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Sustainable Organic Farming, Food Safety and Pest Management: An Evolutionary Game Analysis

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Abstract: There is an increasing realization that industrial, large-scale agriculture can negatively impact both food quality and the environment, and that alternatives should be thoroughly considered. Consisting of various participants with distinct and often competing interests, organic food chains have a dynamic structure. We consider an evolutionary game theory model for the dynamics of an organic supply chain with farmers, their customers and the government as the main stakeholders. After describing stakeholder strategies and constructing appropriate payoff matrices for the interactions between farmers and customers and between farmers and the government, respectively, sufficient conditions for the stability of the equilibria for the associated replicator equations were found. Those conditions were then interpreted in practical terms, the corresponding possible outcomes being determined and numerically illustrated. It was seen that a sustainable shift from a conventional strategy to an organic one requires the efforts of all involved stakeholders. As far as the evolutionary interaction between farmers and customers is concerned, it was seen that the purchasing power and the organic awareness of customers are of the utmost importance for the establishment and diffusion of organic strategies in the supply chain. Furthermore, a situation in which the preferences of farmers and consumers for an organic (or conventional) strategy change periodically may occur. Regarding the evolutionary interaction between farmers and the government, strong support for organic farmers is needed at first, and then the consumption habits and environmental awareness of the consumers can be cultivated. This promotes the establishment, development and enrichment of an organic supply chain which, at a certain point, can persist even without governmental subsidies.

Keywords: evolutionary game theory; stability of equilibria; sustainable farming; organic supply chain

MSC: 91A22; 34D30

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1. Introduction

As early as 4500 years ago, humans already knew how to use pesticides in order to prevent pest damage to their crops, the earliest documented instance of pest control being Sumerians' use of sulfur compounds to get rid of harmful insects. Alternative, non-chemical approaches were pursued in ancient times too. Around 1200 BC, the Chinese were already using predatory ants to protect citrus groves from caterpillars and woodboring beetles. Further, the ancient Egyptians relied upon assembling lines of human drovers in order to repeal locust swarms.

Pesticides may be defined as chemical substances, biological agents (such as viruses or bacteria), antimicrobials and disinfectants that can be used against pests with the purpose of protecting crops from decreases in yield or quality [1]. The efficient use of pesticides has ancillary benefits that include saving time and manpower [2,3]. Besides, pesticide use is sometimes the only feasible way of suppressing insect vectors spreading prevalent diseases.

For instance, Ross [4] pointed out that DDT has been shown, over the past 60 years, to be one of the very few affordable and effective tools against malaria-transmitting mosquitoes. Additionally, the use of insecticide-treated bed nets has been observed to lead to a decrease in the incidence of malaria infection and in infant mortality, as shown for instance in Lindblade et al. [5].

However, while the benefits of pesticide use include higher crop yields and mitigating the spread of vector-borne diseases, their downsides include the accumulation of toxic residues in food products. In 2016, the U.S. Department of Agriculture reported that pesticide residues exceeding tolerance levels set forth by the U.S. Environmental Protection Agency were detected in 0.46 percent (48 samples) of the total samples tested (10,365 samples). In 2006, Lu et al. [6] had measured dietary exposure to organophosphorus in a group of 23 elementary-school-age children through urinary biomonitoring and found that the median urinary concentrations of the specific metabolites for malathion and chlorpyrifos decreased to non-detectable levels immediately after the introduction of organic diets, and remained so until the conventional diets were reintroduced. Other studies have established that prolonged exposure to pesticides is associated with serious health problems such as respiratory problems, memory disorders, dermatological conditions [7], depression, neurological deficits [8], miscarriages and birth defects [9].

There is now overwhelming evidence that pesticide residue buildup leads to undesirable environmental side effects. A quantitative analysis designed to predict amounts of pesticides that would reach surface waters has been conducted in the U.S. as early as the 1970s [10]. According to a study of the U.S. Geological Survey that was conducted from 1992 to 2001, pesticides have been found to pollute virtually every lake, river and stream in the United States. In Calcutta, India's third-largest city, more than 90 percent of water and fish samples taken from a variety of sources contained traces of at least one, but more often of several pesticides [11]. Further, frequent pesticide use favors the selection of resistant pests [12], while also leading to a loss of environmental biodiversity. These matters constitute clear, actionable evidence for the necessity of minimizing pesticide use. As shown in Figure 1, which aggregates data available from PubMed, it is clear that the drawbacks of pesticide use are already well understood by researchers worldwide.

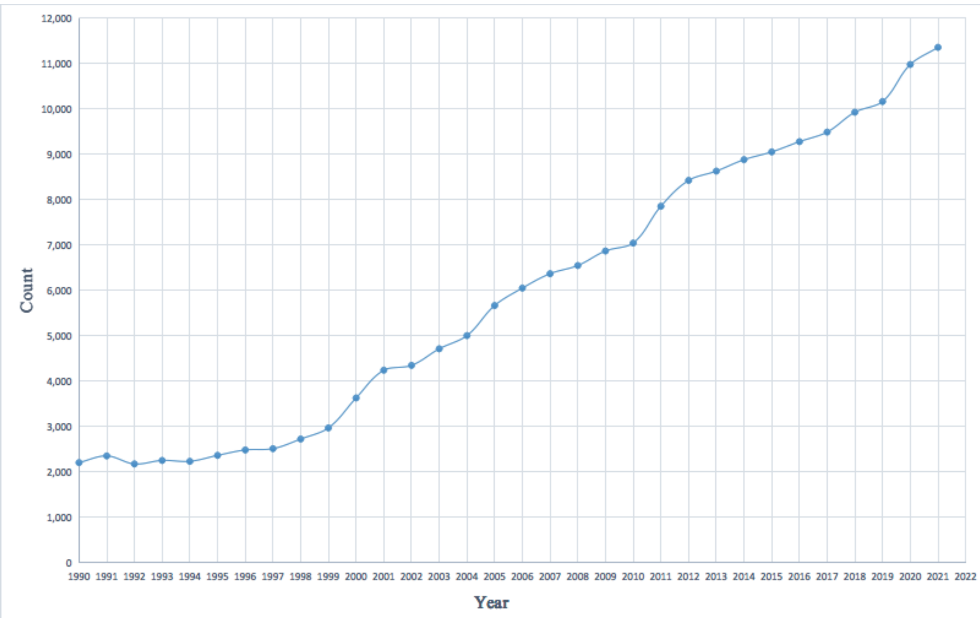

Figure 1. Trends on the publication of research papers about pesticides (source: PubMed).

A 2018 food and beverage survey of almost 1600 consumers conducted by L.E.K Consulting found that 93% of the consumers wanted to eat healthily at least some of the time, while 63% were trying to eat healthily most or all of the time, from which one can extrapolate that most consumers want all-natural and organic foods at least some of the time. However, the most in-demand foods were those which went one step further and did not contain artificial ingredients or preservatives either. This has been interpreted as reflecting consumers' growing desire to look beyond generic all-natural claims and truly understand the specifics and origin of the food they purchase. Healthy eating has, then, become a mainstream trend, with food products being increasingly expected to meet certain attributes of health, ethics and sustainability, which strengthens the belief that it is time to rethink the standards and practices used for food production.

Eyhorn et al. asserted that agricultural practices need to change in order to meet the United Nations Sustainable Development Goals by 2030, and that organic agriculture should be an important part of the strategy devised to achieve these goals [13]. Subsequently, driven by the customer demand for healthy food and sustainable development, farmers have (re)discovered alternative ways of farming. Instead of pesticides, for instance, they are using organic farm inputs as foliar fertilizers, not only adding nutrients at all stages of crop growth, but also mitigating pest infestation [14], with the subsequent produce fetching premium prices on the market [15].

Agricultural subsidies are one of the most commonly used policy tools for governmental support of agriculture [16]. As the demand for organic food is increasing steadily, the U.S. Department of Agriculture is now providing organic producers with subsidies, up to a maximal yearly amount of $20,000, via the Environmental Quality Incentives Program carried through the Natural Resources Conservation Service. However, the applicants need to be certified as organic producers first. The prospective organic producers can also apply for the Farmer's Market Promotion Program, which provides grants for up to more than $100,000 for projects which increase consumer access to farming products. For the organic farmers planning to export their produce outside of the United States, the government provides further loan and grant programs. For example, the Facility Guarantee Program gives payment guarantees to establish distribution facilities for agricultural products abroad. The expected outcomes of these subsidies are increased supply levels, product diversity and price stability, along with opportunities for employment and land use.

China's agricultural subsidy policies had their beginning in the 1950s. From 1980 to 1992, subsidizing agriculture was not a top priority for the government. In 2005, the Ministry of Commerce of the People's Republic of China promulgated the Interim Measures for the Administration of Funds for the Promotion of Trade in Agricultural, Light and Textile Products [17]. From 2006, the Agricultural and Light Textile Products Trade Promotion Fund Project has been providing certified organic producers with appropriate funding. In 2020, the Ministry of Agriculture and Rural Affairs, together with the Ministry of Finance, finished implementing the ecology-oriented reform of the subsidies policy in China.

Most sustainability research concerning organic supply chains, potentially providing insights for further policy development, has been focused on their structure and performances [18–22]. Consisting of various participants with vastly distinct interests, organic supply chains often have a dynamic structure. Kottila et al. [23] pointed out that the main obstacles to the optimization of the organic food chain include poor information management, insufficient communication with customers, and the diverging objectives and needs of the participants in the chain. Additionally, the sustainability of supply chains traditionally focuses on its environmental dimension, but its social and economic integration have been studied only in terms of optimization [24]. As shown in Figure 2, external factors should also be considered in the analysis of the chain.

Evolutionary game theory (EGT), which is able to study the relationships between different participants to the supply chain (stakeholders) in an effective manner, has been applied in management, economics, sociology and other disciplines [25]. Unlike classical game theory, EGT postulates that stakeholders keep on learning and dynamically adjust their actions according to previous successful behavior [26]. This paper applies EGT to analysis of the formation and evolution of an organic supply chain which involves farmers, their customers and the government as the main stakeholders, allowing for the identification of proper stakeholder strategies when affected by the decisions of other participants in the supply chain. The main objectives are to identify the real-world conditions necessary to support a sustainable organic supply chain via a theoretical analysis of relatable, reliable models, and to analyze the outcomes obtained under different scenarios. The key contributions are two evolutionary game models to explain the dynamics of an organic supply chain, which represents a realistic approach to understanding the strategies of the government, farmer and customers, whose roles, functions and objectives all affect the chain dynamics. As a result, we provide a conceptual framework to help stakeholders adjust their actions dynamically, a feature which is not shared by other methods.

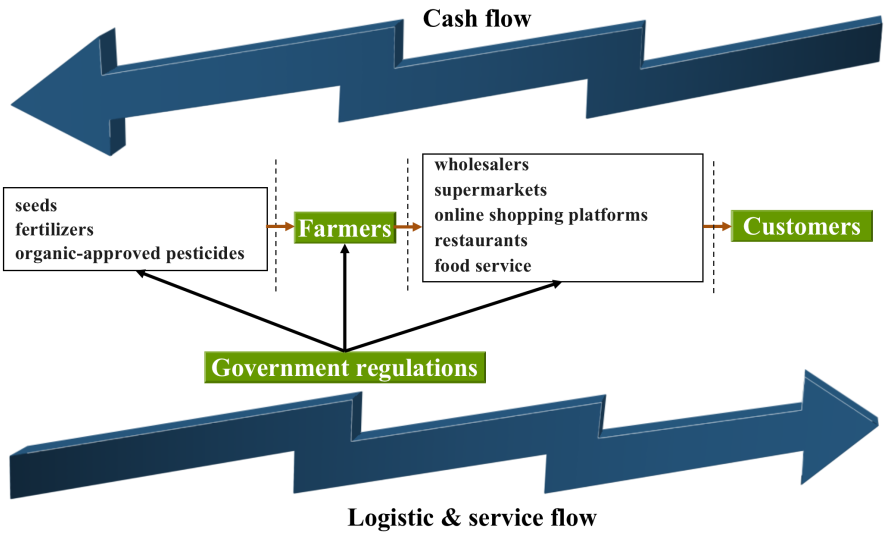

Figure 2. The organic supply chain.

The remaining part of this paper is organized as follows. In Section 2, we review the relevant literature, starting with a historical account of the development of EGT and continuing with relevant recent references concerned with the use of EGT in practical problems and with sustainable supply chain collaboration, respectively, and giving brief accounts of the results presented therein. In Section 3, we introduce several core concepts of EGT and list our evolutionary model assumptions. We then propose the evolutionary scenarios for the interactions between the farmers and the government and between the farmers and their customers, respectively, and determine the associated replicator equations. In Section 4, we analyze the evolutionary interactions via the linearization of the replicator equations in a vicinity of the equilibria, and find sufficient conditions to ensure the evolutionary stability of the respective strategies. The practical implications of these findings are then determined in Section 5 via an analysis of the model parameters, with numerical simulations then performed for an organic supply chain defined ad hoc. Finally, directions for further research are provided in Section 6.

2. Literature Review

2.1. Evolutionary Game Theory

EGT was first developed by Fisher in an attempt to explain the approximate equality of sex ratios in mammals [27]. In 1961, Lewontin was the first to apply game theory for the understanding of evolutionary biology in [28]. The concept of an evolutionarily stable strategy (hereinafter ESS) was first introduced in Maynard Smith in 1972 [29] and then put into widespread circulation by Maynard Smith and Price in 1973 [30]. The seminal text Evolution and the Theory of Games of Maynard Smith appeared in 1982, being followed shortly after by Robert Axelrod's famous work The Evolution of Cooperation, published in 1984 [31]. Since then, EGT has been widely applied to other disciplines such as economics and social sciences as well [32].

The appeal of this theory with explicit biological roots to economists, sociologists, and social scientists is threefold. First of all, evolution often equals cultural evolution, due to beliefs and norms changing over time. Secondly, the hypothesis of limited rationality proposed by evolutionary game theory is, in most cases, more appropriate for predicting the behavior of players than the complete rationality assumption of classical game theory. Thirdly, evolutionary game theory, as an explicitly dynamic approach, is appropriate for modeling strategic interactions, in which each player interacts with the others over a long term, the payoffs being affected by the choices made by others [25].

For instance, Barari et al. used an EGT approach to analyze the behavior of players in the tourism industry [33]. Liu et al. explored the evolution of a cooperative interaction by constructing evolutionary game models with local and asymmetric information, respectively [34,35]. Xu et al. investigated the behavioral strategies and interaction mechanisms of multiple stakeholders in a maritime power system [36] and discussed the influence of shore power implementation on the ESS of the stakeholders. Liu et al. [37] used an EGT analysis to discuss recycling strategies for household medical devices which are subject to governmental rewards and punitive measures, and it was determined that if the government adopts static measures, then there is no equilibrium point, while if either the rewards or the punitive measures are dynamic, then there is a stable equilibrium point. Zhou et al. [38] studied a tripartite evolutionary game associated with environmental pollution control, the stakeholders being the polluting enterprises, the government and the public, respectively, established the replicator dynamics and analyzed the effects of governmental punitive measures on excessive pollution and rewards for the public involved in enterprise supervision.

Matrix games in fuzzy environments that are applicable to multi-objective decision-making problems have been investigated in Karmakar et al. [39] and Seikh et al. [40], those matrix games being solved using the composite relative degree of similarity of the payoffs, rather than the traditional simplex method, a novel defuzzification approach being also proposed. The applicability of the proposed methodology was then illustrated to a biogas plant implementation problem and to a single-use plastic packaging ban problem, respectively.

2.2. Sustainable Supply Chain Collaboration

The importance of coordination mechanisms in improving the sustainability of a food chain has repeatedly been outlined [41,42]. Wu proposed two competitive supply chains with retail price and sales efforts as demand functions [43]. De Giovanni analyzed a closed-loop supply chain with green sales efforts [44]. Basiri and Heydari investigated the coordination issues of a green supply channel by means of a two-stage supply chain [45]. Chen et al. used an evolutionary game approach to examine the inception of green behaviors and of green supply chains in the hotel industry [46].

Consumer environmental awareness plays a vital role in making organic farming a viable alternative. With the rise of consumer environmental awareness, lifestyles have changed [47] and purchasing behaviors have changed as well. Of course, as pointed out in Ishaswini and Datta [48], for instance, consumers would prefer buying green products, but without spending too much.

On one hand, certain governments have started implementing public funding policies to promote organic farming [49]. Neiberg and Kuhnert [50] investigated the role of financial support in Germany and found out that, from the perspective of most organic farmers, policy support for organic farming is of considerable significance. On the other hand, pesticide use may generate higher tax incomes than organic farming for a government. A conflict trade-off is then generated for a government on how to control pesticide usage. Here, the government is assumed to be the first mover who sets up penalties, and the farmers as the followers who observe the penalty policy and then strategically decide for or against the use of pesticides.

In Yu and Khan [51], an evolutionary game model was built to describe the relationship between agricultural product suppliers and their customers in an urban environment, with urban residents as investors and agricultural product suppliers as financiers. Two financing platforms were also considered: network crowdfunding and banking services. It was seen that for the financing of the green agricultural product supply chain (GAPSC), and for narrowing the income gap between urban and rural areas, costs play a significant role. This endeavor is both high-cost and risky, and the urban residents account for the GAPSC's operational risk when deciding whether or not to invest.

The interaction of stakeholders in an organic supply chain is vital for the future development of organic farming [52]. Since a supply chain is susceptible to factors such as farmer benefits, government regulation, technology evolution and customer preference, it is essential to analyze the importance of these factors before constructing an evolutionary game model [24]. By considering the interaction of stakeholders and then analyzing the formation and evolution of an organic supply chain, we would be closer to a clear and comprehensive understanding of the sustainable development of organic farming.

3. Model Description

For further insights into the development of sustainable organic farming and into the evolution of an organic supply chain, we propose an EGT model which helps to analyze the dynamic process of stakeholder strategy selection. The farmers' ultimate goal is to obtain maximal monetary benefits, while the selection of an organic strategy is affected by factors such as peer competition, government policies and consumer preferences. For the sake of simplicity, in this paper we choose the major stakeholders of the organic supply chain to be the farmers, their customers and the government.

Evolutionarily stable strategies (ESS) and replicator dynamics (RD) are two core concepts of EGT [53]. An ESS is a strategy which, if adopted, cannot be invaded by any alternative competing strategy. In other words, if competing deviations can not affect the original, then the original represents an ESS. The concept of RD is used to express the evolutionary dynamics of an entity called a replicator, which has means of creating more or less accurate copies of itself. In EGT, replicators are strategies which compete for dominance according to the payoff yielded by the respective interactions between participants. If there is an occasional error deviation in the game, then the RD can restore it.

In an evolutionary game with n strategies, let $A = \{a_{ij}\} \in R^{n\times n}$ represent the payoff matrix, in which a_{ij} is the payoff when the strategy i is played against the strategy j, $i, j = 1, 2, \cdots, n$. The popularity of each strategy, interpreted as the number of times the strategy is played, is given by x_i, and the corresponding fitness is computed by $U_i = \Sigma_{j=1}^{n} x_j a_{ij}$. The average fitness of the population is denoted by $\bar{U} = \Sigma_{i=1}^{n} x_i U_i$. Hence, the RD can be expressed by the following equation

$$\frac{dX(t)}{dt} = X(U_s - \bar{U}), \tag{1}$$

in which X denotes the proportion of strategy s, U_s is its expected profit, $\bar{U}$ is the average profit of all strategies, and $\frac{dX(t)}{dt}$ denotes the change in the proportion of the strategy over time.

The construction of an evolutionary game model could help to analyze the behavioral characteristics of the strategic choices of stakeholders, who are weighing rational input and output benefits. As the government does not directly participate in the collaborative activities, it resorts to using macro-policies and incentives to promote cooperation in the organic supply chain and to attract more farmers to join in. Farmers may adopt an organic development strategy or stick to conventional farming, and consumer decisions may be volatile due to practical considerations. In this section, we consider a dynamic evolution model involving farmers, customers and the government as the stakeholders. The model assumptions are listed below.

Assumption 1. *Each stakeholder is rational.*

Assumption 2. *No stakeholder can accurately obtain the strategic choices of the other stakeholders. Stakeholders can find optimal strategies only by continuously adjusting their respective strategic choices.*

Assumption 3. *Two different strategies are considered for farmers and customers, namely an organic strategy and a conventional strategy. For farmers, the organic strategy for means that they manage pests in their crops by using appropriate cropping techniques, biological control and natural pesticides; the conventional strategy means that synthetic fertilizers and pesticides are allowed. For customers, the organic strategy means that they prefer buying organic products; the conventional strategy means that they do not give preference to organic products.*

Assumption 4. *The governmental strategy set is (regulatory intervention, non-intervention). Governmental regulatory intervention includes subsidies for organic farming and penalty policies for conventional farming. Governmental non-intervention means that farmers are allowed to choose their strategy freely, without any subsequent administrative measures.*

Assumption 5. *In order to motivate the farmers to adhere to organic farming, the government provides different levels of subsidies and incentives according to the commitment of farmers to organic farming.*

3.1. Description of the Interaction between Government and the Farmers

All symbols and notations used through this subsection in order to build and clarify our evolutionary model are indicated in Table 1. Based on the above-mentioned assumptions and using the list of symbols indicated in Table 1, we may then construct the payoff matrix of the interaction between farmers and the government as indicated in Table 2.

Table 1. Symbols describing the interaction between government and the farmers.

Symbol	Interpretation
b_f	Farmers' long-term benefits from choosing an organic strategy
g_f	Farmers' invested effort
s_f	Farmers' subsidy coefficient
c_{g1}	The costs of governmental regulatory intervention
c_{g2}	Governmental costs of treating pollution when farmers adopt a conventional strategy
c_f	Farmers' costs of selecting an organic strategy
ΔR	Governmental revenue increment from new farmers pursuing an organic strategy as a result of governments' incentives
p_f	Governmental penalties for farmers pursuing a conventional strategy

Table 2. Payoff matrix for the interaction between government and the farmers.

Strategy of the Government	Strategy of Farmers	Payoff	
		Farmers	Government
Regulatory intervention	Organic	$b_f + s_f g_f - c_f$	$-c_{g1} - s_f g_f + \Delta R$
	Conventional	$-p_f$	$-c_{g1} - c_{g2} + p_f$
Non-intervention	Organic	$b_f - c_f$	0
	Conventional	0	$-c_{g2}$

Let us denote by x the probability of governmental regulatory activities occurring and by y the probability of farmers choosing the organic farming strategy. Denote also the expected profit of the government when adopting the regulatory intervention strategy by π_{11}, the expected profit of the government when adopting the non-intervention strategy by π_{12} and the average profit of the government by $\bar{\pi}_1$. Moreover, let us denote by π_{21} and π_{22} the expected profits of farmers adopting the organic and conventional strategies, respectively, and by $\bar{\pi}_2$ the average profit of farmers. Then, the expected profits and the average profit of the government are given by

$$\begin{aligned} \pi_{11} &= y(-c_{g1} - s_f g_f + \Delta R) + (1-y)(-c_{g1} - c_{g2} + p_f), \\ \pi_{12} &= y \cdot 0 + (1-y)(-c_{g2}), \\ \bar{\pi}_1 &= x\pi_{11} + (1-x)\pi_{12}. \end{aligned} \tag{2}$$

Similarly, the expected profits and average profit of the farmers are given by

$$\begin{aligned} \pi_{21} &= x(b_f + s_f g_f - c_f) + (1-x)(b_f - c_f), \\ \pi_{22} &= x(-p_f) + (1-x) \cdot 0, \\ \bar{\pi}_2 &= y\pi_{21} + (1-y)\pi_{22}. \end{aligned} \tag{3}$$

Hence, from (2) and (3), the replicator equations for the strategies of the government and farmers, respectively, are given by

$$\begin{aligned} \frac{dx}{dt} &= x(\pi_{11} - \bar{\pi}_1) = x(1-x)\big(p_f - c_{g1} + y(\Delta R - p_f - s_f g_f)\big), \\ \frac{dy}{dt} &= y(\pi_{21} - \bar{\pi}_2) = y(1-y)\big(b_f - c_f + x(s_f g_f + p_f)\big). \end{aligned} \tag{4}$$

3.2. Description of the Interaction between Farmers and Customers

Similarly, all symbols and notations used throughout this subsection in order to build and clarify our evolutionary model are listed in Table 3.

Table 3. Symbols describing the interaction between farmers and customers.

Symbol	Interpretation
B_f	Farmers' long-term benefits from choosing an organic strategy
C_f	Farmers' costs of investing in organic technology
ΔB	Farmers' extra benefits from fulfilling customers' preferences
L_f	Farmers' losses if their customers choose a conventional strategy
B_c	Customers' long-term benefits from choosing organic products
C_c	Customers' costs of choosing organic products
E_c	Environmental losses paid by customers when two players adopt a conventional strategy

Based on our model assumptions and using the list of symbols indicated in Table 3, we may construct the payoff matrix for the interaction between farmers and customers as in Table 4.

Table 4. Payoff matrix for the interaction between farmers and customers.

Strategy of Farmers	Strategy of Customers	Payoff	
		Farmers	Customers
Organic	Organic	$B_f + \Delta B - C_f$	$B_c - C_c$
	Conventional	$B_f - C_f - L_f$	0
Conventional	Organic	$-\Delta B$	$-B_c$
	Conventional	0	$-E_c$

Let us denote by y the probability of a farmer selecting the organic strategy and by z the probability of a customer selecting the organic strategy. Denote the expected profit of the farmer when adopting the organic strategy by Π_{11}, the expected profit of the farmer when adopting the conventional strategy by Π_{12} and the average profit of the farmer by $\bar{\Pi}_1$. Moreover, denote by Π_{21} and Π_{22} the expected profits of the customer selecting the organic and conventional strategies, respectively, and by $\bar{\Pi}_2$ the average profit of the customers. Then the expected profits and the average profit of farmers are given by

$$\begin{aligned} \Pi_{11} &= z(B_f + \Delta B - C_f) + (1-z)(B_f - C_f - L_f), \\ \Pi_{12} &= z(-\Delta B) + (1-z)\cdot 0, \\ \bar{\Pi}_1 &= y\Pi_{11} + (1-y)\Pi_{12}. \end{aligned} \tag{5}$$

Similarly, the expected profits and the average profit of customers are given by

$$\begin{aligned} \Pi_{21} &= y(B_c - C_c) + (1-y)(-B_c), \\ \Pi_{22} &= y\cdot 0 + (1-y)(-E_c), \\ \bar{\Pi}_2 &= y\Pi_{21} + (1-y)\Pi_{22}. \end{aligned} \tag{6}$$

Hence, from (5) and (6), the replicator equations for the farmers' and customers' strategies, respectively, are given by

$$\begin{aligned} \frac{dy}{dt} &= y(\Pi_{11} - \bar{\Pi}_1) = y(1-y)\big(B_f - C_f - L_f + z(2\Delta B + L_f)\big), \\ \frac{dz}{dt} &= z(\Pi_{21} - \bar{\Pi}_2) = z(1-z)\big(E_c - B_c + y(2B_c - E_c - C_c)\big). \end{aligned} \tag{7}$$

4. Model Findings

4.1. Analysis of the Interaction between Government and Farmers

Analyzing the system (4), we find the following five equilibria

$$(0,0),\ (0,1),\ (1,0),\ (1,1),\ (x^*,y^*) = \Big(\frac{c_f - b_f}{s_f g_f + p_f}, \frac{c_{g1} - p_f}{\Delta R - p_f - s_f g_f}\Big).$$

The Jacobian matrix J is as follows:

$$J = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix}, \tag{8}$$

in which

$$\begin{aligned} J_{11} &= (1-2x)\big(p_f - c_{g1} + y(\Delta R - p_f - s_f g_f)\big), \\ J_{12} &= x(1-x)(\Delta R - p_f - s_f g_f), \\ J_{21} &= y(1-y)(s_f g_f + p_f), \\ J_{22} &= (1-2y)\big(b_f - c_f + x(s_f g_f + p_f)\big). \end{aligned} \tag{9}$$

Remark 1. *Assume that the equilibrium (x^*, y^*) exists. From the definitions of x and y, one sees that*

$$x^*, y^* \in (0,1),$$

that is,

$$b_f < c_f < s_f g_f + p_f + b_f$$

and

$$\Delta R - s_f g_f > c_{g1} > p_f \text{ or } \Delta R - s_f g_f < c_{g1} < p_f.$$

We thereby see that

$$J|_{(0,0)} = \begin{pmatrix} p_f - c_{g1} & 0 \\ 0 & b_f - c_f \end{pmatrix}, \; J|_{(0,1)} = \begin{pmatrix} \Delta R - c_{g1} - s_f g_f & 0 \\ 0 & -b_f + c_f \end{pmatrix},$$

$$J|_{(1,0)} = \begin{pmatrix} -p_f + c_{g1} & 0 \\ 0 & s_f g_f + b_f + p_f - c_f \end{pmatrix},$$

$$J|_{(1,1)} = \begin{pmatrix} -(\Delta R - c_{g1} - s_f g_f) & 0 \\ 0 & -(s_f g_f + b_f + p_f - c_f) \end{pmatrix},$$

$$J|_{(x^*,y^*)} = \begin{pmatrix} 0 & x^*(1-x^*)(\Delta R - p_f - s_f g_f) \\ y^*(1-y^*)(s_f g_f + p_f) & 0 \end{pmatrix}.$$

The stability of the equilibria is summarized in Table 5. From Table 5 we can gather that, if the revenue from penalties is less than the regulatory costs and the benefit gained is less than the cost of adopting an organic strategy, then the government and farmers will choose (non-intervention, conventional), which is Case I. Case II describes that if, for farmers, the benefit of selecting an organic strategy is greater than its cost, but the governmental expenditure, which includes subsidies and the regulatory costs, is greater than the benefits brought by farmers adopting organic strategies, then the government and farmers will choose (non-intervention, organic). As a result, farmers will consciously select an organic strategy without any government action, which is the ideal situation. Case III is that $(1,0)$ is an ESS, that is, when the revenue from penalties is greater than the cost to regulate, but the costs of an organic strategy are greater than the benefits, which include the long-term benefits of an organic strategy, subsidies from the government and opportunity income, the system converges to (regulatory intervention, conventional). Case IV is a mutual win–win cooperation, with both farmers and the government maximizing their respective interests. Finally, the existence of the compromise state (x^*, y^*) implies that the equilibrium state $(0,1)$ is unstable, and it is obvious that the system can never evolve to the compromise state. Also, it is worth noting that Case IV may not always be achievable, while Case II may not be achievable by increasing subsidies alone either. However, if certain preconditions are met, Case IV can be achievable provided that the subsidies policy is carefully implemented, in the sense that the level of subsidies is neither too small nor too large.

Table 5. Stability of the equilibria for the farmer–government interaction.

Case	Equilibrium	Local Stability	Stability Condition
I	(0,0)	ESS	$p_f < c_{g1}$ and $b_f < c_f$
II	(0,1)	ESS	$\Delta R < c_{g1} + s_f g_f$ and $b_f > c_f$
III	(1,0)	ESS	$p_f > c_{g1}$ and $s_f g_f + b_f + p_f < c_f$
IV	(1,1)	ESS	$\Delta R > c_{g1} + s_f g_f$ and $s_f g_f + b_f + p_f > c_f$
V	(x^*, y^*)	Saddle point	Any condition ensuring the existence of (x^*, y^*)

4.2. Analysis of the Interaction between Farmers and Customers

Similarly, for the analysis of the interaction between farmers and customers, let us consider the system (7) and obtain the following five equilibria

$$(0,0),\ (0,1),\ (1,0),\ (1,1),\ (\bar{y}^*,\bar{z}^*) = \left(\frac{B_c - E_c}{2B_c - E_c - C_c}, \frac{C_f + L_f - B_f}{2\Delta B + L_f}\right).$$

The Jacobian matrix $\bar{J}$ is as follows:

$$\bar{J} = \begin{pmatrix} \bar{J}_{11} & \bar{J}_{12} \\ \bar{J}_{21} & \bar{J}_{22} \end{pmatrix}, \tag{10}$$

in which

$$\begin{aligned} \bar{J}_{11} &= (1-2y)\big(B_f - C_f - L_f + z(2\Delta B + L_f)\big), \\ \bar{J}_{12} &= y(1-y)(2\Delta B + L_f), \\ \bar{J}_{21} &= z(1-z)(2B_c - E_c - C_c), \\ \bar{J}_{22} &= (1-2z)\big(E_c - B_c + y(2B_c - E_c - C_c)\big). \end{aligned} \tag{11}$$

Remark 2. *According to the definitions of x and y, if the equilibrium state $(\bar{x}^*, \bar{y}^*)$ exists, one then sees that*

$$\bar{x}^*, \bar{y}^* \in (0,1),$$

that is, the following conditions have to be satisfied

$$(B_c - E_c)(B_c - C_c) > 0$$

and

$$-L_f < C_f - B_f < 2\Delta B.$$

We then see that

$$\bar{J}|_{(0,0)} = \begin{pmatrix} B_f - C_f - L_f & 0 \\ 0 & E_c - B_c \end{pmatrix},\ \bar{J}|_{(0,1)} = \begin{pmatrix} 2\Delta B + B_f - C_f & 0 \\ 0 & -E_c + B_c \end{pmatrix},$$

$$\bar{J}|_{(1,0)} = \begin{pmatrix} -B_f + C_f + L_f & 0 \\ 0 & B_c - C_c \end{pmatrix},$$

$$\bar{J}|_{(1,1)} = \begin{pmatrix} -(2\Delta B + B_f - C_f) & 0 \\ 0 & -(B_c - C_c) \end{pmatrix},$$

$$\bar{J}|_{(\bar{x}^*,\bar{y}^*)} = \begin{pmatrix} 0 & \bar{y}^*(1-\bar{y}^*)(2\Delta B + L_f) \\ \bar{z}^*(1-\bar{z}^*)(2B_c - E_c - C_c) & 0 \end{pmatrix}.$$

The stability of the equilibria is then summarized in Table 6. Of course, the development of the organic supply chain also needs to consider consumer preferences for organic food. As far as the interaction between farmers and customers is concerned, it can be seen from Table 6, Cases VI–IX, that the equilibria will be ESSs under different conditions. Certainly, neither farmers nor customers will select an organic strategy if the benefits are less than the costs. Subsequently, the ideal state $(1,1)$ of an organic supply chain needs the joint effort of both farmers and customers to persist. Finally, the existence of the compromise state $(\bar{y}^*, \bar{z}^*)$ implies that the equilibrium state $(0,1)$ is not stable, and it is obvious that the system can never evolve to the compromise state provided that the ideal state is ESS. Moreover, the stability conditions for Cases VII–IX (equilibria with at least one "organic" component) are all "segregated" into independent conditions for farmers and customers, respectively, unlike what happened for the interaction between the government and the farmers, in which the stability conditions for Case IV were "non-segregated", due to the presence of the term $s_f g_f$ in both. In some sense, as far as the stability conditions for Cases

VII–IX are concerned, the farmer is disconnected from the customer. Additionally, the extra benefits from fulfilling customers' preferences, which appear in the stability conditions of Case IX, have the potential to tip the scales in favor of establishing a sustainable supply chain, provided that the cost–benefit analysis is passed from a customer's viewpoint.

Table 6. Stability of the equilibria for the farmer–customer interaction.

Case	Equilibrium	Local Stability	Stability Condition
VI	(0,0)	ESS	$B_f < C_f + L_f$ and $E_c < B_c$
VII	(0,1)	ESS	$2\Delta B + B_f < C_f$ and $E_c > B_c$
VIII	(1,0)	ESS	$B_f > C_f + L_f$ and $B_c < C_c$
IX	(1,1)	ESS	$2\Delta B + B_f > C_f$ and $B_c > C_c$
X	$(\bar{y}^*, \bar{z}^*)$	Center or Saddle point	Any condition ensuring that $(\bar{y}^*, \bar{z}^*)$ exists

5. Discussion and Practical Implications

The organic strategy of farmers and the organic contribution of multi-stakeholder groups (the government and customers) will now be further discussed within the confines of our evolutionary model as an outcome of our findings.

5.1. Discussion of the Mathematical Results

Note first that the results of the evolutionary game are related to the initial state of the organic supply chain and to the payoff to game players.

To illustrate Case I, as done in Figure 3a, we choose $p_f = 15$, $c_{g1} = 18$, $\Delta R = 8$, $s_f = 0.8$, $g_f = 50$, $c_f = 12$ and $b_f = 10$. Next, we keep the values of the other variables unchanged, and just swap the values of b_f and c_f ($c_f = 10$ and $b_f = 12$) to satisfy the hypotheses of Case II, as shown in Figure 3b. Keeping the interchange between b_f and c_f, we set $c_f = 80$ and further swap the values of p_f and c_{g1} ($p_f = 18$ and $c_{g1} = 15$), so that $(1, 0)$ is an ESS provided that the values of the remaining variables remain unchanged to satisfy Case III. This is described in Figure 3c. Finally, the conditions of Case IV are satisfied by assuming that $p_f = 15$, $c_{g1} = 18$, $\Delta R = 80$, $s_f = 0.8$, $g_f = 50$, $c_f = 12$ and $b_f = 10$. Figure 3d reveals that $(1, 1)$ is an ESS.

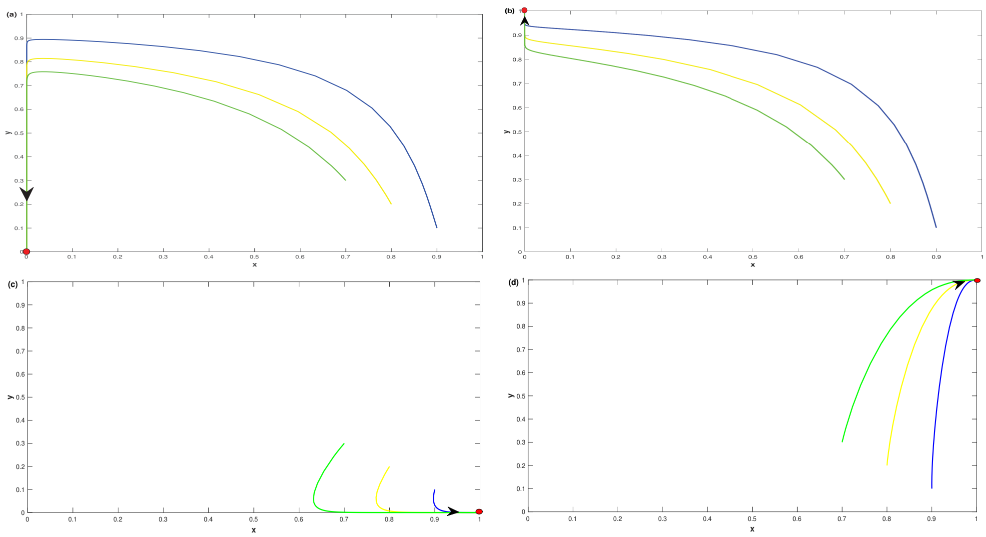

Figure 3. Phase diagrams of Cases I–IV (**a**–**d**). Here, the initial points are $(0.9, 0.1)$ (blue curve), $(0.8, 0.2)$ (yellow curve) and $(0.7, 0.3)$ (green curve). A red point represents an ESS state and the arrow indicates the direction of evolution.

The values of the additional parameters describing the interaction between farmers and customers are $B_f = 12$, $C_f = 10$, $L_f = 9$, $E_c = 10$, $B_c = 12$ and $C_c = 7$. When the value of ΔB is changed from 0 to 5, it is seen that the extra benefits that the farmers obtain by fulfilling the preferences of customers act decisively and push farmers and consumers away from the conventional strategy, as described in Figure 4. In other words, when more and more customers prefer organic products, the continuous influx of extra benefits will push farmers to choose an organic strategy. However, when $B_f = 12$, $C_f = 5$, $L_f = 3$, $E_c = 10$, $B_c = 12$ and $\Delta B = 2$, Figure 5 shows that when the costs of organic products increase, customers withdraw their support for organic products.

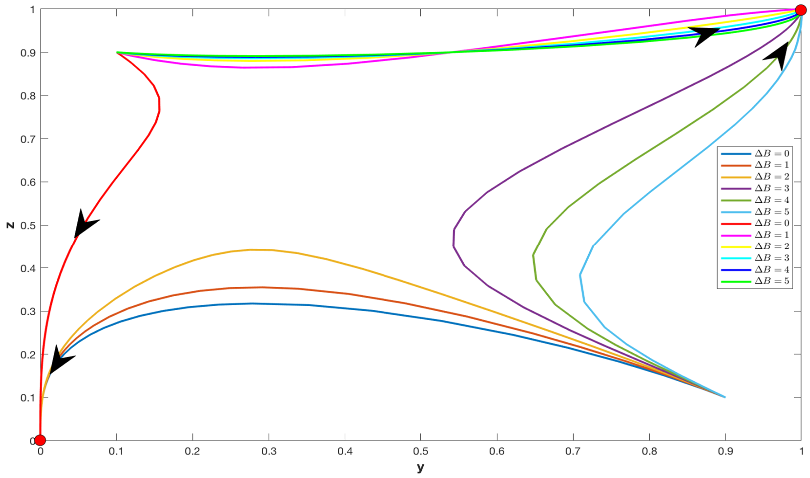

Figure 4. Phase diagrams of Cases VI and IX with different ΔB. Here, the initial points are $(0.9, 0.1)$ and $(0.1, 0.9)$. A red point represents an ESS state and the arrow indicates the direction of evolution.

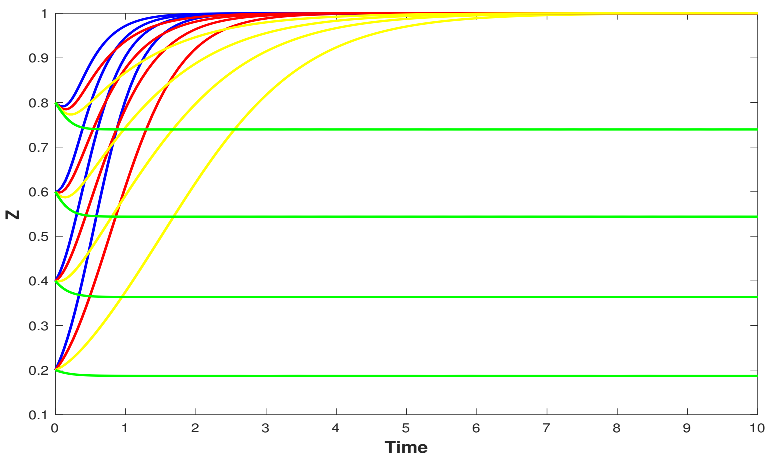

Figure 5. The dynamic evolution of the number of customers as a result of changes in C_c. Here, C_c changes from 9 to 12. The initial points are $(0.8, 0.2)$, $(0.6, 0.4)$, $(0.4, 0.6)$ and $(0.2, 0.8)$. The blue, red, yellow and green curves corresponds to $C_c = 9$, $C_c = 10$, $C_c = 11$ and $C_c = 12$, respectively.

The interaction between farmers and customers involves further complexity, however. When $B_f = 12$, $C_f = 10$, $L_f = 3$, $E_c = 15$, $B_c = 12$, $\Delta B = 5$ and $C_c = 13$, as shown in Figure 6, the compromise state $(\bar{y}^*, \bar{z}^*)$ might be a center, which implies that the preferences of farmers and consumers for an organic (or conventional) strategy change periodically.

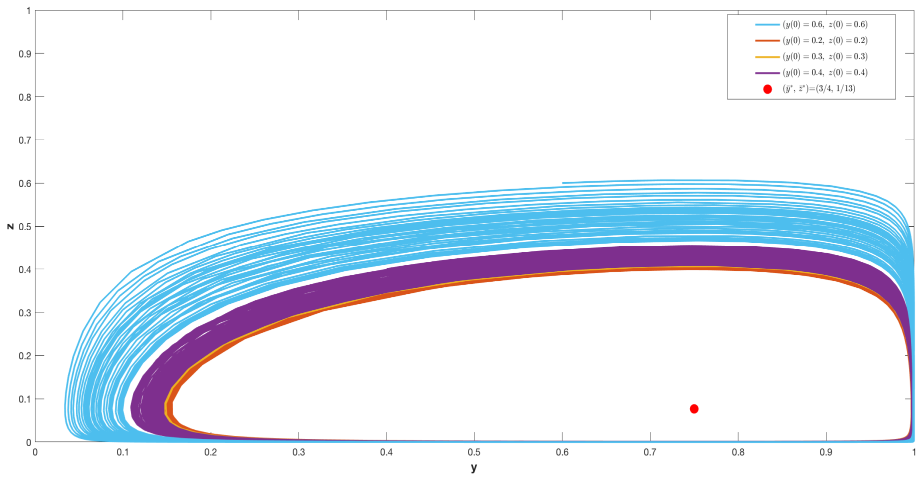

Figure 6. Phase diagram for Case X. Here, $(\bar{y}^*, \bar{z}^*) = (\frac{3}{4}, \frac{1}{13})$ is a center.

5.2. Discussion of Implications

The development of an organic supply chain is an evolutionary process. From the analysis of the evolutionary interaction between farmers and customers, we determined that the purchasing power and organic awareness of customers are of the utmost importance for the establishment and diffusion of organic strategies in the supply chain. Consumption and spending habits, which are difficult to change in a short time, can not only influence the momentary attitude of customers in regard to product worth, but also their long-term financial decisions. The governmental initial regulatory approach is very important. From the results of the evolutionary model, it is seen that the government needs to give a strong support to organic farmers at first, and then gradually cultivate the consumption habits and environmental awareness of the consumers. Once consumers keep on buying organic products, farmers can earn more, which promotes the establishment, development and enrichment of an organic supply chain even without government subsidies.

As far as the evolutionary interaction between farmers and customers is concerned, the purchasing power and the organic awareness of customers are of the utmost importance for the establishment and diffusion of organic strategies in the supply chain.

The results of this paper indicate that the establishment of an organic supply chain requires the joint efforts of all stakeholders, which will in turn bring long-term benefits to all involved entities and foster a mutually beneficial situation.

6. Conclusions

Our theoretical findings lead to the following conclusions. The attitude of farmers towards organic strategies is closely linked to their income. Consequently, comprehensive promotion of organic products must first consider whether or not consumers can really afford them. Additionally, a sustainable shift from a conventional strategy to an organic one requires the efforts of all involved stakeholders. The regulatory intervention of the government and the preference of consumers for organic products are the critical factors in the establishment of an organic supply chain. Although we do not discuss the dynamic interaction between consumers and the government in this paper, the government can also guide and cultivate the environmental awareness of consumers and encourage the consumption of organic products. Our approach can also be applied to shape and solve other decision-making problems involving real-life conflicting situations, such as single-use plastic packaging ban problems, biogas plant implementation problems or market share problems, among others.

This paper has certain limitations. First of all, the investigation is almost entirely theoretical, as the numerical simulations are performed for parameter values which are introduced ad hoc. Future work should address this concern by employing data obtained from a real-world situation. Secondly, our analysis represents just a macroscopic study of the formation and evolution of an organic supply chain, which does not account for the intrinsic differences between each stakeholder group. In addition, using the triple helix structure [54] to clarify the evolution of the relationship between the farmers, consumers and the government is also an aspect of possible future research. Finally, one may also consider the influence of regional and cultural factors, the lag in government regulation intervention and so on.

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Abbreviations

The following abbreviations are used in this manuscript:

DDT	dichloro-diphenyl-trichloroethane
GAPSC	green agricultural product supply chain
EGT	Evolutionary game theory
ESS	Evolutionarily stable strategy
RD	Replicator dynamics

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