosters local economic prosperity. During the evolutionary game process, it is assumed that all participants possess bounded rationality and face information asymmetry. Through multiple rounds of interaction, they ultimately discover the optimal strategies for their respective roles.

Assumption 2: Farmers and CSD can choose whether to actively participate in the adaptive management of AHS under climate change, with their willingness to engage in cooperative behavior denoted as X and Y, respectively, and their reluctance to participate as 1-X and 1-Y. Based on this assumption, specific meteorological services primarily involve providing short-term, medium-term, and long-term weather forecasts, as well as issuing warnings for extreme weather events. For example, the National Oceanic and Atmospheric Administration (NOAA) in the United States offers detailed daily weather forecasts and disaster warnings [22]. By utilizing these services, climate service departments assist farmers in adjusting their planting strategies, thereby better adapting to climate change and protecting agricultural heritage.

Assumption 3: Farmers and CSD have inherent incomes defined as R^F and R^C, respectively. Both parties also incur fixed costs, denoted as $C(\phi^F,t)$for farmers and $C(\phi^C,t)$for CSD. The resources provided by farmers and CSD to combat climate change are defined as H^F and H^C, respectively. The resources expended by farmers and CSD in addressing climate change are represented by $W(\phi^F,t)$ and $W(\phi^C,t)$. If farmers choose not to adapt to climate change and CSD does not provide precise meteorological services, farmers will face a certain risk of natural disasters, with the risk coefficient denoted as $L(\phi^F,t)$. Similarly, if CSD fails to provide precise meteorological services during significant weather disasters, its social reputation and market share might suffer, with the loss coefficient represented as $L(\phi^C,t)$.

Assumption 4: Collaboration between farmers and CSD generates certain benefits. The paper defines α as the benefit distribution coefficient for farmers after collaboration, with the corresponding benefit distribution coefficient for CSD being 1-α. The coefficient β

Table 2 Payoff Matrix for Evolutionary Game under Market Mechanism

		CSD	
		y	1-y
Farmer	x	$R^F + \alpha\beta(H^F + K^C) - W(\varphi^F,t)H^F - C(\varphi^F,t)$ $R^C + (1-\alpha)\beta(H^F + K^C) - W(\varphi^C,t)H^C - C(\varphi^C,t)$	$R^F - W(\varphi^F,t)H^F - C(\varphi^F,t)$ $R^C - W(\varphi^C,t)H^C - C(\varphi^C,t)$
	1-x	$R^F - C(\varphi^F,t)$ $R^C - C(\varphi^C,t)$	$R^F - L(\varphi^F,t)C(\varphi^F,t)$ $R^C - L(\varphi^C,t)C(\varphi^C,t)$

represents the ability of both parties to convert collaborative resources into actual value.

Based on these assumptions, the paper constructs the parameters and payoff matrix for the two-party evolutionary game model of adaptive management for AHS under climate change, as shown in Tables 1 and 2.

Solution of evolutionarily stable strategies under market mechanisms

This paper sets to determine the expected benefits of farmers choosing to actively participate in the protection of Agricultural Heritage Systems (AHS) under the context of climate change as F_{x11}, the expected benefits for not actively participating as F_{x12}, and the average expected benefits as $\overline{F_x}$,, as delineated in Eq. (1):

$$\begin{cases} Fx11 = y\Big(R^F + \alpha\beta(H^F + H^C) - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) + \\ (1-y)\Big(R^F - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) \\ Fx12 = y\Big(R^F - C(\varphi^F, t)\Big) + (1-y)\Big(R^F - L(\varphi^F, t)C(\varphi^F, t)\Big) \\ \overline{Fx} = xFx11 + (1-x)Fx12 \end{cases} \tag{1}$$

The strategy selection dynamics of farmers in the adaptive management evolutionary game of AHS under climate change are represented by Eq. (2):

$$F(\mathrm{x}) = \frac{dx}{dt} = x(Fx11 - \overline{Fx}) = x(1-x)\Big(y\alpha\beta(H^F + H^C) + yC(\varphi^F, t)(1 - L(\varphi^F, t)) - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) \tag{2}$$

Similarly, the expected benefits for Climate Service Departments (CSD) actively participating in the protection of AHS under the context of climate change are denoted as F_{y11}, for not actively participating as F_{y12}, and the average expected benefits as $\overline{F_y}$., as specified in Eq. (3):

$$\begin{cases} Fy11 = x\Big(R^C + (1-\alpha)\beta(H^F + H^C) \\ -W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) + \\ (1-x)\Big(R^C - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) \\ Fy12 = x\Big(R^C - C(\varphi^C, t)\Big) + (1-x)\Big(R^C - L(\varphi^C, t)C(\varphi^C, t)\Big) \\ \overline{Fy} = yFy11 + (1-y)Fy12 \end{cases} \tag{3}$$

The strategy selection dynamics of CSD in the adaptive management evolutionary game of AHS under climate change are illustrated by Eq. (4):

$$F(\mathrm{y}) = \frac{dy}{dt} = y(Fy11 - \overline{Fy}) = y(1-y)\Big(x(1-\alpha)\beta(H^F + H^C) + xC(\varphi^C, t)(1 - L(\varphi^C, t)) - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) \tag{4}$$

By combining Eqs. (2) and (4), we derive the replicator dynamics equation for the two-party evolutionary game system of adaptive management in AHS under climate change. Through stability analysis of the Jacobian matrix, we obtain Jacobian J_1 as shown in Eq. (5):

$$\begin{aligned} &J1 = \begin{bmatrix} J11, J12 \\ J21, J22 \end{bmatrix} \\ &NOTE: \\ &J11 = (1-2x)\Big(y\alpha\beta(H^F + H^C) + yC(\varphi^F, t)(1 - L(\varphi^F, t)) - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) \\ &J12 = x(1-x)\Big(\alpha\beta(H^F + H^C) + C(\varphi^F, t)(1 - L(\varphi^F, t))\Big) \\ &J21 = y(1-y)\Big((1-\alpha)\beta(H^F + H^C) + C(\varphi^C, t)(1 - L(\varphi^C, t)\Big) \\ &J22 = (1-2y)\Big(x(1-\alpha)\beta(H^F + H^C) + xC(\varphi^C, t)(1 - L(\varphi^C, t)) - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) \end{aligned} \tag{5}$$

Table 3 Parameters for the Two-Party Evolutionary Game Model under Market Mechanisms

Parameter	H^F	H^C	$W(\varphi^F,t)$	$W(\varphi^C,t)$	$C(\varphi^F,t)$	$C(\varphi^C,t)$	$L(\varphi^F,t)$	$L(\varphi^C,t)$	α	β
	3	1	0.65	0.7	5	4	1.2	1.1	0.75	0.5

Based on the parameters outlined in Tables 1, 3 presents the assigned values for the parameters of the two-party evolutionary game model under market mechanisms. Given the absence of successful case studies on adaptive management for the protection of AHS under climate change, this paper primarily relies on numerical simulations to demonstrate how changes in certain parameters affect the stability of the evolutionary game system. For instance, it compares the impact of market mechanisms versus government involvement on the system's stability and illustrates the phase diagrams as shown in Fig. 1. On the left side of Fig. 1, the Ordinary Differential Equation (ODE) algorithm is used without considering historical decisions, while on the right side, the Delay Differential Equation (DDE) algorithm accounts for participants' historical decisions, with a lag period of 1 year.

Observing Fig. 1, it is evident that under the given parameters, regardless of whether historical decisions are considered, the evolutionary game system for the protection of AHS under climate change cannot stably converge to the optimal equilibrium point E4 (1,1). This indicates that, in the absence of external incentives, farmers and CSD lack the intrinsic motivation to participate in the adaptive management of AHS. From the perspective of individual rational behavior, when making decisions, farmers and CSD tend to prioritize immediate economic benefits and cost–benefit ratios, overlooking the long-term collective benefits. However, the protection of AHS inherently possesses the characteristics of a public good, being non-excludable and non-competitive, which inevitably leads to the "free-rider" problem. Therefore, the introduction of external incentives by the government is crucial, as government intervention can alter the benefit structure of stakeholders, encouraging them to adopt more proactive approaches in adapting to climate change and protecting AHS within the dynamic evolutionary game system.

A tripartite evolutionary game model under government guidance involving farmer, CSD, and the government

Basic model assumptions

In this paper, we introduce a tripartite evolutionary game model for the adaptive management of Agricultural Heritage Systems (AHS) under the guidance of government intervention, incorporating Hypothesis 5.

Assumption 5: posits that in scenarios where farmers actively implement measures to combat climate change and Climate Service Departments (CSD) provide accurate, high-quality meteorological services, the government will grant corresponding subsidies to both parties, denoted as $M(H^F)$for farmers and $M(H^C)$ for CSD. Conversely, should farmers and CSD fail to actively engage in combating climate change and protecting AHS, the government will impose fines, with penalty coefficients$P(H^F)$for farmers and $P(H^C)$ for CSD. The benefits generated by the government upon successfully establishing an adaptive management mechanism for AHS under climate change are represented as R^G, while the inherent costs incurred during the participation in AHS adaptive management are denoted as C^G. If the government opts not to participate in AHS adaptive management, it incurs neither benefits nor costs. Throughout the tripartite evolutionary game process, farmers, CSD, and the government exhibit bounded rationality and asymmetrical information, ultimately identifying optimal strategies through repeated games.

Based on these assumptions, this paper reconstructs the parameters and payoff matrices for the tripartite evolutionary game model of AHS adaptive management under climate change, guided by government intervention, as shown in Tables 4 and 5.

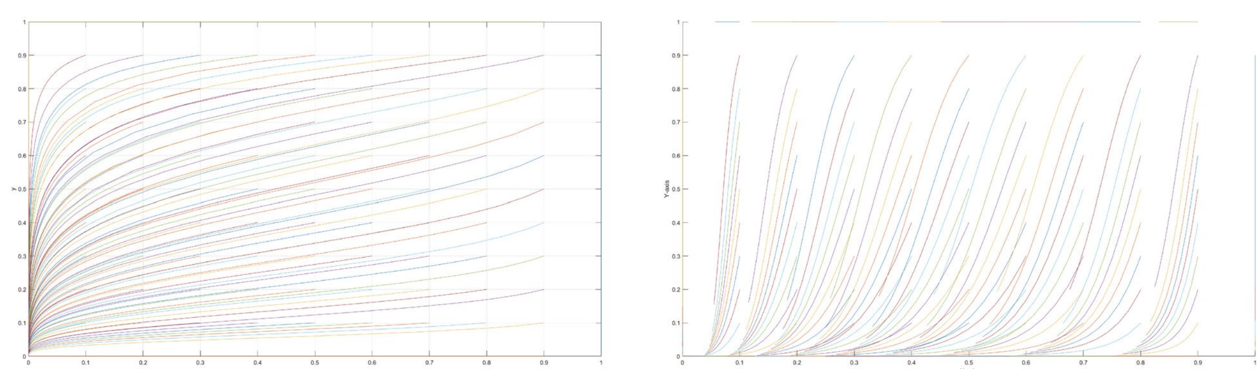

Fig. 1 Phase Diagrams of the Two-Party Game Dynamic System under Market Mechanisms

Table 4 Parameters for the Tripartite Evolutionary Game Model under Government Guidance

Variables	Meaning of the variables	Notes
X	Willingness of Farmer to participate	$0 \le X \le 1$
Y	Willingness of CSD to participate	$0 \le Y \le 1$
Z	Willingness of Government to participate	$0 \le Z \le 1$
R^F	The intrinsic income of a farmer	–
R^C	The intrinsic income of CSD	–
H^F	Resources expended by farmers to address climate change	–
H^C	Resources for CSD to improve precise weather services	–
$W(\varphi^F,t)$	The value coefficient of Farmer resources	$0 < W(\varphi^F,t) < 1$
$W(\varphi^C,t)$	The value coefficient of CSD resources	$0 < W(\varphi^C,t) < 1$
$C(\varphi^F,t)$	The intrinsic costs of a Farmer	–
$C(\varphi^C,t)$	The intrinsic costs of a CSD	–
$L(\varphi^F,t)$	The risk coefficient of Farmer facing climate disasters	$1 < L(\varphi^F,t)$
$L(\varphi^C,t)$	The risk coefficient of CSD facing climate disasters	$1 < L(\varphi^C,t)$
α	Benefit distributing coefficient	$0 < \alpha < 1$
β	The ability to convert resources into profit	$0 < \beta < 1$
$M(H^F)$	Government subsidies for Farmer adapting to climate change	$0 < M(H^F) < 1$
$M(H^C)$	Government subsidies for quality weather services by CDS	$0 < M(H^C) < 1$
$P(H^F)$	The government 's punishment for Farmer not adapting to climate change	$0 < P(H^F) < 1$
$P(H^C)$	The government 's punishment for CDS with poor weather services	$0 < P(H^C) < 1$
R^G	Benefits of government guidance	–
C^G	Costs of government involvement	$0 < C^G$

Table 5 Payoff Matrix for the Tripartite Evolutionary Game under Government Guidance

		CSD	
		Y	**1-Y**
G Z	Farmer X	$R^F + \alpha\beta(H^F + K^C) + M(H^F)H^F - W(\varphi^F,t)H^F - C(\varphi^F,t)$	$R^F + M(H^F)H^F - W(\varphi^F,t)H^F - C(\varphi^F,t)$
		$R^C + (1-\alpha)\beta(H^F + K^C) + M(H^C)H^C - W(\varphi^C,t)H^C - C(\varphi^C,t)$	$R^C - (1 + P(H^C))C(\varphi^C,t)$
		$R^G - C^G - M(H^F)H^F - M(H^C)H^C$	$P(H^C)C(\varphi^C,t) - C^G - M(K^F)K^F$
	Farmer 1-X	$R^F - (1 + P(H^F))C(\varphi^F,t)$	$R^F - (L(\varphi^F,t) + P(H^F))C(\varphi^F,t)$
		$R^C + M(H^C)H^C - W(\varphi^C,t)H^C - C(\varphi^C,t)$	$R^C - (L(\varphi^C,t) + P(H^C))C(\varphi^C,t)$
		$P(H^F)C(\varphi^F,t) - C^G - M(H^C)H^C$	$P(H^F)C(\varphi^F,t) + P(H^C)C(\varphi^C,t) - C^G$
G 1-Z	Farmer X	$R^F + \alpha\beta(H^F + K^C) - W(\varphi^F,t)H^F - C(\varphi^F,t)$	$R^F - W(\varphi^F,t)H^F - C(\varphi^F,t)$
		$R^C + (1-\alpha)\beta(H^F + K^C) - W(\varphi^C,t)H^C - C(\varphi^C,t)$	$R^C - C(\varphi^C,t)$
		0	0
	Farmer 1-X	$R^F - C(\varphi^F,t)$	$R^F - L(\varphi^F,t)C(\varphi^F,t)$
		$R^C - W(\varphi^C,t)H^C - C(\varphi^C,t)$	$R^C - L(\varphi^C,t)C(\varphi^C,t)$
		0	0

Tripartite evolutionary stable strategy under government guidance

The paper sets the expected benefits for farmers choosing to actively participate in AHS adaptive management under climate change as U_{x11}, the expected benefits for not participating actively as U_{x12}, and the average expected benefits as $\overline{U_x}$, as specified in Eq. (6):

$$\begin{cases} Ux11 = yz\Big(R^F + \alpha\beta(H^F + H^C) + M(H^F)H^F - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) + \\ (1-y)z\Big(R^F + M(H^F)H^F - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) + \\ y(1-z)\Big(R^F + \alpha\beta(H^F + H^C) - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) + \\ (1-y)(1-z)\Big(R^F - W(\varphi^F, t)H^F - C(\varphi^F, t)\Big) \\ Ux12 = yz\Big(R^F - (1 + P(H^F))C(\varphi^F, t)\Big) + (1-y)z\Big(R^F - (L(\varphi^F, t) + P(H^F))C(\varphi^F, t)\Big) + \\ y(1-z)\Big(R^F - C(\varphi^F, t)\Big) + (1-y)(1-z)\Big(R^F - L(\varphi^F, t)C(\varphi^F, t)\Big) \\ \overline{Ux} = xUx11 + (1-x)Ux12 \end{cases} \tag{6}$$

The replicator dynamic equation for farmers' strategy selection in the evolutionary game of AHS adaptive management under climate change is given by Eq. (7):

$$U(\mathrm{x}) = \frac{dx}{dt} = x(Ux11 - \overline{Ux}) = x(1-x)\begin{pmatrix} y\alpha\beta(H^F + H^C) + yC(\varphi^F, t)(1 - L(\varphi^F, t)) + \\ z(M(H^F)H^F + P(H^F)C(\varphi^F, t)) - W(\varphi^F, t)H^F - C(\varphi^F, t) \end{pmatrix} \tag{7}$$

Similarly, the expected benefits for CSD actively participating in AHS adaptive management under climate change are set as U_{y11},for not participating actively as U_{y12}, and the average expected benefits as $\overline{U_y}$, as detailed in Eq. (8):

$$\begin{cases} Uy11 = xz\Big(R^C + (1-\alpha)\beta(H^F + H^C) + M(H^C)H^C - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) + \\ (1-x)z\Big(R^C + M(H^C)H^C - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) + \\ x(1-z)\Big(R^C + (1-\alpha)\beta(H^F + H^C) - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) + \\ (1-x)(1-z)\Big(R^C - W(\varphi^C, t)H^C - C(\varphi^C, t)\Big) \\ Uy12 = xz\Big(R^C - (1 + P(H^C))C(\varphi^C, t)\Big) + (1-x)z\Big(R^C - (L(\varphi^C, t) + P(H^C))C(\varphi^C, t)\Big) + \\ x(1-z)\Big(R^C - C(\varphi^C, t)\Big) + (1-x)(1-z)\Big(R^C - L(\varphi^C, t)C(\varphi^C, t)\Big) \\ \overline{U}\mathrm{y} = yUy11 + (1-y)Uy12 \end{cases} \tag{8}$$

The replicator dynamic equation for CSD's strategy selection in the evolutionary game is given by Eq. (9):

$$U(\mathrm{y}) = \frac{dy}{dt} = y(Uy11 - \overline{U}\mathrm{y}) = y(1-y)\begin{pmatrix} x(1-\alpha)\beta(H^F + H^C) + xC(\varphi^C, t)(1 - L(\varphi^C, t)) + \\ z(M(H^C)H^C + P(H^C)C(\varphi^C, t)) - W(\varphi^C, t)H^C - C(\varphi^C, t) \end{pmatrix} \tag{9}$$

Table 6 Eigenvalues of the Jacobian Matrix

Equilibrium	λ_1	λ_2	λ_3
E1(0,0,0)	$\left[\left(L\left(\varphi^F,t\right)-1\right)C\left(\varphi^F,t\right)-W\left(\varphi^F,t\right)H^F\right]$	$\left[\left(L\left(\varphi^C,t\right)-1\right)C\left(\varphi^C,t\right)-W\left(\varphi^C,t\right)H^C\right]$	$\left[P\left(H^F\right)C\left(\varphi^F,t\right)+P\left(H^C\right)C\left(\varphi^C,t\right)-C^G\right]$
E2(1,0,0)	$-\left[\left(L\left(\varphi^F,t\right)-1\right)C\left(\varphi^F,t\right)-W\left(\varphi^F,t\right)H^F\right]$	$\left[(1-\alpha)\beta\left(H^F+H^C\right)-W\left(\varphi^C,t\right)H^C\right]$	$\left[P\left(H^C\right)C\left(\varphi^C,t\right)-C^G-M\left(H^F\right)H^F\right]$
E3(0,1,0)	$\left[\alpha\beta\left(H^F+H^C\right)-W\left(\varphi^F,t\right)H^F\right]$	$-\left[\left(L\left(\varphi^C,t\right)-1\right)C\left(\varphi^C,t\right)-W\left(\varphi^C,t\right)H^C\right]$	$\left[P\left(H^F\right)C\left(\varphi^F,t\right)-C^G-M\left(H^C\right)H^C\right]$
E4(0,0,1)	$\left[\left(M\left(H^F\right)-W\left(\varphi^F,t\right)\right)H^F+\left(L\left(\varphi^F,t\right)+P\left(H^F\right)-1\right)C\left(\varphi^F,t\right)\right]$	$\left[\left(M\left(H^C\right)-W\left(\varphi^C,t\right)\right)H^C+\left(L\left(\varphi^C,t\right)+P\left(H^C\right)-1\right)C\left(\varphi^C,t\right)\right]$	$-\left[P\left(H^F\right)C\left(\varphi^F,t\right)+P\left(H^C\right)C\left(\varphi^C,t\right)-C^G\right]$
E5(1,1,0)	$-\left[\alpha\beta\left(H^F+H^C\right)-W\left(\varphi^F,t\right)H^F\right]$	$-\left[(1-\alpha)\beta\left(H^F+H^C\right)-W\left(\varphi^C,t\right)H^C\right]$	$\left[R^G-C^G-M\left(H^F\right)H^F-M\left(H^C\right)H^C\right]$
E6(1,0,1)	$-\left[\left(M\left(H^F\right)-W\left(\varphi^F,t\right)\right)H^F+\left(L\left(\varphi^F,t\right)+P\left(H^F\right)-1\right)C\left(\varphi^F,t\right)\right]$	$\left[(1-\alpha)\beta\left(H^F+H^C\right)+M\left(H^C\right)H^C+P\left(H^C\right)C\left(\varphi^C,t\right)-W\left(\varphi^C,t\right)H^C\right]$	$-\left[P\left(H^C\right)C\left(\varphi^C,t\right)-C^G-M\left(H^F\right)H^F\right]$
E7(0,1,1)	$\left[\alpha\beta\left(H^F+H^C\right)+M\left(H^F\right)H^F+P\left(H^F\right)C\left(\varphi^F,t\right)-W\left(\varphi^F,t\right)H^F\right]$	$-\left[\left(M\left(H^C\right)-W\left(\varphi^C,t\right)\right)H^C+\left(L\left(\varphi^C,t\right)+P\left(H^C\right)-1\right)C\left(\varphi^C,t\right)\right]$	$-\left[P\left(H^F\right)C\left(\varphi^F,t\right)-C^G-M\left(H^C\right)H^C\right]$
E8(1,1,1)	$-\left[\alpha\beta\left(H^F+H^C\right)+M\left(H^F\right)H^F+P\left(H^F\right)C\left(\varphi^F,t\right)-W\left(\varphi^F,t\right)H^F\right]$	$-\left[(1-\alpha)\beta\left(H^F+H^C\right)+M\left(H^C\right)H^C+P\left(H^C\right)C\left(\varphi^C,t\right)-W\left(\varphi^C,t\right)H^C\right]$	$-\left[R^G-C^G-M\left(H^F\right)H^F-M\left(H^C\right)H^C\right]$

Finally, the expected benefits for the government actively participating in AHS adaptive management under climate change are set as U_{z11}, for not participating actively as U_{z12}, and the average expected benefits as $\overline{U_z}$, as detailed in Eq. (10):

$$\begin{cases} Uz11 = xy\left(R^G - C^G - M(H^F)H^F - M(H^C)H^C\right) + \\ (1-x)y\left(P(H^F)C(\varphi^F,t) - C^G - M(H^C)H^C\right) + \\ x(1-y)\left(P(H^C)C(\varphi^C,t) - C^G - M(H^F)H^F\right) + \\ (1-x)(1-y)\left(P(H^F)C(\varphi^F,t) + P(H^C)C(\varphi^C,t) - C^G\right) \\ Uz12 = 0 \\ \overline{U\mathrm{z}} = zUz11 + (1-z)Uz12 \end{cases} \tag{10}$$

The replicator dynamic equation for the government's strategy selection in the evolutionary game is given by Eq. (11):

Table 7 Signs of Eigenvalues for Local Equilibrium Points

Equilibrium point	Eigenvalues translation			Stability
	λ1	λ2	λ3	
E1(0,0,0)	+,–	+,–	+,–	NESS
E2(1,0,0)	+,–	+,–	+,–	NESS
E3(0,1,0)	+,–	+,–	+,–	NESS
E4(0,0,1)	+,–	+,–	+,–	NESS
E5(1,1,0)	+,–	+,–	+	NESS
E6(1,0,1)	+,–	+	+,–	NESS
E7(0,1,1)	+	+,–	+,–	NESS
E8(1,1,1)	–	–	–	ESS

By combining Eqs. (7), (9), and (11), we derive the replicator dynamics equation for the tripartite evolutionary game system of AHS adaptive management under climate change, guided by government intervention. Stability analysis of the Jacobian matrix yields Jacobian J_2 as shown in Eq. (12):

$$U(\mathrm{z}) = \frac{dz}{dt} = z(Uz11 - \overline{U\mathrm{z}}) = z(1-z)\begin{pmatrix} xyR^G + (1-x)P(H^F)C(\varphi^F,t) + \\ (1-y)P(H^C)C(\varphi^C,t) - xM(H^F)H^F - yM(H^C)H^C - C^G \end{pmatrix} \tag{11}$$

$$\begin{aligned} &J2 = \begin{bmatrix} J11, J12, J13 \\ J21, J22, J23 \\ J31, J32, J33 \end{bmatrix} \\ &NOTE: \\ &J11 = (1-2x)\begin{pmatrix} y\alpha\beta(H^F + H^C) + yC(\varphi^F,t)(1 - L(\varphi^F,t)) + \\ z(M(H^F)H^F + P(H^F)C(\varphi^F,t)) - W(\varphi^F,t)H^F - C(\varphi^F,t) \end{pmatrix} \\ &J12 = x(1-x)\left(\alpha\beta(H^F + H^C) + C(\varphi^F,t)(1 - L(\varphi^F,t))\right) \\ &J13 = x(1-x)\left(M(H^F)H^F + P(H^F)C(\varphi^F,t)\right) \\ &J21 = y(1-y)\left((1-\alpha)\beta(H^F + H^C) + C(\varphi^C,t)(1 - L(\varphi^C,t))\right) \\ &J22 = (1-2y)\begin{pmatrix} x(1-\alpha)\beta(H^F + H^C) + xC(\varphi^C,t)(1 - L(\varphi^C,t)) + \\ z(M(H^C)H^C + P(H^C)C(\varphi^C,t)) - W(\varphi^C,t)H^C - C(\varphi^C,t) \end{pmatrix} \\ &J23 = y(1-y)\left(M(H^C)H^C + P(H^C)C(\varphi^C,t)\right) \\ &J31 = z(1-z)\left(yR^G - M(H^F)H^F - P(H^F)C(\varphi^F,t)\right) \\ &J32 = z(1-z)\left(xR^G - M(H^C)H^C - P(H^C)C(\varphi^C,t)\right) \\ &J33 = (1-2z)\begin{pmatrix} xyR^G + (1-x)P(H^F)C(\varphi^F,t) + \\ (1-y)P(H^C)C(\varphi^C,t) - xM(H^F)H^F - yM(H^C)H^C - C^G \end{pmatrix} \end{aligned} \tag{12}$$

Table 8 Parameter Assignments for the Evolutionary Game Model under Government

Parameter	H^F	H^C	$W(\varphi^F,t)$	$W(\varphi^C,t)$	$C(\varphi^F,t)$	$C(\varphi^C,t)$	$L(\varphi^F,t)$	$L(\varphi^C,t)$
	3	1	0.65	0.7	5	4	1.2	1.1
	$M(H^F)$	$M(H^C)$	$P(H^F)$	$P(H^C)$	R^G	C^G	α	β
	0.1	0.3	0.4	0.3	5	3	0.75	0.5

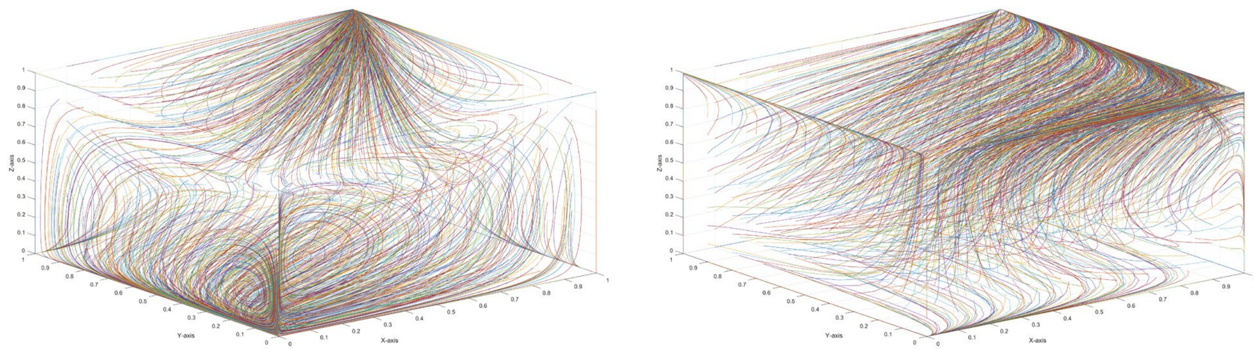

Fig. 2 Phase Diagrams of the Tripartite Dynamic System Evolution under Government

Building on the theoretical framework proposed by Lyapunov [23], this paper delves into the issue of asymptotic stability of equilibrium points within the tripartite evolutionary game of adaptive management of Agricultural Heritage Systems (AHS) under the backdrop of climate change. In evolutionary game theory, the stability of an equilibrium point is a crucial indicator of whether the system can maintain its state over the long term. For an equilibrium point to be considered asymptotically stable in evolutionary games, it must represent a strict pure strategy Nash equilibrium, as opposed to a mixed strategy Nash equilibrium. Based on this theory, our study identifies eight locally stable equilibrium points through the dynamics equations of the tripartite evolutionary game system, namely: E1(0,0,0), E2(1,0,0), E3(0,1,0), E4(0,0,1), E5(1,1,0), E6(1,0,1), E7(0,1,1), and E8(1,1,1). These points serve as the boundaries of the evolutionary game, with internal points not representing pure strategy Nash equilibria, but rather mixed strategy Nash equilibria. Consequently, this study focuses on the asymptotic stability of these eight boundary points. According to research by Friedman [24], the asymptotic stability of an equilibrium point is determined by the signs of the eigenvalues of the Jacobian matrix; specifically, if all eigenvalues of a Jacobian matrix are negative, the equilibrium point is considered an Evolutionarily Stable Strategy (ESS). This paper calculates the eigenvalues for each of the aforementioned eight equilibrium points using the Jacobian matrix (see Table 6).

When conducting stability analysis of the evolutionary model, this study encounters the challenge of numerous and complex model parameters. To more accurately analyze model stability, we propose a fundamental assumption: the payoff for participants must exceed the payoff for non-participation. In other words, the decision-making behavior of participants directly impacts their payoffs, satisfying the following conditions:

$$\left[\alpha\beta\left(H^F+H^C\right)+M\left(H^F\right)H^F+P\left(H^F\right)C\left(\varphi^F,t\right)-W\left(\varphi^F,t\right)H^F\right]>0$$

$$\left[(1-\alpha)\beta\left(H^F+H^C\right)+M\left(H^C\right)H^C+P\left(H^C\right)C\left(\varphi^C,t\right)-W\left(\varphi^C,t\right)H^C\right]>0$$

$$\left[R^G - C^G - M\left(H^F\right)H^F - M\left(H^C\right)H^C\right] > 0$$

The signs of the specific eigenvalues are presented in Table 7.

Furthermore, this paper sets parameters that satisfy the above conditions, and aside from government subsidies and penalties, all other parameters remain consistent with those in Table 3. This approach facilitates the study of the importance of government participation in the adaptive management of AHS against the backdrop of climate change. Specific parameter assignments are shown in Table 8, and the corresponding phase diagrams are illustrated in Fig. 2. On the left side of Fig. 2, the Ordinary Differential Equation (ODE) algorithm is applied, while on the right side, the Delay Differential Equation (DDE) dynamic system evolutionary phase diagram considers participants' historical decisions, with a lag period of 1 year for the DDE algorithm.

The phase diagrams of the tripartite game dynamic system under government guidance, as observed in Fig. 2, reveal that with the addition of external regulation and incentives by the government to the parameters of Table 3, the adaptive management of AHS under climate change more readily achieves an optimized configuration of behavioral strategies. Even considering the inertia of historical decisions, the equilibrium points of the dynamic evolutionary system no longer converge solely to 0 but shift between E1(0,0,0) and E8(1,1,1). This indicates that government external regulation and incentives effectively guide the optimization of resource allocation, promoting the development of AHS protection strategies towards more efficient and sustainable directions. Specifically, by formulating relevant policies, the government provides necessary incentives and support for AHS protection, effectively guiding societal resources towards the field of AHS adaptive management and correcting the "market failure" phenomenon previously present. Without government intervention, individuals are unable to effectively coordinate their actions due to externalities, leading to inefficient resource allocation. However, under government regulation and incentives, by altering the profit structure of actors, individuals' enthusiasm for protecting AHS is stimulated, thereby enhancing societal welfare. Therefore, government regulation and incentives play a crucial role in the adaptive management of AHS under climate change.

Results

This study utilizes MATLAB 2020b software to conduct a simulation analysis of the evolutionary game system for adaptive management of Agricultural Heritage Systems (AHS) under the context of climate change. The aim is to explore the strategic changes of the tripartite game participants in a more intuitive manner. This section specifically investigates the impact of various factors on the behavioral strategies of the game participants. When the game system's stable point is E8 (1,1,1), meaning all parties choose to participate in protective behaviors, the system achieves its optimal state. Given the absence of successful case studies on the adaptive management of AHS protection against climate change, this paper primarily relies on numerical simulation. By setting specific parameter constraints, it simulates the impact of different parameter changes on the stability of the evolutionary game system. Compared to market mechanisms and government participation, parameters are assigned to meet the following constraints under unchanged conditions:

$$\left[\alpha\beta(H^F + H^C) + M\left(H^F\right)H^F + P\left(H^F\right)C(\varphi^F, t) - W\left(\varphi^F, t\right)H^F\right] > 0$$

$$\left[(1-\alpha)\beta(H^F + H^C) + M\left(H^C\right)H^C + P\left(H^C\right)C(\varphi^C, t) - W\left(\varphi^C, t\right)H^C\right] > 0$$

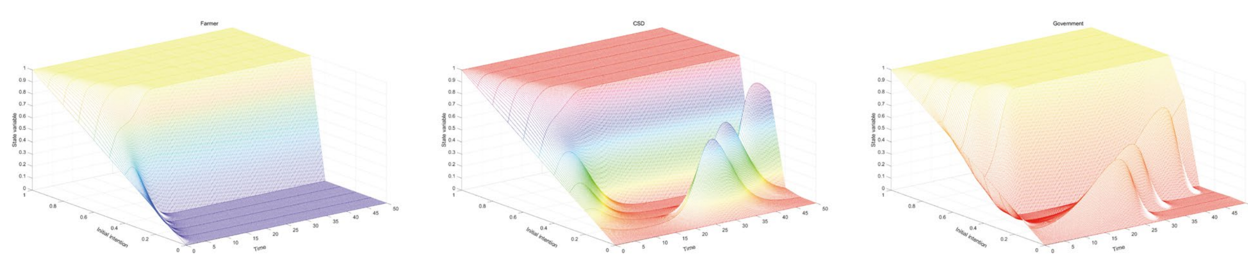

Fig. 3 Sensitivity Analysis of Initial Participation Willingness

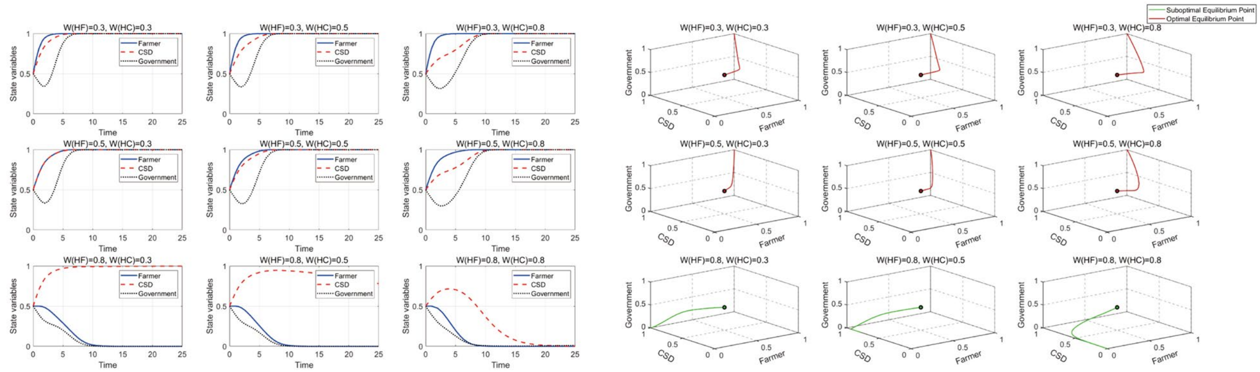

Fig. 4 Sensitivity Analysis of Transition Costs

$$\left[R^G - C^G - M\left(H^F\right)H^F - M\left(H^C\right)H^C\right] > 0$$

Specific parameter assignments are detailed in Table 8, with a simulation timeframe of 25 years, iterating annually. The Delay Differential Equation (DDE) algorithm, with a 1 year lag, is employed in this numerical simulation. Its purpose is to introduce memory and learning mechanisms into the tripartite evolutionary game model of AHS adaptive management. Decision-makers fully consider the previous year's decisions, aiding in more accurately simulating real-world decision-making behaviors.

Sensitivity analysis of initial participation willingness

Under the premise of unchanged parameters, this paper further analyzes how the initial willingness of farmers, climate services department, and governments affects their strategy choices during the evolutionary game process. A sensitivity analysis is conducted for the initial willingness of the three parties, illustrated in Fig. 3. From left to right, Fig. 3 shows the changes in initial participation willingness of farmers, climate services department, and governments under constant parameters, with the x-axis representing time, the y-axis representing initial participation willingness, and the z-axis representing status variables.

Observations from Fig. 3 indicate that the critical value of initial participation willingness in the adaptive management evolutionary game of AHS lies between 0.4 and 0.5. Below this threshold, the equilibrium point of the tripartite evolutionary game system converges to E1 (0,0,0), indicating a general disinterest among parties in participating in AHS adaptive management. Notably, even if the initial willingness of climate services department and governments is below this threshold, their participation willingness still exhibits "mountainous" fluctuations. This phenomenon may stem from an initial lack of awareness regarding the importance and urgency of addressing climate change. When extreme climate disasters occur and impact the AHS, the participation willingness of these departments and governments surges. However, due to the weak participation willingness of farmers, the

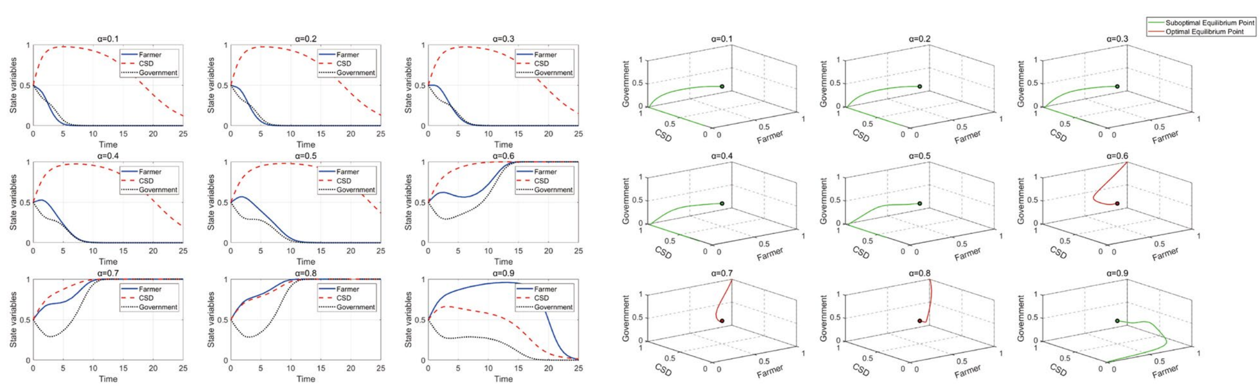

Fig. 5 Sensitivity Analysis of Benefit Distribution

outcome still tends toward non-participation. Above the threshold, the equilibrium point of the tripartite evolutionary game system converges to E8 (1,1,1), indicating a collective inclination towards participating in AHS adaptive management. Therefore, it is crucial for policymakers to enhance the initial participation willingness of farmers, climate services department, and other stakeholders, and to establish effective collaboration mechanisms to achieve adaptive management of AHS under climate change. This could involve strengthening education and training for multiple stakeholders and developing and implementing policies that promote cooperation, thereby fostering a societal atmosphere that proactively addresses climate change and protects AHS, ultimately ensuring sustainable protection and development of AHS.

Sensitivity analysis of transition costs

Building on the analysis in 3.1, this paper sets the initial participation willingness of the three stakeholders at 0.5 and further examines how the costs of adapting to climate change for farmers and climate services department affect their strategy choices during the evolutionary game process. A sensitivity analysis of the transition costs is conducted, with results depicted in Fig. 4. On the left side of Fig. 4, the dynamic evolutionary outcomes of the game are shown, with the x-axis representing time and the y-axis representing status variables. On the right side, specific evolutionary paths are illustrated, with the x-axis for farmers, the y-axis for climate services department, and the z-axis for governments. Parameters are varied with transition cost ratios set at 0.3, 0.5, and 0.8.

Figure 4 reveals that when transition costs are low, meaning the economic burden of adapting to climate change is lighter for farmers and climate services department, both exhibit higher enthusiasm for taking necessary measures to mitigate the impact of climate change on AHS. Lower economic costs reduce the financial barriers to taking action, making proactive adaptation a rational choice for multiple stakeholders. However, as the costs required for proactive adaptation to climate change gradually increase, especially when transition costs exceed the marginal threshold of affordability for all parties, farmers, climate services department, and governments tend to reduce or refrain from participating in proactive climate change adaptation measures for AHS. Notably, farmers are more sensitive to cost changes compared to climate services department, possibly because they directly face the impacts of climate change on agricultural production and have weaker economic resilience, making them more sensitive to cost fluctuations. This indicates that in formulating policies to address climate change, the government should consider the economic resilience and cost sensitivity of different actors to ensure the effectiveness and feasibility of policies. Therefore, to encourage stakeholders to actively respond to climate change and protect AHS, policymakers need to design and implement a series of policy tools that can reduce transition costs, thereby alleviating the economic burden on farmers and climate services department in adapting to climate change and effectively enhancing their willingness and ability to participate in the adaptive management of AHS.

Sensitivity analysis of benefit distribution

Under the assumption that other parameters remain constant, this study sets the initial willingness of the three parties (farmers, climate services department, and the government) to participate at 0.5, based on the analysis in Sect. "Sensitivity Analysis of Initial Participation Willingness". It further examines how the distribution of benefits between farmers and climate services department affects their strategic choices during the evolutionary game process. A sensitivity analysis of benefit distribution is conducted, and the findings are illustrated in Fig. 5. In Fig. 5, the left side displays the dynamic evolutionary outcomes

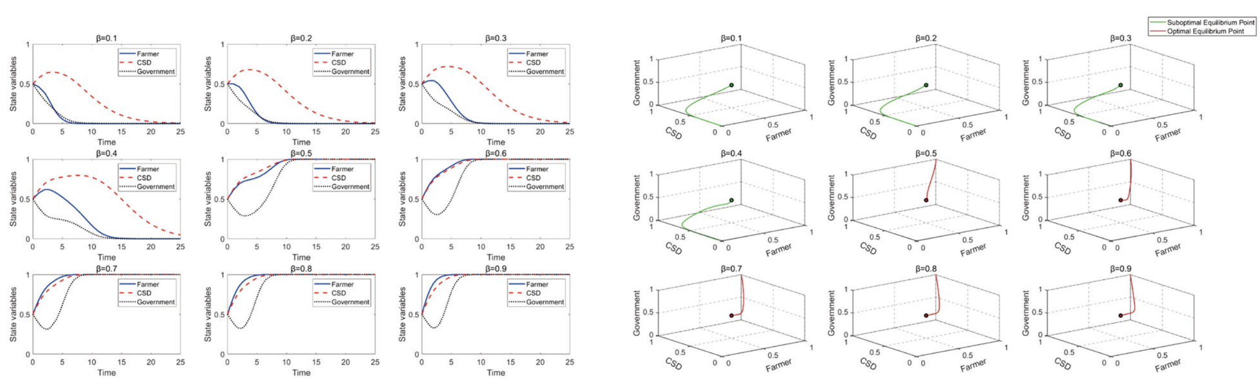

Fig. 6 Sensitivity Analysis of Resource Profitability

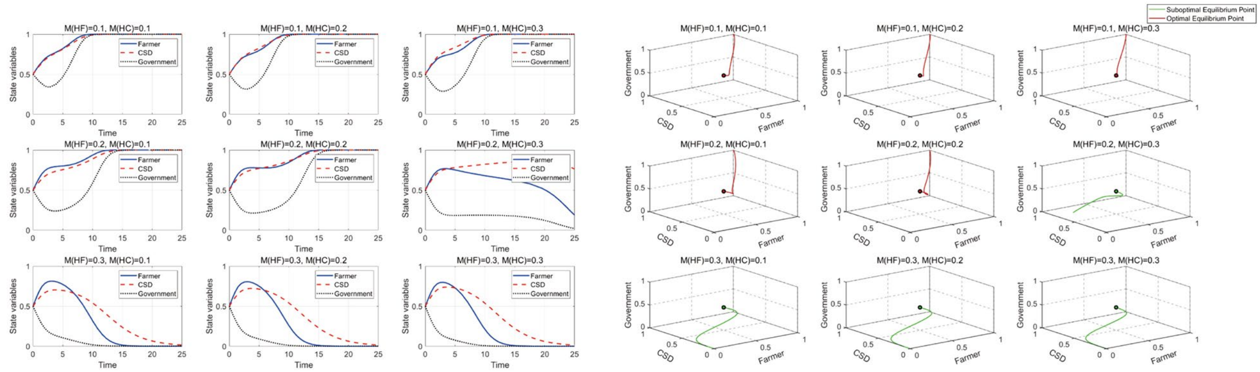

Fig. 7 Sensitivity Analysis of Government Subsidies

of the game, with the x-axis representing time and the y-axis representing state variables. The right side shows specific evolutionary paths, with the x-axis for farmers, the y-axis for climate services department, and the z-axis for the government. Parameters are adjusted for benefit distribution ratios ranging from 0.1 to 0.9.

Figure 5 reveals that during the process of adaptive management of Agricultural Heritage Systems (AHS) under the backdrop of climate change, farmers tend to withdraw from protective actions when they receive lower benefits. This decision is influenced not only by direct economic losses but also by the lack of sufficient incentives from participating in protective activities. Similarly, even if climate services department are willing to engage in protective actions, the absence of farmers ultimately leads them to withdraw. Therefore, to effectively promote the protection of AHS, it is essential to establish an appropriate benefit distribution mechanism. This mechanism should ensure that all stakeholders, including farmers and climate services department, receive reasonable benefits while also promoting the efficient allocation of resources. Policymakers must delve deeply into the cost and benefit distribution of AHS protection activities to ensure a fair correlation between the efforts and benefits of all parties involved. Specifically, policymakers should lead the establishment of a multi-stakeholder benefit-sharing mechanism, encouraging all parties in the dynamic evolutionary game system to actively participate in the protection of AHS under climate change.

Sensitivity analysis of resource profitability

Keeping other parameters constant and building upon the analysis in Sect. "Sensitivity Analysis of Initial Participation Willingness", this study sets the initial willingness of the three parties to participate at 0.5. It further analyzes how the profitability of resources cooperatively utilized by farmers and climate services department affects their strategic choices during the evolutionary game process. A sensitivity analysis of resource profitability is conducted, and the results are depicted in Fig. 6. In Fig. 6, the left side shows the dynamic evolutionary outcomes of the game, with the x-axis representing time and the y-axis representing state variables. The right side illustrates

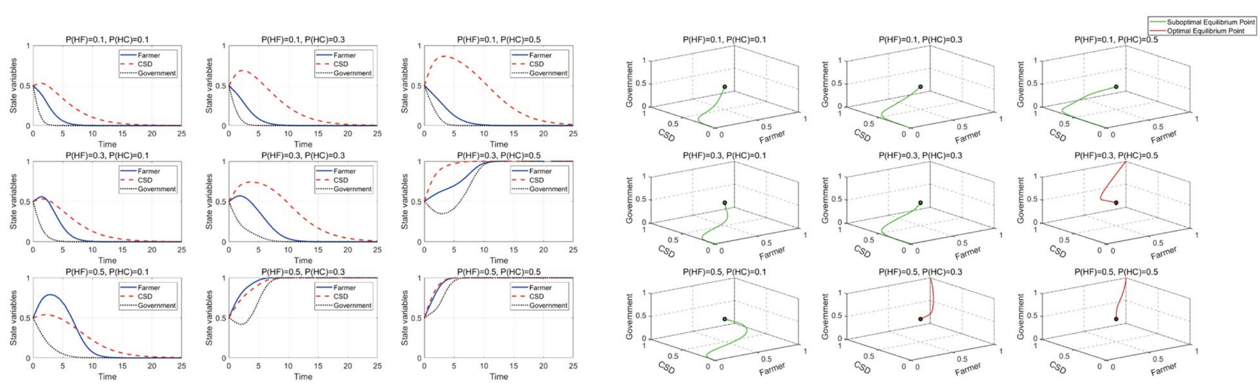

Fig. 8 Sensitivity Analysis of Government Penalties

specific evolutionary paths, with the x-axis for farmers, the y-axis for climate services department, and the z-axis for the government. Parameters are adjusted for resource profitability ratios ranging from 0.1 to 0.9.

Observations from Fig. 6 indicate that in the process of adaptive management of AHS under climate change, when the ability of farmers and climate services department to convert cooperative resources into economic value is low, all parties, including the government, tend to abstain from participation. However, as the ability to convert cooperative resources into economic value gradually improves, the willingness of farmers and climate services department to participate also increases. This suggests that to more effectively promote the protection of AHS under climate change, policymakers need to focus on enhancing the resource conversion capabilities of farmers and climate services department. This includes, but is not limited to, providing technical support, enhancing market access, and improving the value chain of agricultural production and services. By doing so, direct economic benefits from participation in protective activities can be increased, thus boosting the willingness to participate. Enhancing the resource conversion capabilities of farmers and climate services department not only fosters a proactive stance towards the protection of AHS but also promotes the economic sustainability of AHS activities. This is crucial for the long-term protection and sustainable development of AHS.

Sensitivity analysis of government subsidies

Under the assumption that other parameters remain constant and building on the analysis in Sect. "Sensitivity Analysis of Initial Participation Willingness", this study sets the initial willingness of the three key stakeholders—farmers, climate services department, and the government—to participate at 0.5. It further investigates how the intensity of government subsidies impacts the strategic choices of farmers and climate services department within the evolutionary game process. A sensitivity analysis of government subsidy intensity is conducted, illustrated in Fig. 7. In this figure, the left side presents the dynamic evolutionary outcomes of the game, with the x-axis representing time and the y-axis denoting state variables. The right side depicts specific evolutionary paths, with the x-axis for farmers, the y-axis for climate services department, and the z-axis for the government. The analysis explores changes in parameters when government subsidy intensities are set at 0.1, 0.2, and 0.3.

Observations from Fig. 7 indicate that within the context of climate change, the government's subsidy policy exhibits a complex effect on the adaptive management of Agricultural Heritage Systems (AHS). Specifically, as the government's subsidy intensity gradually increases, the willingness of farmers and climate services department to participate indeed rises, indirectly validating the effectiveness of financial subsidy measures in stimulating grassroots stakeholders to engage in the adaptive management of AHS. However, the continuous escalation of this policy approach also leads to a decrease in the government's own willingness to participate. Once the subsidy intensity reaches the government's marginal rationality threshold, due to the excessive financial pressure of subsidies, the government may withdraw its support for the adaptive management of AHS. This phenomenon highlights a core issue: while financial subsidy strategies can effectively stimulate the participation willingness of farmers and climate services department in the short term, their sustainability is severely constrained by the government's fiscal capacity in the long term. Therefore, constructing an adaptive management system for AHS that can both promote active participation from farmers and climate services department and maintain sustained government support is crucial.

Sensitivity analysis of government penalties

With other parameters held constant and based on the analysis in Sect. "Sensitivity Analysis of Initial Participation Willingness", this study sets the initial willingness of the three stakeholders to participate at 0.5. It further examines how the intensity of government penalties affects the strategic choices of farmers and climate services department during the evolutionary game process. A sensitivity analysis of government penalty intensity is conducted, illustrated in Fig. 8. In this figure, the left side shows the dynamic evolutionary outcomes of the game, with the x-axis representing time and the y-axis denoting state variables. The right side depicts specific evolutionary paths, with the x-axis for farmers, the y-axis for climate services department, and the z-axis for the government. The analysis explores changes in parameters when government penalty intensities are set at 0.1, 0.3, and 0.5.

Observations from Fig. 8 reveal that in the context of climate change, when the government's penalty intensity is low, even if the government actively participates in guiding the establishment of an adaptive management system for AHS, farmers and climate services department tend to opt out of the system. This suggests that in the absence of sufficient external constraints and driven by self-interest maximization, farmers and climate services department may adopt a wait-and-see attitude. However, as the government increases penalty intensity, the willingness of farmers and climate services department to actively participate also gradually strengthens. This indicates that an appropriate penalty mechanism can effectively promote proactive actions from farmers and climate services department. From an economic perspective, a suitable government penalty mechanism can create an effective incentive and constraint system. By increasing the cost of non-participation or non-compliance with adaptive management, it encourages farmers and climate services department to weigh individual benefits against potential penalty costs, thus opting to actively participate in the AHS adaptive management system. Therefore, in formulating and implementing policies for the adaptive management of AHS, the government should thoroughly consider penalty intensity to ensure that the penalty mechanism can effectively prevent and reduce non-compliant behaviors while encouraging and facilitating active participation from farmers and climate services department.

Conclusions and policy recommendations

Based on the asymmetry of information and bounded rationality theories, this paper establishes both a two-party evolutionary game model under market mechanisms and a three-party evolutionary game model under government guidance for the adaptive management of Agricultural Heritage Systems (AHS), conducting stability analyses. It discusses the strategic evolution outcomes of various stakeholders under different conditions. Additionally, using Delay Differential Equations (DDE) that account for historical delays, the paper performs numerical simulations and sensitivity analyses, providing a theoretical foundation for the dynamic conservation of AHS under the backdrop of climate change.

The principal conclusions are as follows:

1. In the process of adaptive management of AHS under the backdrop of climate change, relying solely on the autonomous actions of farmers and the Climate Services Department (CSD) is insufficient due to a lack of intrinsic motivation and the inherent externalities associated with the conservation of AHS. This phenomenon, typically referred to as "market failure" in economics, indicates that rational choices by individuals regarding the conservation of AHS, which possess characteristics of public goods, often result in collective action inefficiencies and increase the prevalence of free-rider behavior. However, the introduction of external regulations and incentives by the government can effectively promote the adaptive management of AHS towards more efficient and sustainable directions. By formulating relevant policies and providing necessary regulatory and incentive measures, the government can not only correct market failures but also optimize resource allocation and stimulate individual conservation efforts, thereby enhancing overall social welfare. Therefore, government involvement plays a critical role in the adaptive management of AHS under the backdrop of climate change.
2. Sensitivity analysis on the initial willingness of various stakeholders to participate in the adaptive management of AHS under climate change reveals that when the initial willingness of all parties falls below a critical threshold, the dynamic evolutionary game system tends towards the equilibrium point E1 (0,0,0), where farmers, the CSD, and the government are all unlikely to engage in adaptive management. This reflects the difficulty of achieving effective adaptive management when initial willingness is insufficient, despite potential increases in willingness from the CSD and government in response to extreme climate events, due to the lack of proactive response from farmers. Further analysis shows that when the initial willingness of all parties exceeds the critical threshold, the equilibrium point of the dynamic evolutionary game tends towards E8 (1,1,1), indicating that with higher initial willingness, farmers, the CSD, and the government are more likely to jointly participate in the adaptive management of AHS. Thus, enhancing the initial willingness of farmers, the CSD, and the government is key to successful adaptive management.
3. Sensitivity analysis on the cost of transitioning for various stakeholders in the adaptive management of AHS under climate change shows that when transition costs are low, farmers and the CSD are more inclined to take effective proactive measures to address climate change. This behavior pattern reflects how lower economic costs can motivate stakeholders to adopt adaptive management measures. However, as transition costs increase, especially when exceeding the marginal rational threshold of stakeholders, their willingness to participate significantly decreases, indicating that higher transition costs become a barrier to proactive action. Therefore, in formulating policies to address climate change, the government should consider the economic capacities of different stakeholders and the sensitivity of cost changes, aiming to minimize the economic burden on farmers and the CSD.
4. Sensitivity analysis on the distribution of benefits and resource conversion among multiple stakeholders in the adaptive management of AHS under climate change indicates that a reasonable distribution of benefits is crucial for motivating farmers and the CSD to actively participate in the conservation of AHS. When the benefits derived from conservation

activities are too low, their willingness to participate significantly decreases. Thus, establishing a benefit distribution mechanism that ensures all stakeholders receive fair benefits and promotes the effective allocation of resources is key to protecting AHS. Additionally, enhancing the profitability of resources is vital for directly increasing the economic benefits of farmers and the CSD in conserving AHS. When stakeholders have a low capacity to convert cooperative resources into economic value, even with government guidance and support, it is challenging to stimulate active participation. Therefore, to effectively promote the adaptive management of AHS, the government should focus on optimizing the benefit distribution mechanism and enhancing the profitability of cooperative resources.

5. Sensitivity analysis on the subsidies and penalties provided by the government in the adaptive management of AHS under climate change reveals that these policy tools play a complex and crucial role in stimulating the participation of farmers and the CSD. Firstly, government subsidy policies can effectively increase the willingness of farmers and the CSD to participate by providing economic incentives. However, continuously increasing subsidies not only places financial pressure on the government but may also lead to government withdrawal from conservation efforts once a certain threshold is reached, affecting the sustainability of the policy. Secondly, sensitivity analysis on government penalties shows that an appropriate penalty mechanism can effectively encourage active participation. At lower levels of penalties, farmers and the CSD may adopt a wait-and-see attitude, overlooking the importance of adaptive management. As penalties increase, the willingness of stakeholders to participate also strengthens, underscoring the importance of an appropriate penalty mechanism in promoting the adaptive management of AHS.

Based on the conclusions drawn above, this paper proposes the following policy recommendations for the adaptive management of Agricultural Heritage Systems (AHS) under climate change conditions:

1. Enhancing the willingness of farmers, the Climate Services Department (CSD), and the government to participate is crucial for the effective adaptive management of AHS in the context of climate change. To achieve this, the government should design an appropriate policy framework that ensures all stakeholders receive clear benefits from their involvement in adaptive management. These benefits include direct economic gains, environmental improvements, and enhanced social reputation. For instance, integrating AHS adaptive management with tourism and establishing markets for unique agricultural products can increase economic benefits for stakeholders. Additionally, raising awareness about the importance of AHS adaptive management through media promotion and educational training, as well as awarding certificates of honor to participants, can elevate their social status. Furthermore, establishing transparent and fair rules to protect the interests of all stakeholders and reducing the barriers to participation are essential steps toward increasing stakeholder engagement.
2. Controlling transition costs to reduce the economic burden is another key aspect. In the process of AHS adaptive management, farmers and the CSD inevitably incur certain transition costs. If these costs are not managed effectively, they can hinder participation in AHS adaptive management. Therefore, the government can alleviate these costs through direct financial subsidies, such as providing farmers with drought-resistant crop seeds and improved irrigation systems, and offering low-interest loans to the CSD to address initial funding shortages. Moreover, the government should encourage the research and development of technologies beneficial for AHS adaptive management by fostering collaboration between research institutions and businesses. This not only enhances the availability and reliability of such technologies but also reduces their costs through large-scale production and application. Lastly, considering the uncertainties and potential risks associated with climate change, the government should establish risk-sharing mechanisms, such as agricultural and climate insurance schemes, to distribute risks.
3. Optimizing the benefit distribution mechanism and enhancing the profitability of resources are vital for stimulating active participation from all parties in the adaptive management of AHS under climate change. Therefore, when formulating related policies, the government should ensure that farmers and the CSD share in the economic returns from AHS adaptive management. Initially, the government should guide the commercial utilization of AHS, such as by developing tourism and specialty agricultural products, which not only improves the market profitability of AHS resources but also provides economic incentives to farmers and the CSD. During commercialization, it is crucial to preserve the intrinsic characteristics and ecological environment of AHS. Furthermore, the government should optimize the benefit distribution mechanism to ensure that farmers and the CSD

receive fair economic returns from the conservation and utilization of AHS, for example, by establishing cooperatives and joint-stock companies. Lastly, the government must strengthen the regulation of AHS conservation and utilization to prevent overexploitation and unfair benefit distribution, ensuring the dynamic protection and adaptive management of AHS.

4. Establishing a dynamic subsidy and penalty mechanism to optimize resource allocation is essential in addressing market failures caused by the public goods nature of AHS conservation and externalities. On one hand, the government should adopt a dynamic subsidy mechanism, adjusting the intensity of subsidies based on the actual effects of AHS adaptive management and fiscal sustainability, to ensure that subsidy policies not only stimulate stakeholder participation but also do not impose excessive financial pressure on the government. On the other hand, an appropriate penalty mechanism is an effective way to encourage active participation from farmers and the CSD. The government should design and implement effective penalty mechanisms that increase the opportunity cost of inaction, thereby motivating stakeholders to engage in AHS adaptive management. Overall, in formulating policies for AHS adaptive management under climate change, the government should seek a balance between subsidies and penalties. By ensuring fiscal sustainability, the government should precisely target subsidies to farmers and the CSD, while also designing and implementing effective penalty mechanisms to increase the opportunity cost of negative behaviors, thereby encouraging active participation in the adaptive management of AHS.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

Not applicable. This study did not involve human participants, human data or tissues, or animals. Therefore, it did not require ethical approval from ethical committees or Internal Review Boards.

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