Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 6, 2459 doi: 10.2166/wcc.2022.063

Evolutionary game analysis of water-saving behavior of energy enterprises and food producers from the perspective of water-energy-food nexus

De-chun Huang, Lian-yan Xu *, Zheng-qi He and Jie Cao

Business School, Hohai University, No. 8 Focheng West Road, Nanjing 211100, China
*Corresponding author. E-mail: xulianyan@126.com

L-yX, 0000-0002-7193-2687; Z-qH, 0000-0003-4274-1205

ABSTRACT

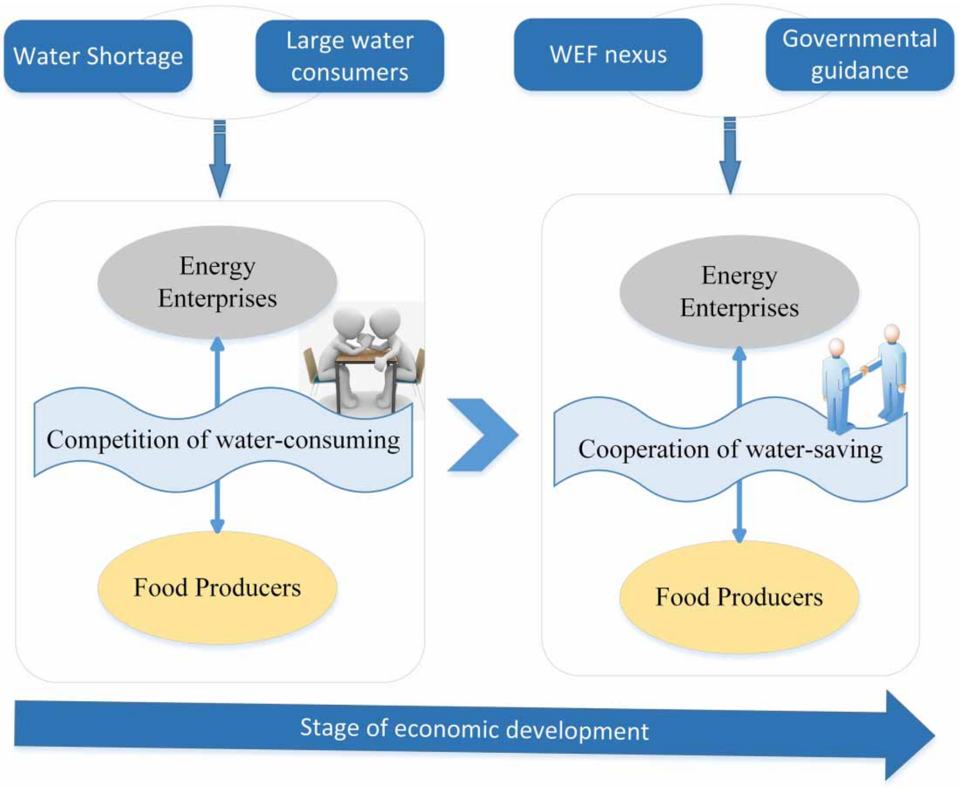
Water resources are not only the essential natural resources for the national economy and people's livelihood but also are the strategic economic resources for the safe production of energy and food. However, the shortage of water resources caused by extreme climate is a great challenge to energy enterprises and food producers. According to the game theory and the theory of economic development stage, this paper constructs an evolutionary game model for local governments, energy enterprises, and food producers. Further, it analyzes the evolutionary stability strategies of the game players at different development stages through simulations. The results indicate that: (1) the game players have different strategies of evolutionary stability at different development stages, while local governments adopting water-saving policies will promote the water-saving behavior of energy enterprises and food producers; (2) the choice of water-saving behavior of energy enterprises and food producers mainly depends on the water-saving costs; (3) the guidance of the government and the management of water-saving cost make the large water consumers realize the transformation from the 'competition of water-consuming' to the 'cooperation of water-saving.' According to the above analysis, many political recommendations are further put forward.

Key words: energy enterprises, evolutionary game, food producers, water-saving, water-energy-food nexus

HIGHLIGHTS

- Researching the water-saving behavior from the perspective of water-energy-food nexus.
- Using the evolutionary game model and the theory of economic development stage to study the water-saving behavior.
- The guidance of the government and the management of water-saving cost make the large water consumers realize the transformation from the 'competition of water-consuming' to the 'cooperation of water-saving'.

GRAPHICAL ABSTRACT



1. INTRODUCTION

China's economy has rapidly risen to become the world's second-largest in the last 40 years of reform and opening up. The demand for water, energy, and food is also increasing. Since 2010, China has become the largest energy consumer in the world. China's total energy consumption has increased from 3.6 billion tons of standard coal in 2010–5 billion tons of standard coal in 2020, nearly 40% (Yuan & Luo 2019). Since 1986, Chinese grain output has steadily ranked first in the world. In 2019, the total grain output of China was 664 million tons, which far exceeded that of other countries and accounted for about 24.4% of the total grain output of the world. However, water resources, energy, and food are mutually supplied and inseparable. Food and energy production depends on the safe supply of water resources, and agriculture and energy are also the two major sectors consuming water (Mahjabin *et al.* 2020). In 2017, the total water consumption of China reached 604.3 billion m^3, where the water consumption from agriculture and energy accounted for more than 70% of the total water consumption (MWR 2017). As food and energy production increases year by year, China's consumption of water resources also increases (Liu *et al.* 2013). However, with climate change, the severe drought in China has caused a shortage of water resources. The shortage of water resources has become an important factor restricting the safe production of energy and food (Marvin *et al.* 2013; Gasbarro *et al.* 2016; Vogel *et al.* 2019).

With the severe shortage of water resources, the competition for water use between the energy and food systems has gradually become the norm (Damerau *et al.* 2016; D'Odorico *et al.* 2018; Hua *et al.* 2020; Qin 2021). Suppose energy enterprises and food producers fail to transfer from the 'competition of water-consuming' to the 'cooperation of water-saving.' In that case, the optimal utilization of water resources cannot be fully realized, and the high-quality development of China will be affected. Therefore, guiding energy enterprises and food producers to save water is significant for ensuring water-energy-food security and sustainable water use management, while it is the research of this paper. In recent years, the Chinese government has paid more and more attention to the conservation and utilization of water resources. In April 2019, the National Development and Reform Commission and the Ministry of Water Resources jointly issued the 'National Water Saving Action plan' in China.

The water-saving behavior of energy enterprises and food producers is significant for alleviating the shortage of water resources. The researchers proposed that the water for food production can be reduced by popularizing water-saving facilities (Tian *et al.* 2017; Cetin & Kara 2019; Nouri *et al.* 2019) and cultivating the drought-resistant crops (Zhang *et al.* 2021). The technological progress of water-saving (Ge *et al.* 2020; Aili *et al.* 2021) and wastewater recycling (Pan *et al.* 2012) can reduce the water for energy production. Furthermore, the development and improvement of the water-energy nexus are essential for several industries and enterprises (Panagopoulos 2021a, 2021b). Although these studies have made significant contributions to alleviating the shortage of water resources, most of them focus on the internal water-saving behavior of the independent water user. They do not comprehensively consider the competition of water use and water-saving behavior among multiple water users from the holistically external perspective.

The Bonn Conference, held in Germany in 2011, firstly combined water, energy, and food as a 'Nexus' (water-energy-food Nexus) (Bazilian *et al.* 2011; Dubreuil *et al.* 2013; Zhang & Vesselinov 2017). With the increasingly severe problem of climate change and the development of economic globalization, the nexus of water resources, energy, and food are getting tighter and tighter. Research from the perspective of the water-energy-food nexus has become a hot spot. Scholars have carried out many types of research about the coupling and coordination of water-energy-food (Rasul & Sharma 2016; Albrecht *et al.* 2018; Pahl-Wostl 2019), the relationship between the water-energy-food system and economic growth (Xu *et al.* 2022), the water-energy-food-land nexus (Lazaro *et al.* 2021; Susnik *et al.* 2021), the water-energy-food-climate nexus (Zhou *et al.* 2022) and so on. The above studies have contributed to the in-depth understanding of the water-energy-food nexus. However, most of these studies focus on the macro-level research and lack of research on the sustainable water use management of the micro subjects with behavioral consciousness such as energy enterprises and food producers.

Societies worldwide have long struggled with the planning and managing of water resources amid growing populations and resource use, competition among users, and, more recently, widespread ecosystem degradation and climate change (Chartzoulakis & Bertaki 2015). Scholars have carried out a series of studies on the necessity (Rosa *et al.* 2020), practice (Qu *et al.* 2013; Ahmad *et al.* 2016), and effectiveness (Long *et al.* 2020) of sustainable water management. These studies effectively promote the progress of researches on sustainable water use management and provide an essential reference for the research of sustainable water management in this paper.

From the perspective of the water-energy-food nexus, this paper focuses on the effect of sustainable water use management of local governments on the energy enterprises and food producers. Because of the publicity and complexity of water resources, the water-saving action is no longer the individual's responsibility. The joint promotion of local governments, energy enterprises, and food producers is necessary. Therefore, promoting water-saving in energy and food production is a technical problem and a real problem of complex stakeholders' different interest demands and behavior conflicts. Evolutionary game theory is widely used to reveal the interests and behaviors of multiple stakeholders and has achieved fruitful results (Wei *et al.* 2010; Kahil *et al.* 2016; Chen *et al.* 2020). As a result, this paper examines the water-saving behavior of energy enterprises and food producers using an evolutionary game model and the critical roles of local governments in guiding the transformation of food producers' and energy enterprises' behaviors from the 'competition of water-consuming' to the 'cooperation of water-saving' over time.

To demonstrate the importance of this work, the innovations and contributions of this paper are summarized as follows: (1) This paper innovatively studies the behavioral choice among multiple sectors with high water consumption from the holistically external perspective of the water-energy-food nexus. (2) This paper innovatively focuses the research of the 'water-energy-food nexus' on the sustainable water use management of the micro-subject energy enterprises and food producers. Their behavioral choices are further analyzed when facing the water use competition. (3) This paper provides the theoretical support for local governments of arid areas to achieve sustainable water use management for high water-consuming energy enterprises and food producers. (4) Putting forward the theory of water-saving development stage according to the theory of economic development stage of Rostow (Rostow 1959).

The following are the primary objectives and contents of this paper: (1) developing an evolutionary game model to understand better the behavioral patterns of local governments, energy enterprises, and food producers; (2) discussing and examining changes in the behavioral choices of energy enterprises and food producers at various stages of economic development; (3) analyzing the process of energy enterprises and food producers from 'water-consuming competition' to 'water-saving cooperation' and demonstrating the critical role of local government in this process.

2. CONSTRUCTION OF EVOLUTIONARY GAME MODEL FOR WATER-SAVING BEHAVIOR OF ENERGY ENTERPRISES AND FOOD PRODUCERS

2.1. Hypothesis of evolutionary game model

Energy and food production has always been the large consumers of water resources, which account for 70% of the total water consumption of China in 2019 (MWR 2019). The shortage of water resources caused by the extreme climate is severe in China, and the water consumption of energy affects the security of grain irrigation. Because of the publicity and complexity of water resources, the water-saving action is no longer the individual's responsibility. The joint promotion of local governments, energy enterprises, and food producers is necessary. The three stakeholders in the water-saving action are all bounded rational individuals: local governments, energy enterprises, and food producers. In this paper, we use local governments to represent the current management departments of water-energy-food, which mainly include the water conservancy departments, the agricultural departments, the energy departments, the environment departments, and the river, lake, and sea management departments. Coal, oil refining, coal-fired power generation, and other energy firms with high water use are among the energy enterprises studied in this article. Food producers are the individuals engaging in grain production, agricultural production enterprises, and farmers.

To explain the model more clearly, this paper makes the following assumptions according to the actual situation:

Hypothesis 1: Local governments, energy enterprises, and food producers constitute a stably complete system. The three stakeholders are all individuals with learning abilities and have the right to choose their behavior plans. Local governments have two strategies: guiding and not guiding, and energy enterprises have two strategies: saving water and not saving water. Food producers also have two strategies: saving water and not saving water. At the time t, the probabilities of correspondingly strategic choices are expressed by x, y, and z ($x, y, z \in [0,1]$).

Hypothesis 2: The cost of guidance of the local governments is C_g. Whether the local governments guide or not, when the energy enterprises and food producers choose the water-saving strategy simultaneously, the regional water resources are fully utilized, and the benefit obtained by the local governments is S_g. As long as energy enterprises or food producers do not choose the water-saving strategy, the value of water resources in the region cannot be maximized. The loss of political achievements is caused by reducing food production, and the substandard energy production within the jurisdiction is W_g.

Hypothesis 3: The benefit of the energy enterprises producing according to the existing technology is S_e, the increased benefit after water-saving is ΔS_e, the cost that energy enterprises pay for water-saving technologies is C_e. If food producers save water, the extra benefit of energy enterprises not saving water is πS_e. In the long term, energy enterprises that do not save water will further aggravate the shortage of water resources, and the losses of energy enterprises and food producers caused by the water shortage are δW_e and δW_f, respectively. The guidance of local governments to energy enterprises includes two means of water-saving reward and resource tax, the executive strengths of the two means are α and β, respectively. The local governments' reward for the energy enterprises saving water is αJ. The costs of energy enterprises for local governments levying resource tax is βT.

Hypothesis 4: The benefit of food producers producing according to the current technology is S_f, the increased benefit after choosing a water-saving strategy is ΔS_f, and the cost that food producers pay for water-saving measures is C_f; If energy enterprises save water, the extra benefits of food producers not saving water is πS_f. In the long term, food producers that do not save water will further aggravate the shortage of water resources, and the losses of energy enterprises and food producers caused by the water shortage are ηW_e and ηW_f, respectively. The local governments' reward for food producers saving water is γJ.

According to the above assumptions about the water-saving behavior of local governments, energy enterprises, and food producers, we construct the profit matrix of game behavior of players as shown in Tables 1 and 2.

2.2. The equilibrium point of the evolutionary process

In the evolutionary game, to finally obtain a stable strategy, players need to constantly adjust the probability values x, y, and z according to the above profit matrix after many games (Lu *et al.* 2021). The process of the dynamic adjustment strategy is the dynamic process of copying. When the dynamic copying equation equals 0, the tripartite strategy evolves to the locally balanced state. Then the equilibrium point of the evolution process of the game players is obtained (Zhao & Liu 2019).

1. According to the game profit matrix, the expected benefit of local governments choosing the strategy of guidance is

$$\begin{aligned} U_g = {} & yz(-C_g - \gamma J - \alpha J + S_g) + y(1-z)(-C_g - \gamma J - W_g + \beta T) \\ & + (1-y)z(-C_g - \alpha J - W_g) + (1-y)(1-z)(-C_g - W_g + \beta T) \end{aligned} \tag{1}$$

Table 1 | Game profit matrix when the governments choose the strategy of guidance (x)

	Food producers choose the strategy of saving water (y)		
Energy enterprises	**Local governments' profit**	**Energy enterprises' profit**	**Food producers' profit**
Strategy of saving water (z)	$S_g - C_g - \gamma J - \alpha J$	$S_e + \Delta S_e - C_e + \alpha J$	$S_f + \Delta S_f - C_f + \gamma J$
Strategy of not saving water (1 – z)	$-C_g - \gamma J - W_g + \beta T$	$S_e - \beta T - \delta W_e + \pi S_e$	$S_f + \Delta S_f - C_f + \gamma J - \delta W_f$
	Food producers choose the strategy of not saving water (1 – y)		
Energy enterprises	**Local governments' profit**	**Energy enterprises' profit**	**Food producers' profit**
Strategy of saving water (z)	$-C_g - \alpha J - W_g$	$S_e + \Delta S_e - C_e + \alpha J - \eta W_e$	$S_f - \eta W_f + \pi S_f$
Strategy of not saving water (1 – z)	$-C_g - W_g + \beta T$	$S_e - \beta T - \delta W_e - \eta W_e$	$S_f - \eta W_f - \delta W_f$

Table 2 | Game profit matrix when the governments choose the strategy of not guiding (1 – x)

	Food producers choose the strategy of saving water (y)		
Energy enterprises	**Local governments' profit**	**Energy enterprises' profit**	**Food producers' profit**
Strategy of saving water (z)	S_g	$S_e + \Delta S_e - C_e$	$S_f + \Delta S_f - C_f$
Strategy of not saving water (1 – z)	$-W_g$	$S_e - \delta W_e + \pi S_e$	$S_f + \Delta S_f - C_f - \delta W_f$
	Food producers choose the strategy of not saving water (1 – y)		
Energy enterprises	**Local governments' profit**	**Energy enterprises' profit**	**Food producers' profit**
Strategy of saving water (z)	$-W_g$	$S_e + \Delta S_e - C_e - \eta W_e$	$S_f - \eta W_f + \pi S_f$
Strategy of not saving water (1 – z)	$-W_g$	$S_e - \delta W_e - \eta W_e$	$S_f - \eta W_f - \delta W_f$

The expected benefit of the local governments choosing the strategy of not guiding is

$$U_{\bar{g}} = yz(S_g) + y(1-z)(-W_g) + (1-y)z(-W_g) + (1-y)(1-z)(-W_g) \tag{2}$$

Therefore, the average benefit of local governments is $\overline{U_g} = xU_g + (1-x)U_{\bar{g}}$.

2. According to the game profit matrix, the expected benefit of food producers choosing a water-saving strategy is

$$\begin{aligned} U_f = {} & xz(S_f + \Delta S_f - C_f + \gamma J) + x(1-z)(S_f + \Delta S_f - C_f + \gamma J - \delta W_f) \\ & + (1-x)z(S_f + \Delta S_f - C_f) + (1-x)(1-z)(S_f + \Delta S_f - C_f - \delta W_f) \end{aligned} \tag{3}$$

The expected benefit of food producers not choosing a water-saving strategy is

$$\begin{aligned} U_{\bar{f}} = {} & xz(S_f - \eta W_f + \pi S_f) + x(1-z)(S_f - \eta W_f - \delta W_f) \\ & + (1-x)z(S_f - \eta W_f + \pi S_f) + (1-x)(1-z)(S_f - \eta W_f - \delta W_f) \end{aligned} \tag{4}$$

Therefore, the average benefit of food producers is $\overline{U_f} = yU_f + (1-y)U_{\bar{f}}$.

3. The expected benefit of energy enterprises choosing a water-saving strategy can be calculated as

$$\begin{aligned} U_e = {} & xy(S_e + \Delta S_e - C_e + \alpha J) + x(1-y)(S_e + \Delta S_e - C_e + \alpha J - \eta W_e) \\ & + (1-x)y(S_e + \Delta S_e - C_e) + (1-x)(1-y)(S_e + \Delta S_e - C_e - \eta W_e) \end{aligned} \tag{5}$$

The expected benefit of energy enterprises not choosing a water-saving strategy is

$$U_{\bar{e}} = xy(S_e - \beta T - \delta W_e + \pi S_e) + x(1-y)(S_e - \beta T - \delta W_e - \eta W_e) \\ + (1-x)y(S_e - \delta W_e + \pi S_e) + (1-x)(1-y)(S_e - \delta W_e - \eta W_e) \tag{6}$$

Therefore, the average benefit of energy enterprises is $\overline{U_e} = zU_e + (1-z)U_{\bar{e}}$.

According to the Malthusian equation, we can obtain the copying dynamic equation Equation (7) of local governments, energy enterprises, and food producers, that is, the three-dimensional dynamic system (I). The derivation of the copying dynamic equation is provided in Supplementary Material, Appendix B.

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)[-y\gamma J - z(\alpha J + \beta T) - C_g + \beta T] \\ \dfrac{dy}{dt} = y(1-y)[x\gamma J + \Delta S_f - C_f + \eta W_f - z\pi S_f] \\ \dfrac{dz}{dt} = z(1-z)[x(\alpha J + \beta T) + \Delta S_e - C_e + \delta W_e - y\pi S_e] \end{cases} \tag{7}$$

In the tripartite game of local governments, energy enterprises, and food producers, the above copying dynamic equation describes the dynamic process of bounded rational groups continuously learning. In the dynamic system (I), if the trajectory starting from any neighborhood of a point eventually evolves towards that point, then the point is locally asymptotically stable, and such a dynamic stable point is the equilibrium point. When the dynamic copying equation Equation (7) equals 0, the tripartite strategy evolves to the locally balanced state. All three players have found an effective Nash equilibrium through constant trials (Selten 1980). The strategy combination corresponding to the Nash equilibrium is the equilibrium point of the evolutionary game. Therefore, to find the balance of water-saving actions, assuming that:

$$\left.\begin{array}{l} dx/dt = 0 \\ dy/dt = 0 \\ dz/dt = 0 \end{array}\right\} \tag{8}$$

when Equation (7) equals Equation (8), it can be proved that there exist eight equilibrium points $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(1,0,0)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$ of the three populations adopting the pure strategy in the system (I). There may be six equilibrium points $\left(\dfrac{\Delta S_e - C_e + \delta W_e - \pi S_e}{-(\alpha J + \beta T)}, 1, \dfrac{\beta T - \gamma J - C_g}{\alpha J + \beta T}\right)\left(1, \dfrac{\gamma J + \Delta S_e - C_e + \delta W_e}{\pi S_e}, \dfrac{\alpha J + \beta T + \Delta S_f - C_f + \eta W_f}{\pi S_f}\right)$, $\left(\dfrac{\Delta S_f - C_f + \eta W_f}{-\gamma J}, \dfrac{\beta T - C_g}{\gamma J}, 0\right)$, $\left(0, \dfrac{\Delta S_e - C_e + \delta W_e}{\pi S_e}, \dfrac{\Delta S_f - C_f + \eta W_f}{\pi S_f}\right)\left(\dfrac{\Delta S_e - C_e + \delta W_e}{-\alpha J - \beta T}, 0, \dfrac{-C_g + \beta T}{\alpha J + \beta T}\right)$, $\left(\dfrac{\Delta S_f - C_f + \eta W_f - \pi S_f}{-\gamma J}, \dfrac{\beta T - \alpha J - \beta T - C_g}{\gamma J}, 1\right)$ of the single population adopting the pure strategy, and the system (I) may not have a mixed strategy equilibrium point. The condition of the first equilibrium point is $0 < \dfrac{\Delta S_e - C_e + \delta W_e}{\pi S_e} < 1$ and $0 < \dfrac{\Delta S_f - C_f + \eta W_f}{\pi S_f} < 1$, and the conditions of the other five equilibrium points can be obtained similarly. The derivation of the equilibrium points is provided in Supplementary Material, Appendix A.

2.3. Stability analysis of equilibrium point

The equilibrium point obtained by the copying dynamic equation may not be the system's evolutionary stability strategy (Gao *et al.* 2019). According to the Lyapunov stability theory, the eigenvalues of the Jacobian matrix can be used to determine the stability of the system's equilibrium point. All eigenvalues of the Jacobian matrix are negatively genuine parts, which is a necessary and sufficient condition for the system to meet the evolutionary stability strategy (Shan & Yang 2019). The Jacobian matrix is a one-order partial derivative matrix which can be obtained by calculating the partial derivative of the copying dynamic equation. By calculating the partial derivative of Equation (7), the 3*3 dimension Jacobian matrix J can be obtained as Equation (9):

$$J = \begin{bmatrix} \partial(dx/dt)/\partial x & \partial(dx/dt)/\partial y & \partial(dx/dt)/\partial z \\ \partial(dy/dt)/\partial x & \partial(dy/dt)/\partial y & \partial(dy/dt)/\partial z \\ \partial(dz/dt)/\partial x & \partial(dz/dt)/\partial y & \partial(dz/dt)/\partial z \end{bmatrix}$$
$$= \begin{bmatrix} (1-2x)[\beta T - y\gamma J - z(\alpha J + \beta T) - C_g] & x(1-x)(-\gamma J) & x(1-x)(-\alpha J - \beta T) \\ y(1-y)\gamma J & (1-2y)[x\gamma J + \Delta S_f - C_f + \eta W_f - z\pi S_f] & y(1-y)(-\pi S_f) \\ z(1-z)(\alpha J + \beta T) & -z(1-z)\pi S_e & (1-2z)[x(\alpha J + \beta T) + \Delta S_e - C_e + \delta W_e - y\pi S_e] \end{bmatrix} \quad (9)$$

where dx/dt, dy/dt, dz/dt are defined in Equation (7).

According to the Lyapunov theory, the equilibrium point is asymptotically stable when all eigenvalues of the Jacobian matrix $\lambda < 0$; the equilibrium point is not stable when there are positive or zero eigenvalues Jacobian matrix.

Take $E_1(0,0,0)$ as an example to analyze the formation of its Jacobian matrix, and further analyze its asymptotic stability. The point $E_1(0,0,0)$ means that $x = 0$, $y = 0$, and $z = 0$. Substituting $x = 0$, $y = 0$, and $z = 0$ into Equation (9), then, the Jacobian matrix J_1 at the equilibrium point $E_1(0,0,0)$ can be obtained as Equation (10).

$$J_1 = \begin{bmatrix} -C_g + \beta T & & \\ & \Delta S_f - C_f + \eta W_f & \\ & & \Delta S_e - C_e + \delta W_e \end{bmatrix}. \quad (10)$$

From Equation (10), the eigenvalues of the above Jacobian matrix J_1 are $\lambda_1 = -C_g + \beta T$, $\lambda_2 = \Delta S_f - C_f + \eta W_f$, $\lambda_3 = \Delta S_e - C_e + \delta W_e$. If λ_1, λ_2, and λ_3 are all less than 0 (i.e., $\beta T < C_g$, $\Delta S_f - C_f + \eta W_f < 0$, and $\Delta S_e - C_e + \delta W_e < 0$), $E_1(0,0,0)$ is an asymptotically stable point. The stability of the equilibrium point of other pure strategies can be obtained similarly. The stability analysis of equilibrium points is shown in Table 3.

3. THE SIMULATION ANALYSIS OF THE EVOLUTIONARY GAME

According to the above analysis, in the tripartite copying dynamic system of local governments, energy enterprises, and food producers, the equilibrium of the evolutionary game of behavioral strategies is affected by many factors. For energy enterprises and food producers, their strategic choice is not only affected by governmental regulation but also by their benefit. The evolutionary stability analysis of this paper is from the following two aspects. The first one is that the water-saving cost of energy enterprises and food producers is higher than the benefit. The second one is that the water-saving cost of energy enterprises and food producers is less than the benefit. Combining with the theory of economic development stage of Rostow (Rostow 1959), this paper puts forward the theory of the water-saving development stage. It discusses game players' behavior changes in the extensive expansion period, the water-saving starting period, the water-saving development period, and the mature water-saving period, respectively (Figure 1).

The MATLAB simulation tool examines the asymptotically stable evolution trajectory of the game model under changing restrictions to depict better the dynamic evolutionary process of strategic decisions of local governments, energy enterprises, and food producers. The initial point of evolution is set to $x = 0.5$, $y = 0.5$, $z = 0.5$. The vertical axis represents the strategies chosen by the local government (x), the strategies chosen by the food producer (y), the strategies chosen by the energy enterprise (z), and the horizontal axis represents the time (t).

3.1. The water-saving costs of energy enterprises and food producers are both higher than the benefits

When the water-saving costs of energy enterprises and food producers are higher than the benefits, $\Delta S_f - C_f + \eta W_f < 0$ and $\Delta S_e - C_e + \delta W_e < 0$. The asymptotic stability of the tripartite evolutionary game system of local governments, energy enterprises, and food producers is shown in Table 4.

Table 3 | The stability analysis of equilibrium points in System (I)

Equilibrium points	Eigenvalues λ_1	λ_2	λ_3	Conditions of asymptotic stability
$E_1(0,0,0)$	$-C_g+\beta T$	$\Delta S_f-C_f+\eta W_f$	$\Delta S_e-C_e+\delta W_e$	$\beta T<C_g$, $\Delta S_f+\eta W_f<C_f$, $\Delta S_e+\delta W_e<C_e$
$E_2(0,0,1)$	$-\alpha J-C_g$	$\Delta S_f-C_f+\eta W_f-\pi S_f$	$-(\Delta S_e-C_e+\delta W_e)$	$\Delta S_f+\eta W_f<C_f+\pi S_f$, $\Delta S_e+\delta W_e>C_e$
$E_3(0,1,0)$	$-\gamma J+\beta T-C_g$	$-(\Delta S_f-C_f+\eta W_f)$	$\Delta S_e-C_e+\delta W_e-\pi S_e$	$\beta T<\gamma J+C_g$, $\Delta S_f+\eta W_f>C_f$, $\Delta S_e+\delta W_e<C_e+\pi S_e$
$E_4(1,0,0)$	$C_g-\beta T$	$\gamma J+\Delta S_f-C_f+\eta W_f$	$\alpha J+\beta T+\Delta S_e-C_e+\delta W_e$	$C_g<\beta T$, $\gamma J+\Delta S_f+\eta W_f<C_f$, $\alpha J+\beta T+\Delta S_e+\delta W_e<C_e$
$E_5(1,1,0)$	$\gamma J-\beta T+C_g$	$-(\gamma J+\Delta S_f-C_f+\eta W_f)$	$\alpha J+\beta T+\Delta S_e-C_e+\delta W_e-\pi S_e$	$\gamma J+C_g<\beta T$, $\alpha J+\beta T+\Delta S_e+\delta W_e<C_e+\pi S_e$, $\gamma J+\Delta S_f+\eta W_f>C_f$
$E_6(1,0,1)$	$\alpha J+C_g$	$\gamma J+\Delta S_f-C_f+\eta W_f-\pi S_f$	$C_e-\Delta S_e-\delta W_e-\alpha J-\beta T$	Instability
$E_7(0,1,1)$	$-\gamma J-\alpha J-C_g$	$-(\Delta S_f-C_f+\eta W_f-\pi S_f)$	$-(\Delta S_e-C_e+\delta W_e-\pi S_e)$	$\Delta S_f+\eta W_f>C_f+\pi S_f$, $\Delta S_e+\delta W_e>C_e+\pi S_e$
$E_8(1,1,1)$	$\gamma J+\alpha J+C_g$	$C_f-\Delta S_f-\eta W_f+\pi S_f-\gamma J$	$C_e-\Delta S_e-\delta W_e+\pi S_e-\alpha J-\beta T$	Instability

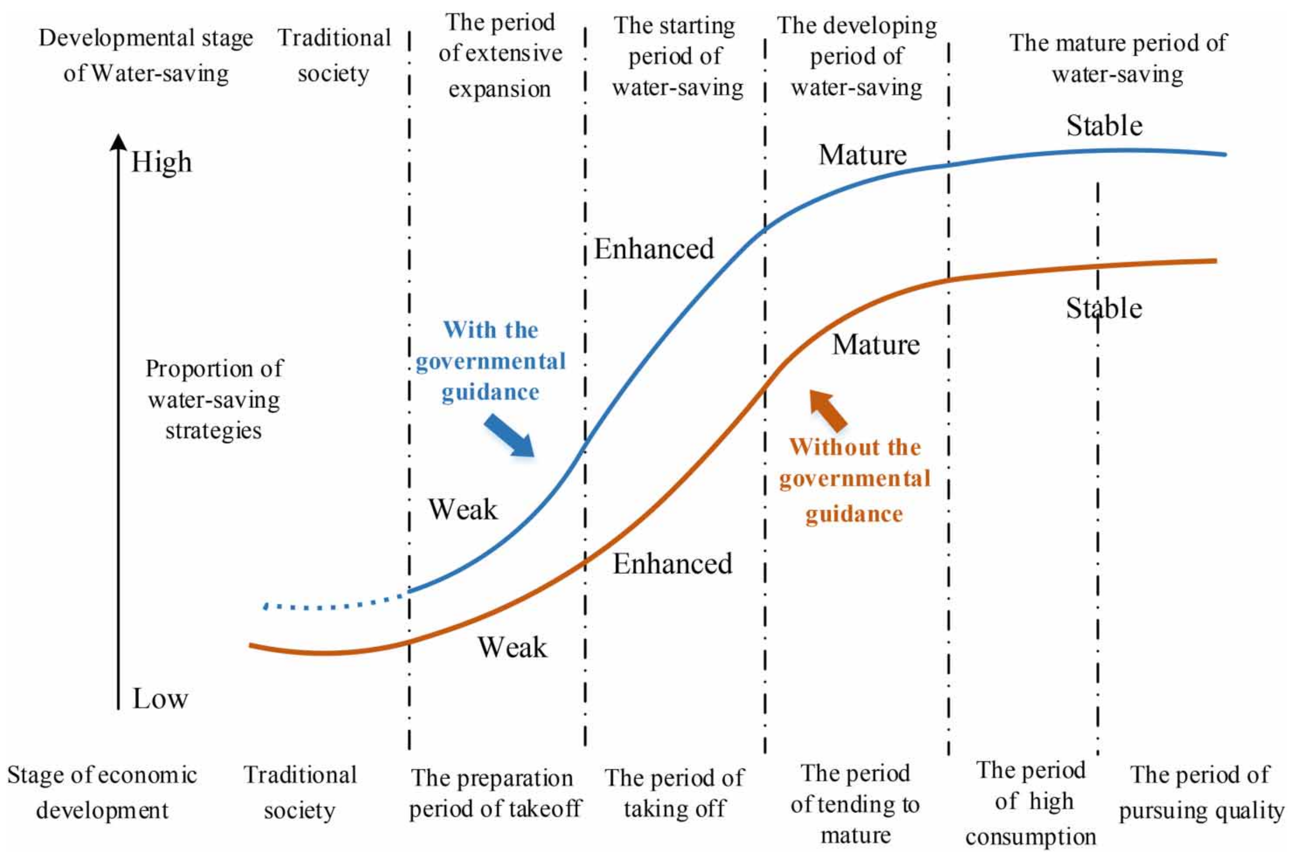


Figure 1 | The stage of economic development and the developmental stage of water-saving.

From Table 4, when the water-saving costs of energy enterprises and food producers are higher than the benefits, their strategic choice depends on whether the local governments guide or not and the intensity of guidance. The following are three situations for further discussion.

Situation (1): When $C_g > \beta T$, the guiding cost is higher than the water resources tax, the local governments will choose the strategy of not guiding. The energy enterprises and food producers who have opportunistic behavior will choose the strategy of not saving water. The asymptotic stable point $E_1(0,0,0)$ is the only evolutionary stable point. According to the behavioral strategy, local governments' purpose in the early stages of development is to foster economic development, industrialization, and urbanization. Therefore, the local governments pay less attention to the intensive utilization of water resources. During this period, agricultural development is still in a highly labor-intensive stage. Water-saving behavior is more expensive for food producers due to the high cost and low popularity of agricultural mechanization. At the same time, the shortage of energy makes accelerating production a top priority. The high water consumption in energy production and the weak awareness of water-saving both make the waste of water resources seriously. And the relatively low level of scientific and technological development makes water-saving technological innovation difficult and leads to the high cost of energy enterprises. Driven by loose regulation and interests, the bounded rational energy enterprises and food producers choose not to save water, resulting in the severe waste of water resources and a potential water shortage crisis. This is a relatively extensive expansion period, and the degree of intensification is low. There was 'competition of water-consuming' between energy enterprises and food producers at this stage.

During the period of extensive expansion, the initial parameter shall meet the conditions: $\Delta S_f - C_f + \eta W_f < 0$, $\Delta S_e - C_e + \delta W_e < 0$ and $C_g > \beta T$. Based on the above the conditions, the initial values of the parameters are set as: the cost of guidance of the local governments $C_g = 0.8$, the local governments' reward for food producers saving water $\gamma J = 0.3$, the increased benefit of food producers after choosing a water-saving strategy $\Delta S_f = 0.2$, the losses of food producers caused by the water shortage $\eta W_f = 0.3$, the cost that food producers pay for water-saving measures $C_f = 0.8$, the extra benefits of food

Table 4 | The stability analysis of equilibrium points when $\Delta S_f - C_f + \eta W_f < 0$ and $\Delta S_e - C_e + \delta W_e < 0$

Equilibrium points	**E_1 (0,0,0)**	**E_2 (0,0,1)**	**E_3 (0,1,0)**	**E_4 (1,0,0)**	**E_5 (1,1,0)**	**E_6 (1,0,1)**	**E_7 (0,1,1)**	**E_8 (1,1,1)**
Eigenvalues λ_1	–	<0	–	–	–	>0	<0	>0
λ_2	<0	<0	>0	–	–	–	>0	–
λ_3	<0	>0	<0	–	–	–	>0	–
Conditions of asymptotic stability	$C_g > \beta T$	Instability	Instability	$\gamma J + \Delta S_f + \eta W_f < C_f$, $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e$ $C_g < \beta T$	$\gamma J + \Delta S_f + \eta W_f > C_f$, $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e + \pi S_e$, $\gamma J + C_g < \beta T$	Instability	Instability	Instability

producers not saving water $\pi S_f = 0.4$, the local governments' reward for the energy enterprises saving water $\alpha J = 0.3$, the costs of resource tax of local governments $\beta T = 0.3$, the increased benefit of energy enterprises after saving water $\Delta S_e = 0.2$, the losses of energy enterprises caused by the water shortage $\delta W_e = 0.3$, the cost that energy enterprises pay for water-saving technologies $C_e = 0.8$, the extra benefit of energy enterprises not saving water $\pi S_e = 0.4$. According to the above parameters, the tripartite evolutionary stability strategies of local governments, energy enterprises, and food producers under the benchmark scenario are shown in Figure 2(a). Over time, the three players of the game finally stabilize at the combined strategy that local governments do not guide, and energy enterprises and food producers both do not save water. Changing the incentives of local governments for water-saving behavior. When $\gamma J = \alpha J = 0.6$, the influence of the change of reward policy on the evolutionary stability strategy is shown in Figure 2(b). Compared to the benchmark scenario, although local governments enhance the reward for water-saving behavior, energy enterprises and food producers still do not adopt the water-saving strategy. Changing the tax of water resources, when βT is 0.6, the influence of the change of water resources tax on the evolutionary stability strategy is shown in Figure 2(c). Compared with the benchmark situation, although an increase in the water resources tax does not affect the strategic choices of the three players in the game, the greater the intensity of the resource tax, the longer the evolutionary time for energy enterprises to reach a stable strategy of not saving water. In the extensive expansion period, local governments are stable in the non-guidance strategy due to the lack of attention to water-saving

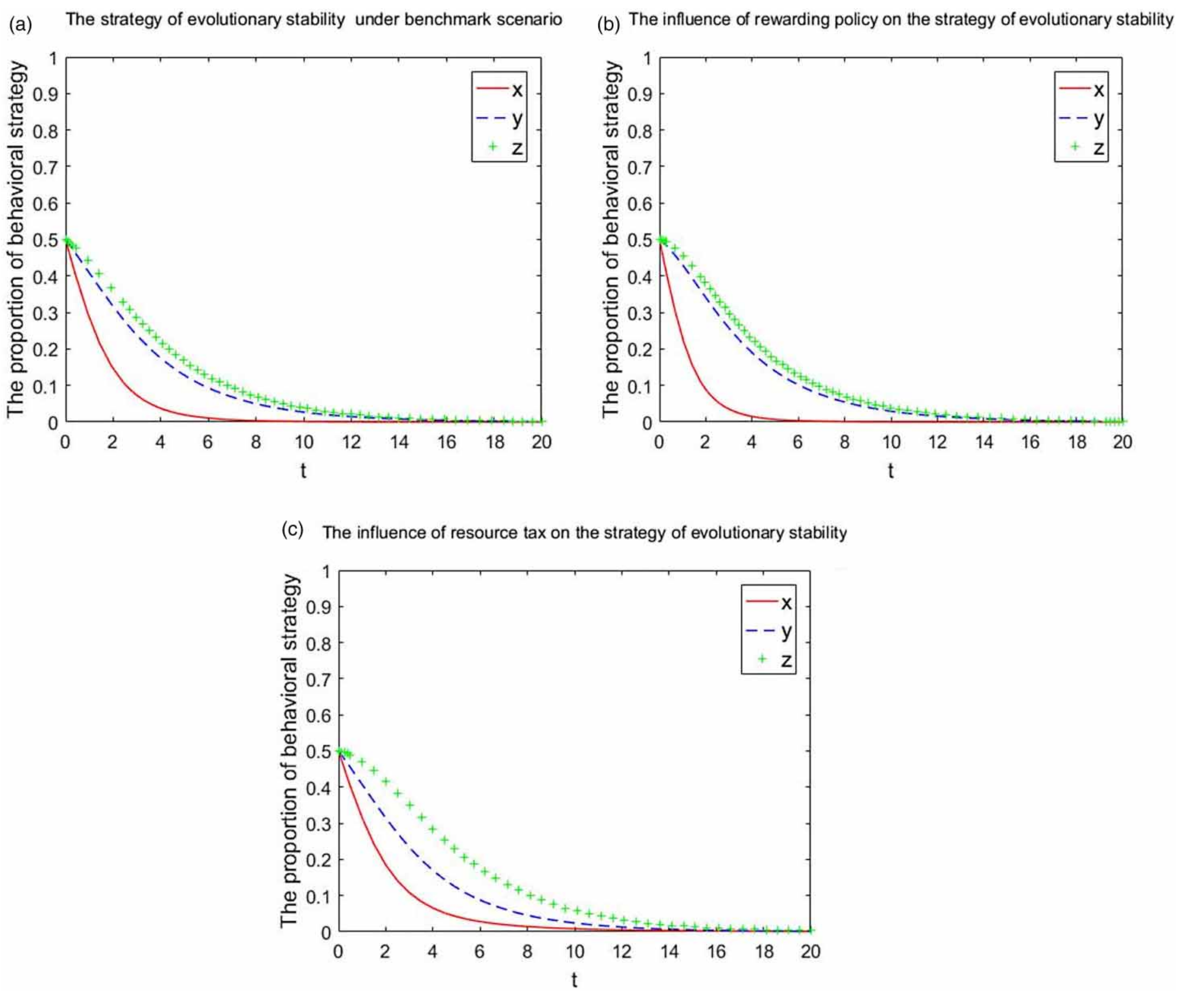


Figure 2 | Evolutionary stability strategy under different scenarios in an extensive expansion period.

problems. Energy enterprises and food producers are stable in the non-water-saving strategy since the water-saving strategy cost is higher than the benefit.

Situation (2): When local governments add the reward of water-saving behavior, $C_g - \beta T < 0$, $\gamma J + \Delta S_f + \eta W_f < C_f$, $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e$. The total cost of energy enterprises and food producers is still significantly higher than the total benefit of water-saving, which indicates that the guidance of the local governments is not enough. Therefore, the energy enterprises and food producers will still adopt the strategy of non-water-saving. The asymptotically stable point E_4 (1,0,0) is the only evolutionary stable point. Compared with Situation (1), after a period of economic development, local governments began to pay attention to the issue of saving water and utilized the water-saving reward and the water resources tax for encouraging large water consumers such as energy enterprises and food producers to save water. During this period, the finance of local governments has some initial accumulation. However, due to the weak financial foundation and many projects requiring support, the guidance of local governments for the intensive use of water resources is not enough. At this time, agriculture is still in the stage of labor-intensive production, the mechanized cost of large-scale water-saving is still very high, and the popularization rate is low. Therefore, food producers still choose the non-water-saving strategy with lower costs despite the temptation of a water-saving reward. Even though local governments will reward water-saving behavior and impose a water resources tax on non-water-saving behavior, energy enterprises will continue to refuse to save water under non-compulsory local government supervision because water-saving technology is still in its infancy and the cost is high. This is the initial period of water-saving, and the degree of water-saving is still low. At this stage, there was a 'competition of water-consuming' between energy enterprises and food producers under the water-saving policy of the government.

In the initial period of water-saving, the initial parameter shall meet the conditions: $\Delta S_f - C_f + \eta W_f < 0$, $\Delta S_e - C_e + \delta W_e < 0$, $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e$, $\gamma J + \Delta S_f + \eta W_f < C_f$, and $C_g - \beta T < 0$. Based on the above the conditions, the initial values of the parameters are set as: the cost of guidance of the local governments $C_g = 0.2$, the local governments' reward for food producers saving water $\gamma J = 0.3$, the increased benefit of food producers after choosing a water-saving strategy $\Delta S_f = 0.2$, the losses of food producers caused by the water shortage $\eta W_f = 0.3$, the cost that food producers pay for water-saving measures $C_f = 1.5$, the extra benefits of food producers not saving water $\pi S_f = 0.4$, the local governments' reward for the energy enterprises saving water $\alpha J = 0.3$, the costs of energy enterprises for local governments levying resource tax $\beta T = 0.3$, the increased benefit of energy enterprises after saving water $\Delta S_e = 0.2$, the losses of energy enterprises caused by the water shortage $\delta W_e = 0.3$, the cost that energy enterprises pay for water-saving technologies $C_e = 1.8$, the extra benefit of energy enterprises not saving water $\pi S_e = 0.4$. According to the above parameters, the tripartite evolutionary stability strategies of local governments, energy enterprises, and food producers under the benchmark scenario are shown in Figure 3(a). The local governments transfer from the 'initial strategy of not guiding' to the 'strategy of guiding,' and the energy enterprises and food producers still choose to adopt the strategy of not saving water since the high water-saving cost and insufficient guidance. As shown in Figure 3(a), with time, the three players of the game finally stabilize at the stage of local governments guiding, and both energy enterprises and food producers do not save water. Changing the incentives of the local governments for the water-saving behavior. When $\gamma J = \alpha J = 0.6$, the influence of the change of reward policy on the evolutionary stability strategy is shown in Figure 3(b). Compared with the benchmark situation, although the local governments increase the reward for the water-saving behavior, energy enterprises and food producers still stabilize at the strategy of not saving water since the water-saving cost is too high. Changing the tax of water resources, when βT is 0.6, the influence of the change of water resources tax on the evolutionary stability strategy is shown in Figure 3(c). Compared with the benchmark situation, although an increase in resource tax does not affect the strategic choices of the three parties in the game, the greater the intensity of the water resources tax, the longer the evolution time for energy enterprises to reach a stable strategy of not conserving water. In summary, in the initial period of water-saving, local governments began to pay attention to intensive water resources. They will guide the water-saving strategies of large water consumers. However, energy enterprises and food producers will stabilize at the strategies of not saving water since the water-saving cost is higher than the benefit.

Situation (3): When $\gamma J + \Delta S_f + \eta W_f > C_f$ and $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e + \pi S_e$, the local governments strengthen the guidance so that the total cost of saving water for food producers is less than the total benefit of saving water. Thus, food producers choose the strategy of saving water. The asymptotically stable point E_5(1,1,0) is the only evolutionary stable point. During this period, local governments continue to pay attention to the issue of saving water and utilize the water-saving reward and the water resources tax for encouraging large water consumers such as energy enterprises and food producers to save water. Compared with Situation (2), the improvement of agricultural water-saving technology leads to a

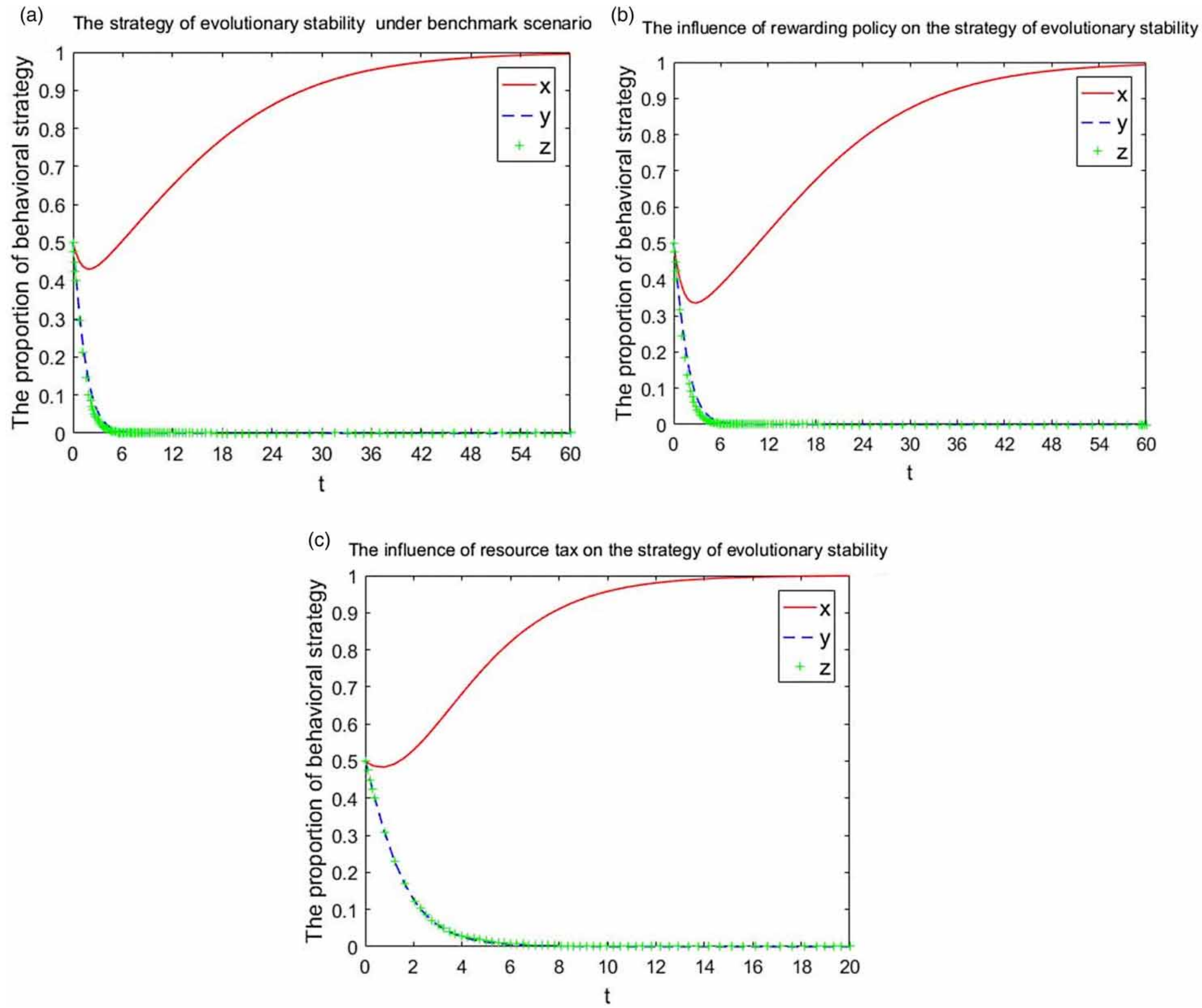


Figure 3 | Evolutionary stability strategy under different scenarios in the initial period of water-saving.

decrease in the water-saving cost. The total water-saving benefit is greater than the water-saving cost of food producers. As a rational 'economic man,' food producers will voluntarily choose the water-saving strategy. However, similar to Situation (2), even though local governments will reward water-saving behavior and levy a water resources tax for non-water-saving behavior, energy enterprises will continue to choose not to save water under non-compulsory local government supervision because water-saving technology is complex and expensive. This is the developing period of water-saving, and the level of water-saving is still modest. At this point, energy enterprises and food producers are transitioning from 'water-consuming competition' to 'water-saving cooperation.'

In the developing period of water-saving, the initial parameter shall meet the conditions: $\Delta S_f - C_f + \eta W_f < 0$, $\Delta S_e - C_e + \delta W_e < 0$, $\gamma J + \Delta S_f + \eta W_f > C_f$ and $\alpha J + \beta T + \Delta S_e + \delta W_e < C_e + \pi S_e$. Based on the above the conditions, the initial values of the parameters are set as: the cost of guidance of the local governments $C_g = 0.1$, the local governments' reward for food producers saving water $\gamma J = 0.3$, the increased benefit of food producers after choosing a water-saving strategy $\Delta S_f = 0.2$, the losses of food producers caused by the water shortage $\eta W_f = 0.3$, the cost that food producers pay for water-saving measures $C_f = 0.5$, the extra benefits of food producers not saving water $\pi S_f = 0.4$, the local governments' reward for the energy enterprises saving water $\alpha J = 0.3$, the costs of energy enterprises for local governments levying resource tax $\beta T = 0.8$, the increased benefit of energy enterprises after water-saving $\Delta S_e = 0.2$, the losses of energy enterprises

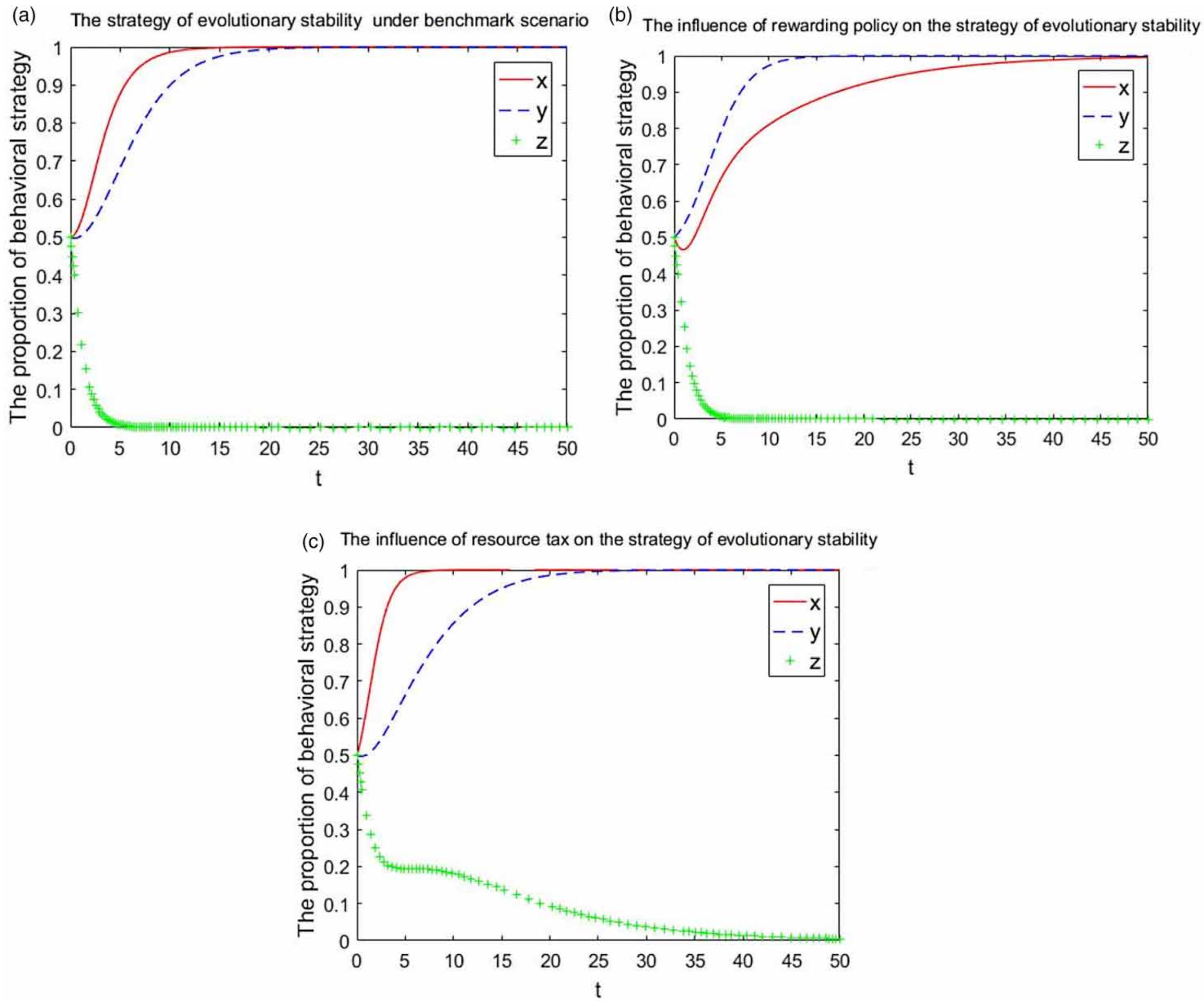


Figure 4 | Evolutionary stability strategy under different scenarios in the developing period of water-saving.

caused by the water shortage $\delta W_e = 0.3$, the cost that energy enterprises pay for water-saving technologies $C_e = 2$, the extra benefit of energy enterprises saving water water $\pi S_e = 0.4$. According to the above parameters, the tripartite evolutionary stability strategies of local governments, energy enterprises, and food producers under the benchmark scenario are shown in Figure 4(a). The local governments are stable in the guidance strategy. The water-saving benefit of food producers is greater than the water-saving cost. Food producers gradually transferred from the strategy of not saving water to the strategy of saving water and finally stabilized at the strategy of saving water. Due to the bottleneck of water-saving technology and the high cost, energy enterprises still adopt the strategy of not saving water. The three players of the game finally stabilize in the strategies local governments choose to guide, food producers save water, and energy enterprises do not save water. Changing the incentives of local governments for water-saving behavior when $\gamma J = \alpha J = 0.6$, the influence of the change of reward policy on the evolutionary stability strategy is shown in Figure 4(b). Compared with the benchmark situation, even though food producers continue to use the water-saving strategy, the greater the intensity of the water-saving reward, the quicker the time it takes for food producers to attain a stable water-saving strategy. Changing the tax of water resources, when βT is 1.5, the influence of the change of the water resources tax on the evolutionary stability strategy is shown in Figure 4(c). Although an increase in the water resources tax does not affect the strategic choices of the three players in the game, the greater the intensity of the water resources tax, the longer it takes for energy enterprises to establish

Table 5 | The stability analysis of equilibrium points when $\Delta S_f + \eta W_f > C_f + \pi S_f$ and $\Delta S_e + \delta W_e > C_e + \pi S_e$

Equilibrium points		E_1 (0,0,0)	E_2 (0,0,1)	E_3 (0,1,0)	E_4 (1,0,0)	E_5 (1,1,0)	E_6 (1,0,1)	E_7 (0,1,1)	E_8 (1,1,1)
Eigenvalues	λ_1	–	<0	–	–	–	>0	<0	>0
	λ_2	>0	>0	<0	>0	<0	>0	<0	<0
	λ_3	>0	<0	>0	>0	>0	<0	<0	<0
Conditions of asymptotic stability		Instability	Instability	Instability	Instability	Instability	Instability	asymptotic stability	Instability

a stable strategy of not saving water. Therefore, in the developing period of water-saving, the reward strategy of local governments promotes food producers to stabilize in the water-saving strategy. The water resources tax of local governments has a reverse coercion effect on the water-saving strategy of energy enterprises in the short term. In the long run, the strategic choice of energy enterprises depends on multiple factors such as the regulation of local governments and the water-saving cost.

3.2. The water-saving costs of energy enterprises and food producers are both less than the benefits

When the water-saving costs of energy enterprises and food producers are less than the benefit, $\Delta S_f + \eta W_f > C_f + \pi S_f$ and $\Delta S_e + \delta W_e > C_e + \pi S_e$. The asymptotic stability of the tripartite evolutionary game system of local governments, energy enterprises, and food producers is shown in Table 5.

From Table 5, when the water-saving cost is less than the water-saving benefit, energy enterprises and food producers will eventually choose the strategy of saving water after long-term evolution, whether the local government guides it. At this time, the asymptotic stable point E_7(0,1,1) is the only evolutionary stable point, which indicates that compared with the reward and tax of local governments, the profit of water-saving technology influences the strategic choice of energy enterprises and food producers more directly and significantly. During this period, the awareness of intensive water resources of the whole society is robust, the water-saving technology is mature, and the water-saving cost is low. As the bounded rational 'economical people,' energy enterprises and food producers will also spontaneously choose water-saving strategies. The serious water-wasting and the potential water shortage crisis will be gradually alleviated. This is the mature period of water-saving, and the degree of water-saving is high. At this point, energy companies and food producers have realized the change from 'water-consuming competition' to 'water-saving cooperation ' and optimized water resource usage.

In the mature period of water-saving, the initial parameter shall meet the conditions: $\Delta S_f + \eta W_f > C_f + \pi S_f$ and $\Delta S_e + \delta W_e > C_e + \pi S_e$. Based on the above the conditions, the initial values of the parameters are set as: the cost of guidance of the local governments $C_g = 0.1$, the local governments' reward for food producers saving water $\gamma J = 0.3$, the increased benefit of food producers after choosing a water-saving strategy $\Delta S_f = 0.5$, the losses of food producers caused by the water shortage $\eta W_f = 0.2$, the cost that food producers pay for water-saving measures $C_f = 0.1$, the extra benefits of food producers not saving water $\pi S_f = 0.2$, the local governments' reward for the energy enterprises saving water $\alpha J = 0.3$, the costs of energy enterprises for local governments levying resource tax $\beta T = 0.3$, the increased benefit of energy enterprises after saving water $\Delta S_e = 0.5$, the losses of energy enterprises caused by the water shortage $\delta W_e = 0.2$, the cost that energy enterprises pay for water-saving technologies $C_e = 0.1$, the extra benefit of energy enterprises not saving water $\pi S_e = 0.2$. According to the above parameters, the tripartite evolutionary stability strategies of local governments, energy enterprises, and food producers under the benchmark scenario are shown in Figure 5(a). As people become more conscious of the importance of conserving water and science and technology advance, the cost of conserving water is less than the benefit of conserving water. Energy enterprises and food producers gradually transferred to the water-saving strategy and finally stabilized in the water-saving strategy. The large water consumers spontaneously save water, and the local governments also gradually stabilize from the initial guiding strategy to the strategy of not guiding. From Figure 5(a), with time, the three players of the game finally stabilized in the strategy that the local governments do not guide, and the energy enterprises and food producers both save water. Changing the reward of local governments for the water-saving behavior, when $\gamma J = \alpha J = 0.6$, the influence of the change of reward policy on the evolutionary stability strategy is shown in Figure 5(b). It can be seen that after the increase in the reward of local

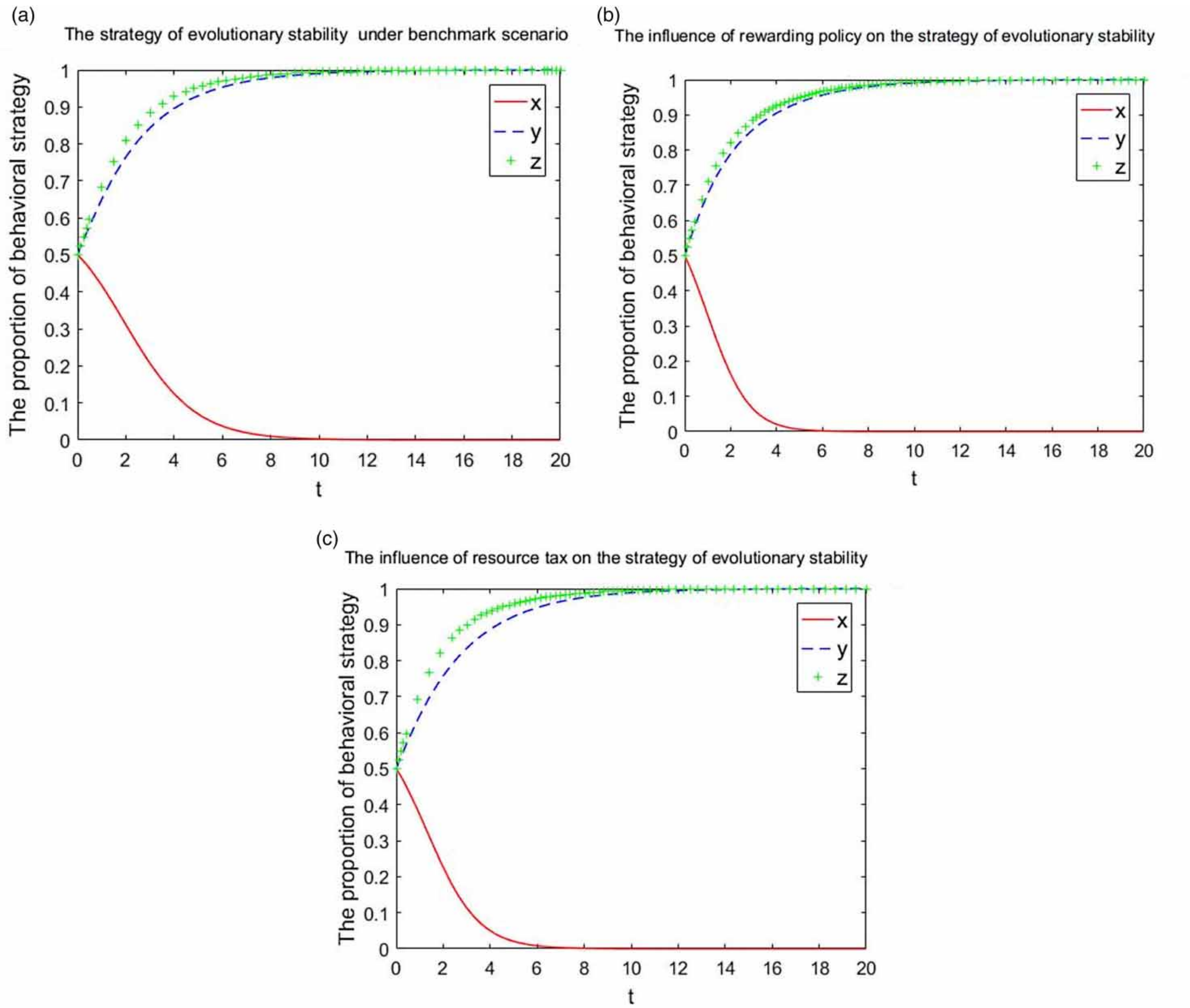


Figure 5 | Evolutionary stability strategy under different scenarios in the mature period of water-saving.

governments for water-saving, energy enterprises and food producers are still stable in the water-saving strategy, and there is no difference from the benchmark situation. Changing the tax of water resources, when βT is 0.6, the influence of the water resources tax on the evolutionary stability strategy is shown in Figure 5(c). Compared with the benchmark situation, although a change in the water resources tax does not affect the strategic choices of the three players in the game, the greater the intensity of the water resources tax, the shorter the evolutionary time for energy enterprises to establish a stable water-saving strategy. Therefore, in the mature period of water-saving, energy enterprises and food producers will adopt the water-saving strategy.

4. RESULTS

According to the theory of economic development stage and the analysis and discussion of the simulations in the previous section, the main contradictions faced by different stages of economic development are different. Therefore, we further summarize and interpret the results as follows:

1. The stability strategy of System (I) is not immutable, and the stability strategy of the game system is different with different stages of economic development. In the extensive expansion period of water-saving, energy enterprises and food producers

are stable in the non-water-saving strategy. On the contrary, in the mature period of water-saving, energy enterprises and food producers will adopt the water-saving strategy.
2. During the progress from the period of extensive expansion to the mature period of water-saving, large water consumers' water-saving behavior requires the government's guidance. The study of this paper shows that when the local government levies the tax on water resources, the time for energy enterprises to choose the strategy of not saving water becomes more extended, and the time of choosing the strategy of saving water becomes shorter. By adopting a series of water-saving policies, the local governments promote the water-saving behavior of energy enterprises and food producers.
3. The choice of water-saving behavior of energy enterprises and food producers is influenced by the guiding policies of local governments and depends on the water-saving cost. During the period of extensive expansion, the initial period of water-saving, and the developing period of water-saving, with the strengthening guidance and the reduction of water-saving costs, energy enterprises and food producers gradually transfer from the strategy of not saving water to the strategy of saving water together.
4. In the mature period of water-saving, energy enterprises and food producers have realized the transformation from the 'competition of water-consuming' to the 'cooperation of water-saving,' and the utilization of water resources has been maximized.

5. CONCLUSIONS

The shortage of water resources caused by extreme climate change has hugely exacerbated the water resource competition between energy enterprises and food producers. Therefore, from the perspective of the water-energy-food nexus, this paper introduces the game theory, puts forward the theory of the water-saving development stage according to the theory of economic development stage of Rostow (Rostow 1959), constructs the evolutionary game model composed of local governments, energy enterprises, and food producers, and further analyzes the strategic choices of the three players in different development stages. This work could apply to countries and regions with serious water use competition between food and energy production, such as Northwest China, Ethiopia, etc. Future research should focus on analyzing the influence of specific policies issued by local governments on the water-saving behavior of energy enterprises and food producers.

6. POLITICAL RECOMMENDATIONS

The study in this paper would provide a basis for the behavioral choices of energy enterprises and food producers and provide a reference for the political decision-making of the local governments. According to the above results and conclusions, the political recommendations are given as follows:

1. At different stages of economic development, the government should adopt different guidance strategies for water-saving. Local governments must guide the water-saving behavior through 'one policy at a time.' In the period of extensive expansion, local governments should actively promote the intensive water resources while devoting the economic development to prepare for the early entry into the society of intensive resources and the realization of regionally sustainable development. In the initial period of water-saving and the developing period of water-saving, the government should design the guiding policy of 'rewarding the good and punishing the bad' and use the two-way incentive effect of special funds.
2. To reduce the water-saving cost of large water consumers, the governments should support the innovation of water-saving technology. Local governments should encourage high-tech innovation, including constructing facilities to save water and promote drought-resistant grain varieties. As one of the major water consumers, the energy industry should be included in the annually technological transformation and upgrading plan of the Ministry of Industry and Information Technology. The financial support for technological transformation projects should be strengthened through industrial funds, bond financing, and special taxes on resources.
3. To improve the water-saving concept of large water consumers, the governments should strengthen the publicity of intensive water resources. Local governments should adopt the suggestions of experts and scholars in many aspects, especially economists' suggestions about the economic development stage and sustainable development. Moreover, local governments should also strengthen the guidance of intensive water resources and improve the water-saving consciousness of large water consumers. Thus, a society of intensive resources will be constructed as soon as possible, and sustainable development will be realized.

4. The government should raise the levying standard of resources tax to reverse coerce the water-saving behavior of large water consumers. Keeping the water resources tax in the local area can make up for the cost of guidance of local governments. On the one hand, the government should dynamically increase resource taxes to achieve the double dividend of user payment and resource tax reform; on the other hand, the government should implement the resource tax unique fund system and ensure that all resource tax revenue is used as special funds for intensive use of local natural resources and environmental protection.

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the Postgraduate Research Innovation Program of Jiangsu Province (no. KYCX21_0444), the Fundamental Research Funds for the Central Universities, the Major Project of National Social Science Foundation of China (Grant No. 19ZDA084), and the Fundamental Research Funds for the Central Universities (no. B200207010). We appreciate the editor and anonymous reviewers for their beneficial comments and suggestions that improve the quality of this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICTS OF INTEREST STATEMENT

The authors declare there is no conflict.

REFERENCES

Ahmad, T., Ahmad, K. & Alam, M. 2016 Sustainable management of water treatment sludge through 3'R' concept. *Journal of Cleaner Production* **124**, 1–13. doi:10.1016/j.jclepro.2016.02.073.

Aili, A., Zhao, D. L., Tan, G., Yin, X. B. & Yang, R. G. 2021 Reduction of water consumption in thermal power plants with radiative sky cooling. *Applied Energy* **302**. doi:10.1016/j.apenergy.2021.117515.

Albrecht, T. R., Crootof, A. & Scott, C. A. 2018 The water-energy-food nexus: a systematic review of methods for nexus assessment. *Environmental Research Letters* **13** (4). doi:10.1088/1748-9326/aaa9c6.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J. & Yumkella, K. K. 2011 Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* **39** (12), 7896–7906. doi:10.1016/j.enpol.2011.09.039.

Cetin, O. & Kara, A. 2019 Assesment of water productivity using different drip irrigation systems for cotton. *Agricultural Water Management* **223**. doi:10.1016/j.agwat.2019.105693.

Chartzoulakis, K. & Bertaki, M. 2015 Sustainable water management in agriculture under climate change. *Efficient Irrigation Management and Its Effects in Urban and Rural Landscapes* **4**, 88–98. doi:10.1016/j.aaspro.2015.03.011.

Chen, Z., Chen, F. & Yu, R. 2020 Introducing water-saving service or not? modeling analysis of competing high-water-consumption manufacturers. *Urban Water Journal* **18** (1), 9. doi:10.1080/1573062X.2020.1857798.

Damerau, K., Patt, A. G. & van Vliet, O. P. R. 2016 Water saving potentials and possible trade-offs for future food and energy supply. *Global Environmental Change-Human and Policy Dimensions* **39**, 10. doi:10.1016/j.gloenvcha.2016.03.014.

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G. K., Seekell, D. A., Suweis, S. & Rulli, M. C. 2018 The global food-energy-water nexus. *Reviews of Geophysics* **56** (3), 456–531. doi:10.1029/2017rg000591.

Dubreuil, A., Assoumou, E., Bouckaert, S., Selosse, S. & Maizi, N. 2013 Water modeling in an energy optimization framework – the water-scarce middle east context. *Applied Energy* **101**, 268–279. doi:10.1016/j.apenergy.2012.06.032.

Gao, X., Shen, J., He, W., Sun, F., Zhang, Z. & Guo, W. 2019 An evolutionary game analysis of governments' decision-making behaviors and factors influencing watershed ecological compensation in China. *Journal of Environmental Management* **251**. doi:10.1016/j.jenvman.2019.109592.

Gasbarro, F., Rizzi, F. & Frey, M. 2016 Adaptation measures of energy and utility companies to cope with water scarcity induced by climate change. *Business Strategy and the Environment* **25** (1), 18. doi:10.1002/bse.1857.

Ge, W. J., Zhao, Y. B., Song, S. W., Li, W. D., Gao, S. S. & Chen, T. F. 2020 Thermal characteristics of dry cooling tower reconstructed from obsolete natural draft wet cooling tower and the relevant thermal system coupling optimization. *Applied Thermal Engineering* **174**. doi:10.1016/j.applthermaleng.2020.115202.

Hua, E., Wang, X. Y., Engel, B. A., Sun, S. K. & Wang, Y. B. 2020 The competitive relationship between food and energy production for water in China. *Journal of Cleaner Production* **247**. doi:10.1016/j.jclepro.2019.119103.

Kahil, M. T., Dinar, A. & Albiac, J. 2016 Cooperative water management and ecosystem protection under scarcity and drought in arid and semiarid regions. *Water Resources and Economics* **13**, 14. doi:10.1016/j.wre.2015.10.001.

Lazaro, L. L. B., Giatti, L. L., Bermann, C., Giarolla, A. & Ometto, J. 2021 Policy and governance dynamics in the water-energy-food-land nexus of biofuels: proposing a qualitative analysis model. *Renewable & Sustainable Energy Reviews* **149**. doi:10.1016/j.rser.2021.111384.

Liu, S. L., Wang, Y. X. & Mao, X. H. 2013 Calculation and analysis of water footprint in Shunyi District of Beijing. *Applied Mechanics and Materials* **295–298**, 4. doi:10.4028/www.scientific.net/AMM.295-298.964.

Long, D., Yang, W. T., Scanlon, B. R., Zhao, J. S., Liu, D. G., Burek, P., Pan, Y., You, L. Z. & Wada, Y. 2020 South-to-North water diversion stabilizing Beijing's groundwater levels. *Nature Communications* **11** (1). doi:10.1038/s41467-020-17428-6.

Lu, S., Lian, Z., Sun, H., Wu, X., Bai, X. & Wang, C. 2021 Simulating trans-boundary watershed water resources conflict. *Resources Policy* **73**. doi:10.1016/j.resourpol.2021.102139.

Mahjabin, T., Mejia, A., Blumsack, S. & Grady, C. 2020 Integrating embedded resources and network analysis to understand food-energy-water nexus in the US. *Science of the Total Environment* **709**. doi:10.1016/j.scitotenv.2019.136153.

Marvin, H. J., Kleter, G. A., Noordam, M. Y., Franz, E., Willems, D. J. & Boxall, A. 2013 Proactive systems for early warning of potential impacts of natural disasters on food safety: climate-change-induced extreme events as case in point. *Food Control* **34** (2), 12. doi:10.1016/j.foodcont.2013.04.037.

MWR 2017 *China Water Resources Bulletin.* China Water & Power Press, Beijing, China.

MWR 2019 *China Water Resources Bulletin.* China Water & Power Press, Beijing, China.

Nouri, H., Stokvis, B., Galindo, A., Blatchford, M. & Hoekstra, A. Y. 2019 Water scarcity alleviation through water footprint reduction in agriculture: the effect of soil mulching and drip irrigation. *Science of the Total Environment* **653**, 241–252. doi:10.1016/j.scitotenv.2018.10.311.

Pahl-Wostl, C. 2019 Governance of the water-energy-food security nexus: a multi-level coordination challenge. *Environmental Science & Policy* **92**, 356–367. doi:10.1016/j.envsci.2017.07.017.

Pan, L. Y., Liu, P., Ma, L. W. & Li, Z. 2012 A supply chain based assessment of water issues in the coal industry in China. *Energy Policy* **48**, 93–102. doi:10.1016/j.enpol.2012.03.063.

Panagopoulos, A. 2021a Beneficiation of saline effluents from seawater desalination plants: fostering the zero liquid discharge (ZLD) approach – a techno-economic evaluation. *Journal of Environmental Chemical Engineering* **9** (4). doi:10.1016/j.jece.2021.105338.

Panagopoulos, A. 2021b Water-energy nexus: desalination technologies and renewable energy sources. *Environmental Science and Pollution Research* **28** (17), 21009–21022. doi:10.1007/s11356-021-13332-8.

Qin, Y. 2021 Global competing water uses for food and energy. *Environmental Research Letters* **16** (6). doi:10.1088/1748-9326/064091.

Qu, X. L., Alvarez, P. J. J. & Li, Q. L. 2013 Applications of nanotechnology in water and wastewater treatment. *Water Research* **47** (12), 3931–3946. doi:10.1016/j.watres.2012.09.058.

Rasul, G. & Sharma, B. 2016 The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy* **16** (6), 682–702. doi:10.1080/14693062.2015.1029865.

Rosa, L., Chiarelli, D. D., Rulli, M. C., Dell'Angelo, J. & D'Odorico, P. 2020 Global agricultural economic water scarcity. *Science Advances* **6** (18). doi:10.1126/sciadv.aaz6031.

Rostow, W. W. 1959 The stages of economic growth. *The Economic History Review* **12** (1), 16.

Selten, R. 1980 A note on evolutionarily stable strategies in asymmetric animal conflicts. *Journal of Theoretical Biology* **84** (1), 93–101. doi:10.1016/s0022-5193(80)81038-1.

Shan, H. & Yang, J. 2019 Sustainability of photovoltaic poverty alleviation in China: an evolutionary game between stakeholders. *Energy* **181**, 16. doi:10.1016/j.energy.2019.05.152.

Susnik, J., Masia, S., Indriksone, D., Bremere, I. & Vamvakeridou-Lydroudia, L. 2021 System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. *Science of the Total Environment* **775**. doi:10.1016/j.scitotenv.2021.145827.

Tian, D., Zhang, Y. Y., Mu, Y. J., Zhou, Y. Z., Zhang, C. L. & Liu, J. F. 2017 The effect of drip irrigation and drip fertigation on N_2O and NO emissions, water saving and grain yields in a maize field in the North China Plain. *Science of the Total Environment* **575**, 1034–1040. doi:10.1016/j.scitotenv.2016.09.166.

Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D. & Frieler, K. 2019 The effects of climate extremes on global agricultural yields. *Environmental Research Letters* **14** (5), 054010. doi:10.1088/1748-9326/ab154b.

Wei, S., Yang, H., Abbaspour, K., Mousavi, J. & Gnauck, A. 2010 Game theory based models to analyze water conflicts in the middle route of the south-to-north water transfer project in China. *Water Research* **44** (8), 17. doi:10.1016/j.watres.2010.01.021.

Xu, L. Y., Huang, D. C., He, Z. Q. & Zhu, Y. 2022 An analysis of the relationship between water-energy-food system and economic growth in China based on ecological footprint measurement. *Water Policy* **24** (2), 345–362. doi:10.2166/wp.2022.182.

Yuan, J. H. & Luo, X. G. 2019 Regional energy security performance evaluation in China using MTGS and SPA-TOPSIS. *Science of the Total Environment* **696**, 133817. doi:10.1016/j.scitotenv.2019.133817.

Zhang, X. D. & Vesselinov, V. V. 2017 Integrated modeling approach for optimal management of water, energy and food security nexus. *Advances in Water Resources* **101**, 1–10. doi:10.1016/j.advwatres.2016.12.017.

Zhang, X. X., Zhou, S., Bi, J. G., Sun, H. F., Wang, C. & Zhang, J. N. 2021 Drought-resistance rice variety with water-saving management reduces greenhouse gas emissions from paddies while maintaining rice yields. *Agriculture Ecosystems & Environment* **320**. doi:10.1016/j.agee.2021.107592.

Zhao, T. & Liu, Z. 2019 A novel analysis of carbon capture and storage (CCS) technology adoption: an evolutionary game model between stakeholders. *Energy* **189**, 116352. doi:10.1016/j.energy.2019.116352.

Zhou, Y. C., Wei, B., Zhang, R. & Li, H. 2022 Evolution of water-energy-food-climate study: current status and future prospects. *Journal of Water and Climate Change* **13** (2), 463–481. doi:10.2166/wcc.2021.450.

First received 12 February 2022; accepted in revised form 19 May 2022. Available online 3 June 2022