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Organic Agriculture and the Prisoner's Dilemma in Pest Management--- ---A 2-Farmer Case

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Abstract: Pest management is one of the key components of modern agriculture. Pesticide overapplication has generated plenty of environmental problems on our Earth. Organic agriculture is a practicable strategy which can realize a sustainable use of agricultural resources and has lots of environmental, economic, and social benefits. But improper pest management will result in a Prisoner's Dilemma and lead to the failure of organic agriculture. This paper is going to set a simplified 2-player game model to discuss the feasibility to resolve such a problem.

Keywords: Prisoner's Dilemma;Pest Management; Organic Agriculture; Strategy; Learning by Doing

I. Introduction

With the world population booming and the huge improvement of living conditions, the global food demand is sharply increasing. In order to improve the yield to match the growing food demand, more pesticides are applied to the fields, generating lots of environmental problems. Agriculture generated 10% of the total carbon emission (equivalent to about 656 million metric tons of CO_2) in the United States [1]. There is no time to waste to adjust current pest management strategies to save our planet.

Organic agriculture is a popular strategy to encourage organic fertilizer use and natural pest management without any pesticide application. Organic agroecology greatly improves the environmental quality. To realize an organic agricultural system, it is necessary for all the farmers in the nearby regions to cooperate with the other, or they will be trapped into a Prisoner's Dilemma.

II. Traditional Pest Management

Traditional agriculture monotonically applies pesticides to protect the crops from the overwhelming pests [2]. But it will worsen the global environmental change.

Pesticide overapplication is one of the main causes of soil fertility decrease [3], soil contaminant increase [4][5], and a significant source of agricultural water pollutants [5]. Besides, the manufacturing process of the pesticides generates plenty of carbon emission [6][7][8]. And improper application methods may lead to air pollution [9]. Generally, it is very unfriendly to environment protection and the realization of UN's Sustainable Development Goals.

And insecticide, a kind of pesticides, can increase the vulnerability in the microbial food chain, resulting in yield decline [10]. With the higher pressure from food security, farmers will expand and exhaust more lands. Or, they will try to apply more pesticides to kill more pests in order to keep the yield. Such a positive feedback cycle will accelerate the ecological destruction process.

The traditional pest management method cannot bring our world a sustainable future. Our Earth is in need of some other strategies in pest management, such as organic agriculture.

III. Organic Agriculture

Generally, organic agriculture is a strategy which integrates soils, crops, animals, and society as an aggregate to manage the food production systems [2].

In an organic agricultural system, chemical fertilizer is prohibited [2]. People recycle household wastes and green manures to produce organic fertilizers and bio-fertilizers [11]. Organic fertilizers and bio-fertilizers are not so nutritious as chemical fertilizers, but support the land sustainability better [11].

Organic agriculture uses a natural management to control the pests [12]. It calls on for the concept of "zero pesticide". It relies on the local agroecology itself to limit the pest impact on the crops. Research has pointed out that organic agroecology has less chemical fertilizer input and less disturbance to soil physical properties, which enhances the plant resistance to the insects [13] to reduce their harm to yield.

Organic agriculture has lots of positive environmental, economic, and social effects on our world:

1. From the perspective of sustainable development, organic agriculture is more environmentally-friendly. It helps to persist the soil fertility and protect the local biodiversity [12]. And it keeps the biological balance potential of the farm [12], a significant measurement of the self-recovery capacity of the ecosystem. With zero pesticide input, the carbon emission in its corresponding production process disappears, either.
2. From the perspective of the consumers, the organic food has been experimentally proved as more nutritious [12]. Due to the less chemical fertilizer input [2], organic food has a lower potential to be polluted. people are very likely to recognize this kind of high-quality food. The expanding market is a strong evidence of its popularity [14]. Aschemann-Witzel, et al. showed that people are willingness to pay about 30% premium to purchase the organic foods [15].
3. From the perspective of the producers, the organic products are more attractive in the market, their selling prices are significant higher [16]. For most common crops, the yields may decrease a little, but the increased price is able to make up this yield loss confidentially. With about the same level of production cost, organic agriculture can generate more further profits for the producers. Besides, with a better soil property sustained [13], the producers can repeat the use of their lands for a longer time with less crop rotation and lower costs in soil recovery.

Attracted by the greater income and the policy support from the governors and agricultural cooperations, more and more farmers are promoting organic agriculture. The number of organic farms is continuously growing all around the world since 1997 [12].

But there are some farm managers who are questioning organic farming [14]. While organic agriculture has so many benefits, they still keep a careful attitude based on three main worries:

1. There are plenty of uncertainties of how the reduction in the pesticide use results in yield change [17]. Agribusiness is a risky business [18]. The debt-to-asset ratio of agribusiness, a significant measurement of its risk, stays at around 0.15 in the United States last year [19], shows that about 15% of the production materials on-farm are borrowing from the financial institutions, which is not a small number. If a strategy has too many uncertain factors that will greatly impact the output, it will be very difficult for it to be chosen, as no one is willing to suffer the risk of not being able to pay back the debt or trapped into huge credit problems.
2. Compared to traditional agriculture, organic agriculture is a very different production style. The change from traditional agriculture to organic agriculture requires the transition in lots of aspects: education, technology, labor inputs, etc. [2] Lots of farms do not have such resources to complete this giant transformation. For example, the population in agricultural industry is experiencing a decline during the recent years, but an organic agriculture is more labor-dependent than a traditional one, which results in a labor shortage [14][20].
3. To realize the goal of "zero pesticide", the farmers have to expect their neighbors that they will also adopt the same strategy, or they will have a risk to get economic loss and be trapped in a Prisoner's Dilemma.

These worries are significant barriers on the path to realize the organic agriculture.

The following part of this paper will focus on such a Prisoner's Dilemma in pest management and its resolution.

IV. Prisoner's Dilemma in Organic Agriculture

Due to the idea of "zero pesticide" in the organic strategy, a consistency among all the farms becomes necessary. With the natural management of which, the pests still exist, but under effective control. The number and distribution of the pests stays in a specific balance to guarantee the crop production progress.

But if one of the farms breaks this consistency and start to use pesticides, the balance will disappear. And all the pests will come to the farms which do not apply pesticides and destroy most of the crops there. The farms who apply the pesticides will take up the market and become the local oligopolies, while all the other farms experience a pest disaster with an extremely low yield and generate negative profits. To reduce the risk to become the latter farms, all the farmers will finally be more conservative and come back to the traditional strategy in pest management, even if the profit for a cooperative organic structure is higher the traditional one.

V. Model

The model is based on the Prisoner's Dilemma discussed in the previous part and compute the profit table (payoff form) for each strategy to analyze the decision-making process for each farmer.

- **Assumptions**

There are three assumptions to guarantee the validity of this model:

1. Each farmer in the model is rational, which means that he/she will make a decision to maximize his expected payoff;
2. This is a simultaneous game, where all the farmers are making decisions at the same time and cannot know the other farmers' decisions in advance;
3. The farmers are homogeneous, as the model only considers the situation that all the fields nearby plant the same species of crops and need to till, seed, irrigate, fertilize, and harvest at the same time to fit the life cycle of that crop.

- **Normal Payoff Form**

To simplify the problem, there are only two farmers in the model, each of which has two strategies to choose:

1. Organic Strategy: in this strategy, he/she will apply no pesticides to naturally manage the pests;
2. Traditional Strategy: in this strategy, he/she will apply normal quantity of pesticides to control the pests.

The profit is the difference between the revenue and the expense. And we assume a much higher price for organic products as they are more attractive in the market.

If both farmers choose the same kind of strategy, they will experience a normal production and marketing process.

But if one of them chooses the organic strategy but the other chooses the traditional strategy, the pests in the latter farm will run to the former farm to destroy all the crops there, with a revenue of 0. And the latter farm will take up the market and experience a price doubling.

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	(P_OQ_O-C, P_OQ_O-C)	(-C, $2P_TQ_T$-C)
Traditional (T)	($2P_TQ_T$-C, -C)	(P_TQ_T-C, P_TQ_T-C)

Table 1. Payoff Form (Initial Condition)

*Notations: P_O-Competitive Price of Organic Crop in the Market; P_T-Competitive Price of Traditional Crop in the Market; Q_O-Quantity of Organic Crop Output in a Normal Condition; Q_T-Quantity of Traditional Crop Output in a Normal Condition; C-Production Cost; (X_1, X_2)-Profit of Farmer 1, Profit of Farmer 2

- **Payoff Form with Simulated Values**

We want to plug simulated values in our model with a specific situation in crop production.

We choose organic and inorganic alfalfa as the observed crops. The observed unit is 1 acre for each farm. From the data retrieved from the databases of Purdue University and University of California-Davis, we get that the average output of inorganic and organic alfalfa are 4.47 tons/acre and 4.02 tons/acre, while the average market price are $132.16/ton and $162.75/ton [16]; and the average production cost is $211.76/acre [21]. We plug these data into our payoff form to visualize the situation.

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	(442.50, 442. 50)	(-211.76, 969.75)
Traditional (T)	(969.75, -211.76)	**(379.00, 379.00)**

Table 2. Payoff Form with Simulated Values (Initial Condition)

**Bold text marks the pure strategy Nash equilibrium*

- **Equilibrium**

Solve the game, then "Traditional" will be the dominant strategy for both farmers, which make them to choose it.

The equilibrium will be (T, T). And the farmers fail to realize organic agriculture.

Compared to (T, T), (O, O) can generate more profits for both farmers, but they give up choosing it, with a rational decision-making process. They are trapped into a typical Prisoner's Dilemma.

VI. Solution

When a Prisoner's Dilemma arises, both sides in the game will not satisfy the result. They would like to have some new ways to optimize the result. In most cases, a strategic move is one of the most effective solutions.

Strategic move isa precedent conditional offer before the game starts [22]. A player can negotiate with the other players with several conditions and try to change their minds to influence the decision-making process. For example, A mother says to her son: "If you do not play bad tomorrow, I will not punish you."

- **Strategic Move: Promise and Threat**

Promises and threats are the classical strategic moves between the players in a game model.

In order to realize the goal of organic agriculture, both the farmers can try to make a strategic move. In each strategic move, a first mover is required. As the two farmers are homogeneous, to simplify the model, Farmer 1 will be set as the default first mover.

A complete strategic move includes a promise and a threat. In this situation, in order to reach the optimized balance at (O, O), the promise will be: "If you (Farmer 2) choose the organic strategy, I (Farmer 1) will choose the organic strategy." and the threat will be: "If you (Farmer 2) choose the traditional strategy, I (Farmer 1) will choose the traditional strategy."

- **Failure and Credibility Problem**

Unfortunately, this strategic move fails to reach the goal, either the promise or the threat.

For the promise: "If you (Farmer 2) choose the organic strategy, I (Farmer 1) will choose the organic strategy.", there is a credibility problem within it. When Farmer 2 choose the organic strategy, for Farmer 1, compared to the organic strategy, the traditional strategy can yield a higher payoff for him. So, his promise will be explicit. Incredible promises always fail in games.

For the threat: "If you (Farmer 2) choose the traditional strategy, I (Farmer 1) will choose the traditional strategy.", there is no credible issues. When Farmer 2 choose the traditional strategy, the traditional strategy will also become Farmer 1's best choice. So, they will reach an equilibrium at (T, T). But the purpose of a threat is to prevent the opponents to choose the specific strategy indicated. If the threat is credible, it will not fail. But the final equilibrium will not be desirable.

Both the promise and threat fail. We reject to conclude that this Prisoner's Dilemma is able be solved by a simple strategic move.

- **Advanced Strategic Move: Agreement**

With the failure in both the promise and threat, a more advanced strategic move gets involved in the game to achieve the goal.

Agreement is an advanced strategic move [22]. Its characteristic is like contract, which has a mandatory. All players in the game have to promise that they will choose a specific strategy, or they will be punished.

There are two kinds of agreement:

1. The first kind of agreement will only punish the farmer who chooses the traditional strategy when the other farmer chooses the organic strategy. The punishment is a fine, defined as F in the model.

The new payoff form is:

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	(P_OQ_O-C, P_OQ_O-C)	(-C, $2P_TQ_T$-C-F)
Traditional (T)	($2P_TQ_T$-C-F, -C)	(P_TQ_T-C, P_TQ_T-C)

Table 3. Payoff Form (First Kind of Agreement)

And the payoff form with simulated values is:

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	(442.50, 442. 50)	(-211.76, 969.75-F)
Traditional (T)	(969.75-F, -211.76)	(379.00, 379.00)

Table 4. Payoff Form with Simulated Values (First Kind of Agreement)

With the game theory computations, we find that when F is\$527.25/acre or higher, the traditional strategy will not be the dominant anymore and the farmers has the opportunity to choose the organic strategy.

But when we solve for the solution of the game, we find that the optimized plan for both farmers to reach the Nash equilibrium is always a mixed strategy, which means that the farmers will swing from these two strategies. Because this kind of agreement does not punish the farmers when both of them choose the traditional strategy, the organic strategy can never be the pure dominant strategy (as $379.00 is always greater than -$211.76). And our goal of organic agriculture cannot be completely realized. Then, we need to adjust this agreement, comes to the second kind of agreement.

2. The second kind of agreement will punish the farmer as long as he/she chooses the traditional strategy. Even if both farmers choose the traditional strategy, the punishment will also be executed. The punishment is also a fine.

The new payoff form is:

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	(P_OQ_O-C, P_OQ_O-C)	(-C, $2P_TQ_T$-C-F)
Traditional (T)	($2P_TQ_T$-C-F, -C)	(P_TQ_T-C-F, P_TQ_T-C-F)

Table 5. Payoff Form (Second Kind of Agreement)

And the payoff form with simulated values is:

Farmer 1 \ Farmer 2	Organic (O)	Traditional (T)
Organic (O)	**(442.50, 442. 50)**	(-211.76, 969.75-F)
Traditional (T)	(969.75-F, -211.76)	(379.00-F, 379.00-F)

Table 6. Payoff Form (Second Kind of Agreement)

With the game theory computation, we find that when F is $590.76/acre or higher, the organic strategy will become the dominant, which means both farmers will choose organic agriculture for their alfalfa production.

Usually, this kind of agreement will be realized as agricultural cooperation in real-world food production practice [23]. The cooperative farmers sign a contract for their farm to ensure their obligations. Andreoni, et al. [24] has proved the feasibility to make a rational cooperation in such a game of Prisoner's Dilemma.

VII. Conclusion

Organic agriculture is more self-recoverable and environmental-friendly. It can generate plenty of environmental, economic, and social welfares to the producers, consumers, and our Earth.

Organic agriculture fits the goals of sustainable development better and is expected a bright future. But there are still lot of resistances which preventing its growth: the Prisoner's Dilemma in pest management is a crucial one. On the path to promote organic agriculture, it is necessary for the policymakers to design some possible strategies to work out them. Agricultural cooperation is supposed to be a great practice.

According to our analysis, the game deduction has proved the necessity to draft an agreement, which is usually realized as an agricultural cooperation in the daily life. With the regulations in the cooperation, both farmers in the model (in real world, all the participants) will be constrained to choose the organic strategy to realize the goal of organic agriculture.

"Learning-by-doing" model is one of the most commonly-used models to investigate the farmers' behaviors. But it assumes that the relationship of farmers' behaviors is motivated from simple imitations [25][26]. The Prisoner's Dilemma discussed in this paper suppose that the behaviors may also originates from a competition mechanism. Our research may provide a new direction to explain the "learning-by-doing" model.

VIII. Limitations and Future Research Possibilities

- **A More Advanced Model**

The real-world situation is much more complex than this 2*2 diagram.

Current model only observes the game with two farmers and only gives each farmer two choices. The real-world actuality may involve more farmers and each farmer can have more strategies, while the quantity of pesticides they choose to apply may fall in a continuous range.

Besides, within a n-farmer model, the distance between each two farms is different. The distances and spatial relationships may influence the number of pests run to other farms.

With more advanced linear algebra and econometrics techniques, it is possible to construct a more advanced model, which will be closer to the reality and guide the real-world organic agriculture practice more effectively.

- **Data Availability**

Our data sources are very limited. The weather, soil condition, and price level differ from state to state, from year to year. We use the yield and revenue data from the average level in United States during 2015–2019 in a database called FINBIN, but the expense data of a specific county in northern California in 2016. The mixed data sources reduce the effectiveness of the research. If we can have better data sources, which means the data come from the same specific region at the same specific time, the research will have a better value to be referred.

- **Observation Availability**

In the situation of (O, T) and (T, O), we assume that the pests will destroy all the crops. This assumption needs an experimental proof. If the yield remaining is low, but not 0, we may have to adjust our model. Besides, it is also very expensive to set an experimental field and watch the pests to destroy all the fruits without taking an action.

- **Another Research Topic: Incentive to Join the Agreement**

In order to grant each individual's liberty, current legal system cannot compulsorily enforce the farmers to join an agreement. So, it is necessary to have some incentives to encourage them. This topic is in need to be discussed more deeply in further researches.

The real-world case study only considers an existing cooperation, while our paper has not discussed the process to build up such a cooperation. When everyone stays in a traditional agricultural system, it is very important to make the first step. But the high fixed cost for settlement or limited access to the infrastructure may block the path sometimes. To encourage the farmers to join a cooperation requires policy supports, such as providing a specific kind of extension service, like what IPM program are doing in Oklahoma. Free services in plant disease detection or insect diagnose [27] will be very attractive for a farmer to participate a cooperation. But they have not collected enough evidence to explain this correlation between the extension service and farmers' willingness to participate.

If possible, an empirical model can be constructed to observe how the incentives affect farmers' willingness to join the cooperation.

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