Modeling the Impacts of Farmer Coordination on Food Supply Chain Structure

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Abstract. To increase profitability, farmers often decide to form strategic partnerships with other farmers, pooling their resources and outputs for greater efficiency and scale. These coordination decisions can have far-reaching and complex implications for overall food supply chain structural emergence, which in turn impacts system outcomes and long-term sustainability. In this paper, we describe an agent-based model that explores the impact of farmer coordination decisions on the development of food supply chain structure over time. We capture the effects of volume-price relationships and farmers' autonomy premia on the rate of farmer coordination and the number and size of groups that form. Results indicate that under many conditions, coordination groups tend to consolidate over time, which suggests implications for overall supply chain structural resilience.

1 Introduction

Individual farm-level decision-making directly impacts large-scale food supply chain (FSC) outcomes and long-term sustainability, which are critical to human and environmental health. Because of the importance of these outcomes, many mathematical models have been developed to explore the impacts of farm management decisions on the FSC. These models typically study the relationship between farm inputs (e.g. crop selection, fertilizers, pesticides, water) and outputs (e.g. food yields, profits, pollutants), with an aim to inform policy and/or guide farmer decision-making. Many optimization models and, more recently, some agent-based models (ABMs) of farm management decisions have been developed for this purpose (see [1-4] for reviews).

While farm management decisions are indeed critical to FSC outcomes, farmer decisions regarding coordination with other FSC members – such as whether to coordinate, with whom, and how – are equally important. Although farm-level coordination decisions are motivated by individual farmers' objectives of increased profit and/or decreased risk [5-6], they can have far-reaching and complex implications for overall FSC structural emergence, which in turn impact the outcomes and long-term sustainability of the FSC. Of particular importance is the effect of farmer coordination decisions on the degree of FSC centralization. Coordinated FSC production and distribution can lead to efficiencies and economies of scale through large-scale production and distribution of food [7]; however, some argue that FSCs with decentralized and diverse structure are desirable because their lower resource intensity makes them inherently more stable and resilient [8]. Coordination decisions also affect transportation decisions, which impact resource consumption (e.g. fuel). When farmers coordinate, they can consolidate their output and make more efficient transportation choices. However, large-scale coordination can encourage long-distance distribution of volumes that exceed regional consumption, which increases transport fuel consumption. Finally, these decisions impact social and economic measures amongst the farming community, in the forms of income and autonomy. Coordination can help farming communities build economic strength through scale, but if the implemented coordination mechanism involves significant losses to farmer autonomy, the net effect to the overall system can be negative [10-11]. Because the types of coordination mechanisms that farmers choose to implement for individual benefit can have positive or negative impacts on overall FSC outcomes, understanding the factors that influence the choice of coordination mechanism is important.

Two types of coordination can occur among FSC members: 1) vertical coordination, which occurs among different FSC echelons, (e.g. between farmers and distributors) and 2) horizontal coordination, which occurs among members within the same FSC echelon. This paper focuses on farm-level horizontal coordination, in which farmers form strategic partnerships with other farmers to pool their resources and their outputs for greater efficiency and scale. Such coordination has become increasingly critical for small- and medium-sized farmers to remain profitable, enabling them to access markets in which customers prefer large and consistent volumes and to reduce costs through resource-sharing, particularly in post-harvest processing and distribution [11]. However, in deciding whether to coordinate, farmers must balance the potential benefits of coordination with the costs, which include the time, effort, and expenses involved with managing the coordination, as well as a loss of autonomy. This loss of autonomy is of particular importance, because autonomy is one of the most highly-valued aspects of the farming profession [12]. In fact, farmers are often willing to sacrifice significant increases in income to maintain their autonomy [5-6].

Successful farmer coordination, in which all parties benefit from and are satisfied with the arrangement, depends on the selection and implementation of an appropriate FSC coordination mechanism. According to Xu & Beamon [13], this depends on the coordinating farmers' operating environment, which is characterized by:

- Market factors, such as customer requirements, transport costs, and infrastructure

- The interdependence among the farmers, which can be characterized by the farmers' value of autonomy, their relative sizes, and their financial situations
- Environmental uncertainty, introduced through such factors as demand, prices, and weather
- Information technology in place/available, such as inventory management software to enable knowledge-sharing

The attributes of an appropriate coordination mechanism should match the characteristics of this operating environment. Per Xu and Beamon [13], relevant coordination mechanism attributes include:

- The *resource-sharing structure* – possible values can range from no resource sharing among farmers, to operational-level information sharing, to a strategic alliance among coordinated farmers
- The *decision style* – possible values can range from centralized, in which one member has control and makes decisions for the coordinated group, to decentralized, in which each member makes decisions autonomously
- The *level of control* – possible values can range from a situation in which members follow strict rules and monitor each other frequently, to a situation in which there is very little monitoring
- *Risk/reward sharing* – possible values can range from a situation in which the risk-benefit ratio is fair, to a situation in which the risk-benefit ratio is unfair, with one member taking on less risk/responsibility but receives more benefits

For successful coordination, farmers should select a coordination mechanism implementation method that best matches the desired coordination mechanism attributes. Depending on the operating environment and mechanism attributes, examples of appropriate implementation methods include:

- An informal coordination arrangement in which neighboring farmers share equipment and consolidate their products for efficient transport to market, with each farmer making autonomous decisions (including crop selection) and sharing revenues and costs fairly
- A formal coordination structure in which one farmer (the "grower-shipper") acts as a centralized consolidation, processing, and shipping point, creating contracts with supplier farmers to provide a designated crop type that is monitored by the grower-shipper for minimum quality/quantity standards, at a price that unfairly benefits the grower-shipper
- A cooperative coordination structure in which farmers coordinate to produce a variety of products to meet their customers' demands with profits shared fairly and equal votes among members

In all of these examples of farmer coordination mechanism implementation methods, being a part of the coordinated group provides benefits to its members, through shared and efficient use of resources, volume consolidation for better prices, and improved access to markets. However, in each of these examples, the coordinated farmers must pay some type of coordination management cost and lose some degree of autonomy as a result of coordination. Therefore, the decision to coordinate depends on how much a farmer's autonomy is worth to him, how much he stands to gain as a result of the coordination, and how much autonomy he will lose through the coordination, given the characteristics of the coordination partner(s) and the nature of the coordination mechanism.

In this paper, we describe an ABM that we use to study a specific farmer coordination mechanism and the degree to which it is implemented, given different operating environment characteristics. In particular, we study the effects that farmer autonomy premia and system pricing structures have on farmers' decisions to join and leave coordinated farmer groups. The results provide insight into the impact of individual-level farmer coordination decisions on overall FSC structure.

2 Methodology

To investigate the effects of farmer coordination decisions on the overall emergent FSC structure and outcomes, we develop an ABM model of a theoretical FSC using NetLogo 5.0.2. ABM is well-suited to modeling farmer coordination in FSCs, allowing us to capture interactions among boundedly-rational farmers and the stochastic behavior of their environment.

2.1 Farmer Agents

A single breed of agent participates in the coordination process: the farmer agent. 50 farmers in each of four distinct geographic regions (for a total of 200 farmer agents) are assigned x- and y-coordinates and a farm "size" in acres. There are five 100-acre farms, 15 50-acre farms, and 30 25-acre farms in each region. Regardless of size, each farmer is assigned $10,000 at the start of each replication, and he begins the replication working independently (i.e., not as part of a coordinated group). The farmer's only objective is to select, grow, and sell crops to make as large a profit as possible to achieve the largest possible personal utility. Farmers each have a personal utility function, which maps annual profit values to utility values and assumes that all farmers are risk-averse. Farmers are also assigned an autonomy premium [5-6], the value of which determines the amount of extra profit a farmer would need to acquire as a member of a coordinated group to achieve an equivalent utility as an independent producer. For example, if an independent farmer with an autonomy premium of 1 achieved a utility value of 0.80 as a result of acquiring $30,000 in profit last year, as a member of a coordinated group, that farmer would require $30,000 + ($30,000 * 1) = $60,000 dollars in profit in a given season to achieve a utility value of 0.80. It is assumed that, farmers are predisposed to work independently (i.e., a farmer's autonomy premium is always positive).

2.2 Full FSC Model Overview

The farmer coordination decision process is one part of a larger agent-based FSC model. Prior to the farmer coordination process, farmer agents select a crop based on past and expected future selling price. The farmer then produces the selected crop, with yields based on random weather and regional effects, and sells as much of his yield as he can to regional distributors for the best price possible. The farmer incurs production and distribution costs and acquires sales revenue, and the difference between these values is his annual profit. A farmer will always choose to fulfill demand for his crop in his own region first (based on the assumption that transport costs are less); if he has remaining inventory after this sale, he will sell to other regions. After all the farmer agents have sold their crops, each farmer evaluates his profits and corresponding utility values. The utility values drive the farmer's decisions on 1) crop choice for next season and 2) coordination with other farmers. After making these decisions, the process begins again with the start of a new year. In this paper we will focus specifically on the farmer coordination process.

2.3 Farmer Coordination Process

Because the objective of each farmer agent is to acquire as much annual profit as possible, and farmers prefer to work independently, it follows that for farmers to decide to coordinate with one another, there must be an incentive for doing so that has the potential to increase a farmer's annual profit. As a representation of the size and volume advantages that exist in real life (i.e., higher sales volumes typically result in better prices and better access to markets), a volume-based pricing function is used to determine the median price per unit that a farmer will be paid for selling a certain volume. This pricing function is known to all farmers. This relationship between median unit price and volume gives farmers an incentive to coordinate with other farmers – coordination groups consolidate their crops before selling, giving them a volume and price advantage over independent farmers. It is assumed that a farmer can only be a member of one coordination group at a time, contributing his entire yield to that group, and that the group only produces one crop type at a time.

Figure 1 describes the farmer coordination process, which begins with each farmer agent assessing his group status (i.e., independent or a coordination group member) and his utility. If the farmer is currently working independently, and if after three years of independent production a farmer has found himself to be "dissatisfied" on average (i.e., his utility is below his threshold value), he begin to seek out other farmers for coordination. The farmer begins by ranking other farmers in his region by increasing distance and decreasing profitability, where the distance is weighted more heavily than profitability. This choice mirrors real-life farmers' preferences to work with others that they know and that are located in their own community [5]. The seeking farmer (the "Sender") selects the most highly-ranked farmer (the

“Receiver”), where the Receiver can be an independent farmer or a member of a coordinated group, but cannot have been rejected by the Sender in any previous searches in the current year. Next, the Sender and Receiver calculate their expected combined yield, a value that is assumed to be known to both Sender and Receiver, which is then applied to the pricing function to determine the expected group profit.

Using these values, as well as their own current profits ($p_{current}$) and autonomy premia (a), the farmers will each calculate a minimum acceptable expected individual profit (p_{min}) that would convince them to coordinate:

$$p_{min} = p_{current} + (p_{current} * a)\ . \quad \textbf{(1)}$$

That is, the expected coordinated profit (p_{group}) must be at least as large as each farmer’s current profit plus an added premium that accounts for his loss of autonomy. If the Receiver is currently a member of a coordinated group, it is assumed that the group has no autonomy premium and is guaranteed to benefit from gaining the Sender as a new member. For the Sender and Receiver, if their expected share of the expected group profit does not exceed their minimum expected profit, the only way that they will consider coordinating is to negotiate a profit premium that will give them an extra share of the group profits. This extra share is d, the “differential”:

$$d = \frac{p_{min}}{p_{group}} - \frac{y_{sender}}{y_{group}} \quad \textbf{(2)}$$

where y_{sender} and y_{group} are the expected Sender and group yields, respectively. A non-zero differential indicates unfair sharing of profits – d will be positive if the farmer’s current profit was larger than expected, negative if the current profit was less than expected, and zero if the current profit equals the expected profit. This suggests that if a farmer is doing poorly, he will be willing to give up some of his fair share just to enable him to join the group. The concept of using a differential as a basis for negotiation comes from [14-15], which describe the possibility for farmer groups to entice new members with differential premia if it is worthwhile for the group to give up some of their fair share of profits to gain the benefit of the new member’s volume.

At this point, the Sender and Receiver begin negotiating the value of the differential that the Sender will be assigned upon coordination. The Sender begins the negotiation process by bidding the maximum differential that he can reasonably expect, which is the value of the Receiver’s expected share of profits. The Receiver counteroffers by bidding the minimum differential that he would be willing to give up to the Sender. If the Sender rejects the Receiver’s counteroffer, he will respond with a bid that is the midpoint between 1) his most recent bid and 2) either the Receiver's most recent bid or the Sender's minimum value, whichever is larger. The Receiver will respond in kind, and this process will continue until either 1) the difference between the Sender’s and Receiver’s bids is less than a predetermined amount, in

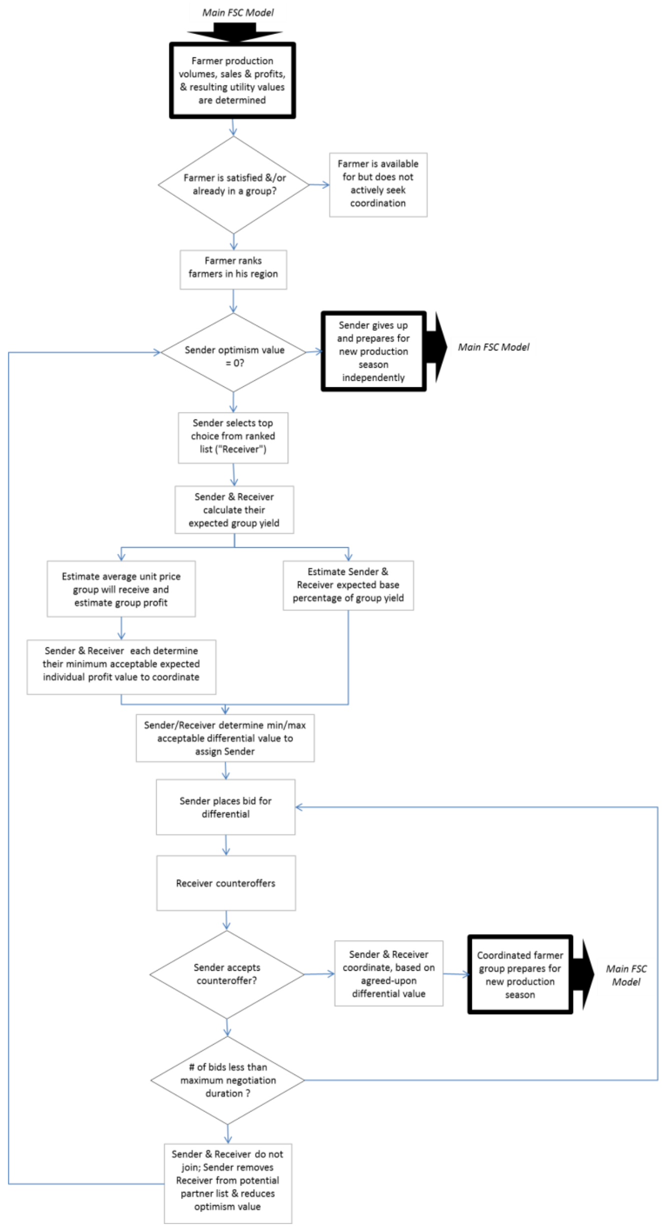

Fig. 1. Flowchart representation of the farmer coordination process.

which case they reach agreement, or 2) a predetermined maximum duration of bidding has been reached, in which case the Sender and Receiver are unable to agree on an acceptable differential. If the negotiation is successful, this indicates that the Sender and Receiver believe that coordinating at the agreed-upon differential value is expected to benefit them, and the Sender joins the Receiver in a coordination group. In this case, the Sender has a three-year "contract" with the Receiver – if the Sender is dissatisfied on average during this three-year period, he can choose to leave the group and begin producing independently again.

If the negotiation is unsuccessful, the Sender's "optimism" level is reduced. The Sender then selects the next best choice from his ranked list and begins the search process again, continuing this iteratively until he either successfully coordinates with another farmer or his optimism level is reduced to zero, whereupon he gives up and decides to continue producing independently next season.

3 Results

Given the importance of farm-level coordination decisions, understanding the degree to which farmers select coordination over remaining independent and the resulting impact of these decisions on FSC structure are of interest. The model was used to run experiments to test the impact of different farmer autonomy premium values, crop prices, and price-volume function structure on these outputs. Table 1 shows the values of the input parameters that were used for these experiments. For each experimental set of parameter values, 30 replications of 300 time steps (years) each were run.

Table 1. Experimental parameters and values

Parameter	Description	Possible Values
a	autonomy premium value for all farmers	0.25, 2, 4
p	median selling price per crop unit for all crops	\$0.10, \$1.00, \$5.00
q	price function curvature coefficient	1,000, 50,000

Figures 2a, b, and c show the relationship over time between the values of the input parameters in Table 1 and the percent of farmers that are members of a coordinated group (i.e. not independent) at the end of each year, for p = \$0.10/unit, \$1.00/unit, and \$5.00/unit, respectively. Figure 3 depicts the evolution of the total number of and size of coordinated farmer groups in the system for the parameter set [a = 2, q = 50,000, p = \$5.00].

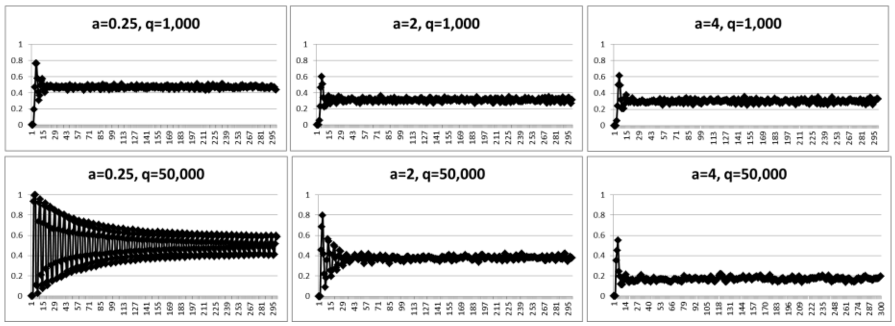

Fig. 2a. Percentage of farmers working in coordinated groups at the end of each season when median prices are set at $0.10/crop unit (average values over 30 replications).

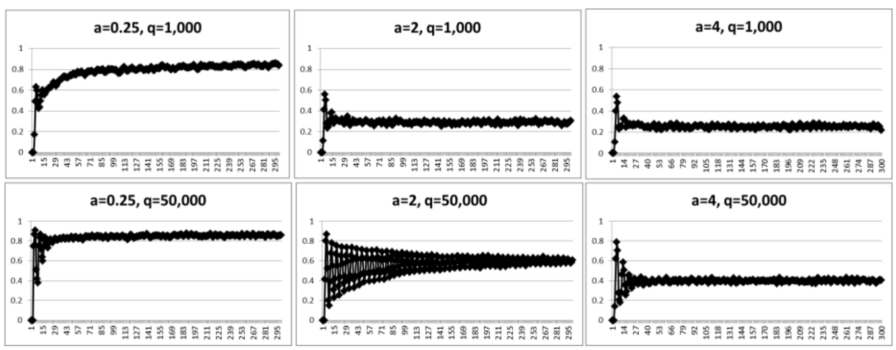

Fig. 2b. Percentage of farmers working in coordinated groups at the end of each season when median prices are set at $1.00/crop unit (average values over 30 replications).

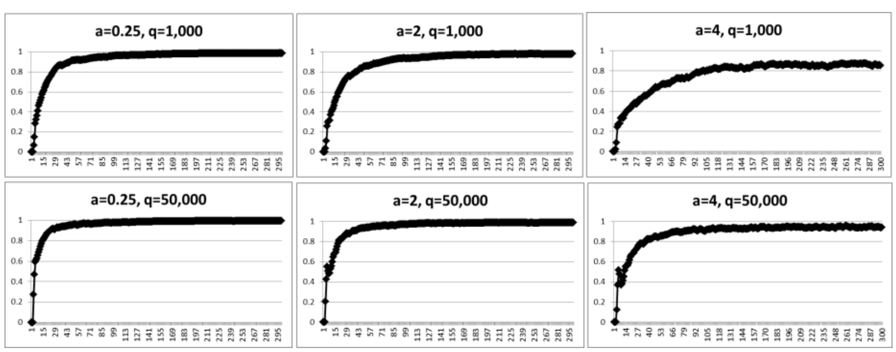

Fig. 2c. Percentage of farmers working in coordinated groups at the end of each season when median prices are set at $5.00/crop unit (average values over 30 replications).

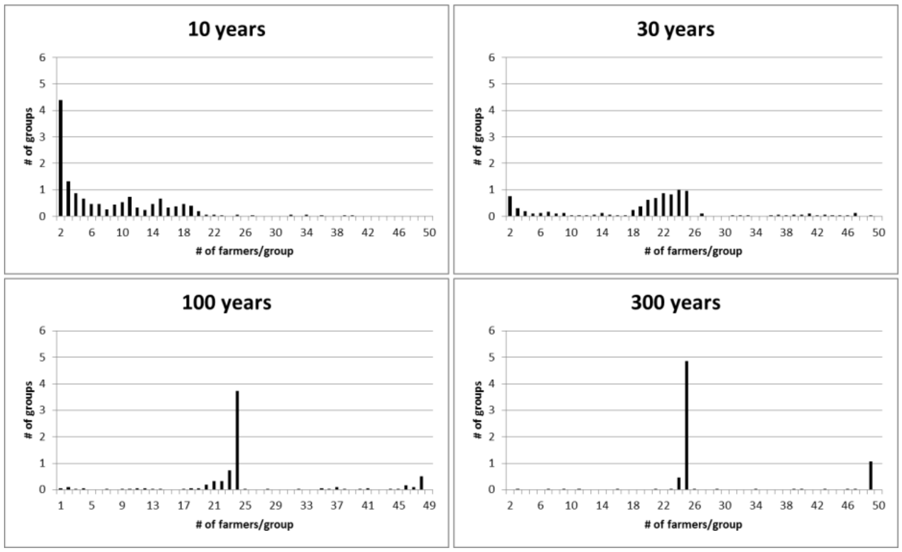

Fig. 3. Number of coordinated farmer groups of size > 1 and corresponding group sizes after 10, 30, 100, and 300 years for parameter values a = 2, q = 50,000, and p = $5.00 (average values over 30 replications).

4 Discussion

Figures 2a, b, and c indicate that increasing the value of a farmer's crop (and therefore his profitability) increases the percentage of farmers who decide to coordinate, as well as the stability of the coordination. This result is most striking when the unit price is highest (Figure 2c) – although the percentage increased slowly (over 50-70 years), in each case, nearly all of the farmers eventually joined coordinated groups, and this percentage remained stable throughout the replication. At this price level, neither the farmers' autonomy premia nor the price function had much impact on the percentage of coordinated farmers. Figure 2b shows that a similar pattern results when the price is set to $1.00 and the farmers' autonomy premium is very low (a = 0.25). When the price is set to $1.00 and the farmers' autonomy premium is medium or high (a = 2 or 4), the percentage of grouped farmers is much lower, but in the cases where the price function coefficient creates a strong positive relationship between volume sold and unit price received (q = 50,000), and the autonomy premium is medium (a = 2), the percentage converged and remained stable at approximately 60%. When the price is low (p = $0.10), the percentage of coordinated farmers is even lower, especially as autonomy premium increases.

These results indicate that when prices and profits are high and farmers are satisfied, although they might not immediately decide to coordinate, once they do coordinate, they remain satisfied and have no incentive to leave their group. This is especially true when the pricing function is such that consolidating yields with other farmers leads to significantly higher prices. At the other end of the spectrum, when prices and profits are extremely low and farmers are struggling, the volume-price advantage of working in coordinated groups does not offer enough incentive for most farmers to join or remain in groups. In general, more farmers decide to coordinate and remain in groups when their autonomy premia are lower and the relationship between price and volume is strongly positive, which is an intuitive result.

Figure 3 gives additional insight into the farmers' coordination behavior. After 10 years, there were many small-sized groups, most of which were 2-farmer partnerships. Over time, however, the number of groups decreased while the group size increased. For example, at the end of a typical replication, there were only seven groups in the system, six of which contained 25 farmers each, and the largest of which contained 49 farmers. This output is representative of the coordination behavior at other parameter values, although the large groups are less stable when prices are low. Interestingly, these results reflect the behavior of many actual FSCs, in which farmers' crop choices become limited by regional consolidation and regional monocultures develop. This outcome reduces regional crop diversity and can potentially lead to a less-resilient regional FSC that relies on other regions (and therefore long-distance transport) to fulfill demand for other crops.

5 Conclusion

Farmer coordination decisions have a significant impact on FSC performance and structural emergence over time. In this paper we have used an ABM of the FSC to study the impacts of farmer autonomy premia, prices, and price-volume relationships on farmers' decisions to coordinate with one another. The results of these experiments provide insight into the ways in which farmer coordination decisions impact FSC outcomes, including the evolution of the percentage of farmers that decide to coordinate and the number and size of farmer groups over time. While this paper focused on one type of coordination mechanism implementation method, in which coordination groups produce a single crop type and sell for volume advantages, future work will allow for other possibilities, in which crop variety is also valued. Studying the effects of high variability of demand, prices, and yields on farmer coordination and subsequent FSC outcomes is also of interest. Additionally, the impact of vertical coordination among farmers and other FSC members will be captured. ABM allows us to gaining a better understanding of the impact of individual-level coordination on emergent FSC properties, which can be valuable in guiding individual decisions and policy toward a resilient and sustainable food supply.

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Appendix: Overview, Design concepts, and Details Protocol

1 Overview

1.1 Purpose

To gain insight into the impact of individual-level farmer coordination decisions on overall food supply chain structure

1.1 Entities, State Variables, and Scales

The model is composed of a total of 200 “farmer” agents, with 50 farmers in each of four distinct geographic regions. Each farmer is assigned a region in [0,1,2,3] and a set of x- and y-coordinates that defines his geographic location, as well as a farm “size” in acres, which is set to 100, 50, or 25 acres. At any point during the simulation, a farmer is either “independent” or “coordinated”, meaning that he is either working by himself or part of a coordinated farmer group. Farmers have a “cash” attribute, measured in dollars, which decreases when farmers pay for operational costs and increases with revenues from crop sales. The difference between revenues and costs each year is the farmer’s annual “profit”, which is also measured in dollars. Farmers each have a convex and increasing utility function, with values ranging from 0 to 1 (unit-less), which maps their annual profit values to utility values. Farmers are also assigned a utility “threshold” value (unit-less) that designates the utility value below which the farmer is dissatisfied. Farmers are also assigned a non-negative unit-less autonomy premium, the value of which determines the amount of extra profit a farmer would need to acquire as a member of a coordinated group to achieve an equivalent utility as an independent producer.

Each farmer has a “current crop” attribute, which takes on a value in [0,1,2,3], designating the crop type that the farmer is currently producing, as well as a “current yield” attribute, which is measured in units of crop produced and designates the amount of crop that a farmer was able to produce in a given year. Each farmer has “yield history” and “profit history” lists to which they append their yield and profit outcome values at the end of each time step. These lists act as a memory bank for the farmers.

Coordinated farmers each have a “differential” value, designating the percentage over/under their fair share of group yields that they have negotiated as a condition of their joining the coordinated group. Coordinated farmers also have a “current group” attribute, which is the set of farmers with whom the farmer is currently coordinated.

The farmers exist in an environment in which there are four distinct geographic regions. Expected yield values differ for each crop type in each region, representing the fact that some crops are better suited to certain regional attributes, such as climate. In each time step, each region experiences a randomly-selected “weather” event, which partially determines the yield outcomes for farmers in that region. Each region also generates its own “demand” for each crop type at the start of each time step, which determines how much each farmer can sell and therefore how much profit he can make.

The sets of farmer agents that comprise the coordinated farmer groups are agent collectives that have their own attributes, including a "size" value, which is the sum of the member farmers' acreages, a "current crop" value, which designates the single crop type that all members are currently producing, a "current yield", which is the sum of the member farmers' current yields, and a "current profit" value, which is the profit that the coordinated group makes by selling the consolidated quantity of all member farmers' yields.

Each time step constitutes one year, and simulations were run for 300 years.

1.2 Process Overview and Scheduling

See Figure 1 for a more detailed graphical farmer coordination process overview.

- Each farmer/farmer group runs 'Crop Production and Sale', with agents producing crops in random order and selling crops in order of size, from largest to smallest.
- In random order, each farmer agent runs 'Farmer Utility Evaluation'; any farmers that find themselves to be independent and "dissatisfied" will be randomly selected to proceed with the following submodels in the coordination process.
- Each of these "dissatisfied" farmers (the "Senders") runs 'Ranking of Potential Coordination Partners' and selects the most-preferred farmer on this list (the "Receiver") for further evaluation.
- The Sender and Receiver farmer agents run 'Estimation of Coordination Decision Values'.
- Using estimated decision values, the Sender and Receiver proceed to 'Negotiation'.
- Sender and Receiver run "Update State Variables" to update attribute values based on the result of the negotiation. If the negotiation was unsuccessful, the Sender selects the next farmer on his ranked list and the new Sender and Receiver repeat the coordination process.

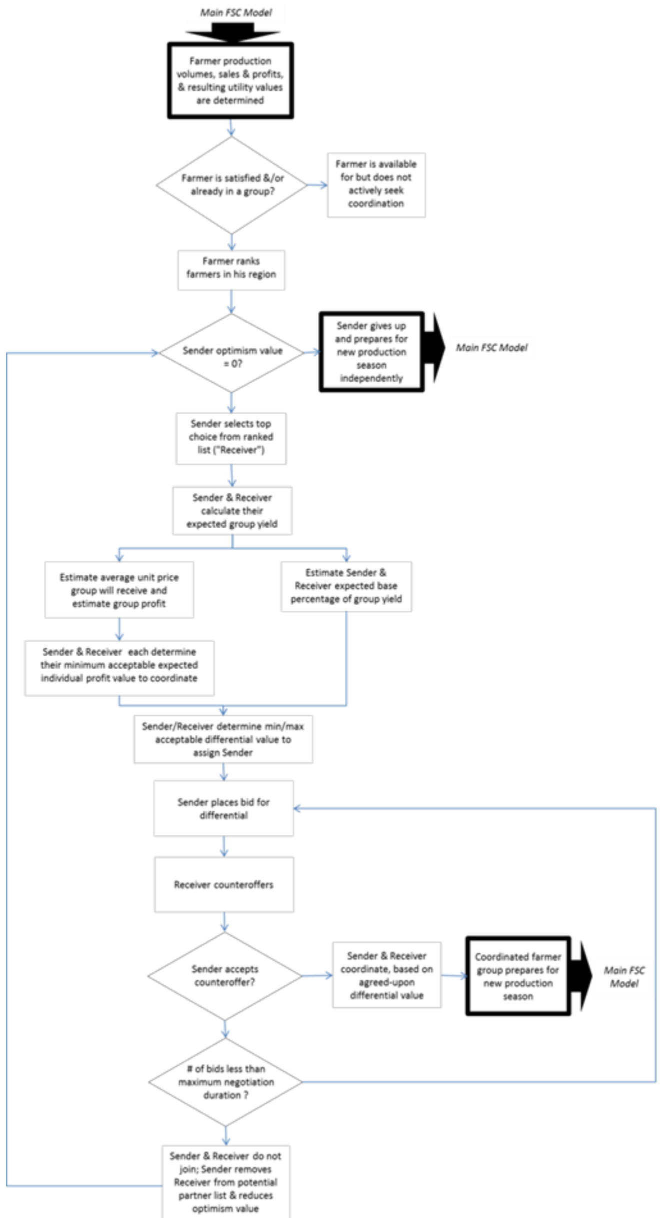

Fig. 2. Flowchart representation of the farmer coordination process.

2 Design Concepts

2.1 Emergence

The resulting FSC structures and outcomes – size and number of coordinated farmer groups and the distribution of crop types produced in each region – are emergent phenomena.

2.2 Adaptation

The agents in this model do not adapt. Their utility functions, satisfaction thresholds, and processes for choosing coordination partners and negotiating coordination terms are fixed throughout the simulation run.

2.3 Objectives

The farmer agent's only objective is to achieve the largest utility as possible in each time step, which maps to the farmer's profit. His desire to achieve this objective is reflected in his coordination decision process, which is driven by the objective of making as large a profit as possible in each time step. The collective coordinated farmer groups do not have objectives of their own outside each individual farmer member's objective.

2.4 Learning

The agents in this model do not exhibit any learning as a consequence of their experiences.

2.5 Prediction

The farmer agents use expected yield values of other farmers/farmer groups, as well as their own current yield and profit values, to predict 1) the expected yield of a potential coordination group, 2) the expected unit price that the group would receive at that volume, and 3) the farmer's own expected share of the group's profits. These estimates are used to determine the value of joining a group and determine the outcome of the farmers' decisions to coordinate.

2.6 Sensing

As they go through the coordination process, all farmer agents are assumed to know the size and expected yield of their potential coordination partner. In contrast, an agent's own autonomy premium, current profit, and utility are known only to itself.

2.7 Interaction

Farmer agent interactions occur 1) with potential coordination partners, and 2) within coordinated groups. The interactions between potential coordination partners are direct and involve a negotiation for the share of group profits. The interaction within coordinated groups is simple, involving only a consolidation of output yield and a distribution of profits, which is an indirect interaction.

2.8 Stochasticity

Regional demand for each crop type, regional weather, individual farmer yield, and actual unit prices received when a farmer/farmer group sells its yield are all stochastic variables. For each of these variables, a triangular distribution is used to determine its actual value at each time step. This stochasticity mirrors the natural randomness that occurs in these values in real life.

2.9 Collectives

Farmer coordination groups are agent collectives that emerge as a result of the coordination process. These groups are represented as sets of farmer agents that collectively sell their consolidated yields and then distribute profits among farmer members.

2.10 Observation

The data collected from this model for analysis include:

- The percentage of farmer agents that are members of a coordinated group. This observation is collected at the end of every time step.
- The number of coordinated groups and their respective size (i.e. the number of farmer members they contain). This observation is collected at the end of every time step.
- The fill rate for each crop type in each region. This observation is collected at the end of every time step.

3 Details

3.1 Initialization

The model is always initialized with 200 farmer agents (with 50 farmers in each of the four regions), each of which is assigned a “cash” attribute value of $10,000 at the start of each replication. The farm size distribution is initialized with (5) 100-acre farms, (15) 50-acre farms, and (30) 25-acre farms in each of the four regions. Each farmer is initialized as working independently (i.e., not as part of a coordinated group), and accordingly, their "current group" attribute is initialized to "self". All farmers are initialized with the same utility function and satisfaction threshold. Depending on the experiment being run, all farmers are initialized with the same autonomy premium value (0.25, 2, or 4). At the start of a replication, each farmer selects a "crop type" (0, 1 ,2, or 3) that he believes, based on expected values, will produce the largest profit for him. Farmers' "differential" attribute value is initialized to 0.

3.2 Input Data

The model does not use input data to represent time-varying processes.

3.3 Submodels

3.3.1 Crop Production and Sale

Farmer agents select a crop based on past and expected future selling price. The farmer then produces the selected crop, with yields based on random "weather" and regional effects, and sells as much of his yield as he can for the best price possible. The farmer incurs production and distribution costs and acquires sales revenue, and the difference between these values is his annual profit. A farmer will always choose to fulfill demand for his crop in his own region first (based on the assumption that transport costs are less); if he has remaining inventory after this sale, he will sell to other regions. If a farmer runs out of cash, he can no longer participate in the simulation.

3.3.2 Farmer Utility Evaluation

If the farmer is currently working independently, and if after three years of independent production a farmer has found himself to be "dissatisfied" on average (i.e., his utility is below his threshold value), he will enter the coordination process and will begin to seek out other farmers for coordination. If the farmer is currently a member of a coordination group and is "dissatisfied", he will leave the group and begin working independently in the next time step.

3.3.3 Ranking of Potential Coordination Partners

The farmer begins this process by ranking other farmers in his region by 1) increasing distance and 2) decreasing profitability, where the distance is weighted more heavily than profitability. This choice mirrors real-life farmers' preferences to work others that they know and that are located in their own community [5]. After developing a ranked list of farmers, the seeking farmer (the "Sender") begins an iterative search process. The Sender first selects the most highly-ranked farmer on his list (the "Receiver"), where the Receiver can be an independent farmer or a member of a coordinated group, but cannot have been rejected by the Sender in any previous searches this year.

3.3.4 Estimation of Coordination Decision Values

Next, the Sender and Receiver calculate their expected combined yield, a value that is assumed to be known to both Sender and Receiver, which is then applied to the pricing function to determine the expected group profit. Using these values, as well as their own current profits ($p_{current}$) and autonomy premia (a), the farmers will each calculate a minimum acceptable expected individual profit (p_{min}) that would convince them to coordinate:

$$p_{min} = p_{current} + (p_{current} * a) \ . \tag{1}$$

That is, the expected coordinated profit (p_{group}) must be at least as large as each farmer's current profit plus an added premium that accounts for his loss of autonomy. If the Receiver is currently a member of a coordinated group, it is assumed that the group has no autonomy premium and is guaranteed to benefit from gaining the Sender as a new member. For the Sender and Receiver, if their expected share of the expected group profit does not exceed their minimum expected profit, the only way that they will consider coordinating is to negotiate a profit premium that will give them an extra share of the group profits. This extra share is d, the "differential":

$$d = \frac{p_{min}}{p_{group}} - \frac{y_{sender}}{y_{group}} \tag{2}$$

where y_{sender} and y_{group} are the expected Sender and group yields, respectively. A non-zero differential indicates unfair sharing of profits – d will be positive if the farmer's current profit was larger than expected, negative if the current profit was less than expected, and zero if the current profit equals the expected profit. This suggests that if a farmer is doing poorly, he will be willing to give up some of his fair share just to enable him to join the group. The concept of using a differential as a basis for negotiation comes from [14-15], which describe the possibility for farmer groups to entice new members with differential premia if it is worthwhile for the group to give up some of their fair share of profits to gain the benefit of the new member's volume.

3.3.5 Negotiation

At this point, the Sender and Receiver begin negotiating the value of the differential that the Sender will be assigned upon coordination (the Receiver will be assigned the negative of the differential value the Sender is finally assigned). The Sender begins the negotiation process by bidding the maximum differential that he can reasonably expect, which is the value of the Receiver's expected share. The Receiver counteroffers by bidding the minimum differential that he would be willing to give up to the Sender. If the Sender rejects the Receiver's counteroffer, he will respond with a bid that is the midpoint between 1) his most recent bid & 2) either Receiver's most recent bid or Sender's minimum value, whichever is larger. The Receiver will respond in kind, and this process will continue until either 1) the difference between the Sender's and Receiver's bids is less than a predetermined amount, in which case they reach agreement, or 2) a predetermined maximum duration of bidding has been reached, in which case the Sender and Receiver are unable to agree on an acceptable differential.

3.3.6 Update State Variables

If the negotiation is successful, this indicates that the Sender and Receiver believe that coordinating at the agreed-upon differential value is expected to benefit them, and the Sender joins the Receiver in a coordination group. In this case, the Sender has a three-year "contract" with the Receiver – if the Sender has been dissatisfied on average during this three-year period, he can choose to leave the group and begin producing independently again.

If the negotiation is unsuccessful, the Sender's "optimism" level is reduced. The Sender then selects the next best choice from his ranked lists and begins the search process again, continuing this iteratively until he either successfully coordinates with another Farmer or his optimism level is reduced to zero, whereupon he gives up and decides to continue producing independently next season.