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Assessing Regional Farm-to-Institution Food Distribution Systems: An Agent-Based Approach

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Abstract

The long-term sustainability and resilience of the industrial food supply system is threatened by its extremely high rate of resource consumption and its lack of structural complexity. Seeking a safer, healthier, and more sustainable alternative, farmers and consumers are increasingly participating in localized food systems. Scaling up the capacity of localized food supply chains (FSCs) to meet growing consumer demand will require the development of new types of marketing and distribution channels. The farm-to-institution channel, in which farmers sell their products directly to institutional and retail customers, is of particular interest. This paper describes an agent-based approach to modeling and analyzing FSCs, with an aim of investigating the impact of farm-to-institution distribution on emergent FSC structure and sustainability outcomes.

Keywords

Agent-based simulation models, food supply chains, sustainable agriculture, local food systems

1. Introduction

Though it is extraordinarily productive in the near term, the industrial food supply system faces many serious long-term environmental and social sustainability challenges. In particular, industrial food supply chains (FSCs) are characterized by long-distance transport, high fossil fuel and water consumption, toxic outputs to the environment, and often unfair labor practices. There are also concerns that the extreme consolidation that has occurred in industrial agriculture has reduced FSC resilience due to a lack of sufficient diversity and complexity. In contrast, localized food systems, with their shorter FSCs, reduce the number of intermediaries and spatial distance between producers and consumers, potentially reducing the energy and ecological costs of long-distance transportation while redistributing value along the FSC [1]. Such systems may also enable consumers to demand greater producer accountability for ecological degradation [2]. While the industrial food system supports regional specialization and large-scale monoculture production, localized FSCs have a decentralized structure and regionally-diverse output, which increase their resilience and stability through the ability to be flexible and adaptable in the face of change (e.g., climate change impacts, fluctuating energy costs) [3-4]. Because a localized food system does not require that the practices of constituent FSC actors be sustainable, localization does not guarantee system sustainability [5], and there is disagreement about how “local” food should be defined [6]. However, proponents of localized food systems believe that they offer a safer, healthier, and more sustainable alternative to the industrial food system.

In response to these concerns, the local food movement has grown tremendously in the past decade. Direct-to-consumer food sales in the U.S. increased three-fold from 1992 to 2007 (from $404 million to $1.2 billion), and the number of farmers’ markets listed in USDA National Farmers Market Directory has increased more than four-fold from 1994 to 2013 [7]. Interest in supporting local food systems is also rising among federal, state, and local policymakers, who are incorporating local foods into programs designed to reduce food insecurity, support small farmers and rural economies, encourage more healthful eating habits, and foster closer connections between farmers and consumers [8]. However, the challenges of "scaling up" the capacity of local FSCs and coordinating local production and distribution to meet this increased demand have become apparent [1]. The scale of direct farmer-to-consumer marketing channels is limited – both farmers and consumers often find farmers' markets to be inconvenient [9]. However, the structure of conventional industrial FSCs are not conducive to localized distribution. In particular, participants in industrial FSCs highly value economies of scale: institutional buyers tend to aggregate their purchases for logistical convenience, and distributors provide them with incentives for meeting specified purchasing volumes [10]. Medium- and small-sized producers struggle to participate within this system because they lack the necessary scale to satisfy large-scale distributor volume and price point requirements [11]. One potential solution is the development of a farm-to-institution marketing channel, in which farmers sell their crops directly to institutional and retail customers (e.g., schools, hospitals, restaurants) [12]. The successful implementation of this strategy as a means of scaling up localized food systems will likely require additional grower collaboration and coordination to expand product availability and streamline delivery and ordering processes [9]. Gaining a better understanding of the types of coordination mechanisms and infrastructure required to support the development of regional FSCs is an important step in the critical process of improving the sustainability and resilience of food systems. In this paper, we describe an agent-based methodology for studying the emergence of different types of FSC structures over time, as well as the sustainability implications of those structures. Agent-based simulation is a modeling tool that is well-suited to capturing the complexity of dynamic and stochastic FSCs, particularly the behaviors, decisions and interactions of the autonomous, intelligent, and interconnected actors that inhabit them [13-16]. This paper focuses on crop distribution through two different market channels: indirect sales through distributors, and direct farm-to-institution sales.

2. Methodology

To investigate how the availability of farm-to-institution distribution channels affects the emergence of FSC structure and sustainability over time, we develop an agent-based simulation model of a theoretical FSC using NetLogo 5.0.2. The model is composed of three primary agent types (farmers, distributors, and institutional customers), each representing a different FSC echelon. These agents autonomously pursue their own individual objectives and interact with one another to produce, distribute, and purchase crops.

2.1 Model Entities

Crops are simple entities that are demanded, produced, and traded by agents. Each crop is classified by its type, where crops of different types are assumed to be distinct and non-substitutable. Each crop type is further classified as being either conventional (Class 0) or regional (Class 1), depending upon the distance the crop travels from its source to the point of consumption (i.e., regionally-sourced/distant). Each crop type has its own sets of production cost and selling price parameters, which are fixed throughout a simulation replication. It is assumed that all crop types are perishable and cannot be stored in inventory from one time-step to the next. *Farmers* are agents that are capable of producing crops. There are 50 farmers of varying size in each of four distinct geographic regions. In a given season, each farmer is limited to producing a single crop type, although a farmer may change crop types from one season to the next. The farmer's only objective is to select, grow, and sell crops to make as large a profit as possible, thereby achieving the largest possible personal utility. Farmers are assigned a utility threshold value that designates the utility value below which the farmer is "dissatisfied". Farmer dissatisfaction may trigger a change in behavior, such as a decision to switch to a different crop type, and/or a decision to join or leave a coordinated farmer group. To engage in crop production and sale, a farmer must have sufficient funds to pay for production, harvest, and transportation costs – otherwise, his state changes to "out of business", and he is removed from the model for the duration of the model replication. No new farmers can join the system during a replication. A single *distributor agent* is assigned to each of the four regions. The distributor agents act as intermediaries between farmers and customers and as inventory consolidation points. Their primary activities are negotiating crop prices with and purchasing crops from farmers, and then selling these crops to customers. Distributors may purchase crops from farmers in any region; however, they are only allowed to sell to customers that are located in their own regions. A distributor's objective is to fill its demand in as few transactions as possible, while paying the lowest price possible. Distributors compete for farmers' business and will adapt their procurement strategies as necessary over time in response to successful/unsuccessful bids and system supply-demand ratios. It is assumed that a distributor's profit margins on regional and conventional crops are the same, which is often true in reality [10]. Each *institutional customer agent* represents a certain percentage of his region's demand for each crop type. In each region, there are two large-sized customers, eight medium-sized customers, and forty small-sized customers, each of which represents 10%, 5%, or 1% of the region's total demand, respectively. Each customer belongs to either Class 0 or Class 1: Class 0 customers value conventional and regionally-produced crops equally, while Class 1 customers prefer regionally-produced crops. Each customer's utility depends on how well its demand is being met. For Class 0 customers, conventional and regional crop classes provide equivalent increases in utility for each unit purchased, while Class 1 customers only receive half as much utility from purchasing a unit of conventional crop as they would from a regional crop.

2.2 Full FSC Model Overview

The crop distribution process is one component of a larger agent-based FSC model (Figure 1). Prior to crop distribution, each farmer agent selects and produces a single crop type, with yields based on random weather and regional effects. The farmers sell as much of their yields as they can to distributors and/or regional customers for the best prices possible. Each farmer then evaluates his profit and corresponding utility value, which drives the farmer's decisions on 1) crop type for next season and 2) coordination with other farmers. Dissatisfied farmers may decide to form coordinated groups with other farmers, whereby they can achieve greater scale for better prices and improved market access. The distributors allocate crops to their regional customers, who then evaluate their utility values (based on how well their demand was filled) and determine their purchasing strategies for the next season. The process then begins again with the start of a new time-step (i.e., a new growing season). In this paper we will focus specifically on the crop distribution process.

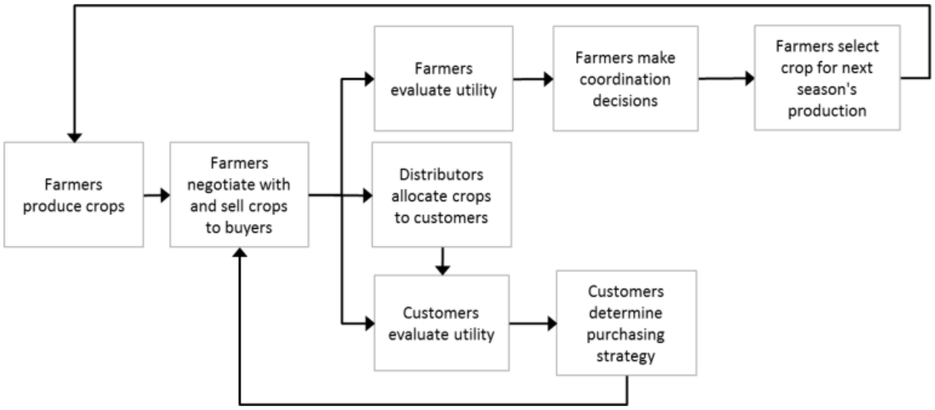

Figure 1: Full FSC model overview: single time-step

2.3 Crop Distribution Process Overview

Once the farmers have harvested their crops, the next step is to try to sell the crops to distributors and/or regional customers. This process occurs one crop type at a time. It is assumed that all distributors have perfect knowledge of their customers' demands, as well as the overall global supply-demand ratio for each crop type. Each farmer with inventory of the current crop type (a "seller") is assigned a probability of being the next producer selected to go to market. A seller's probability of being selected is proportional to his relative crop volume, because larger farmers are assumed to have more market clout. However, the selection process is stochastic, which reflects the randomness of the timing of market readiness – regardless of volume, the timing of crops' ripeness and harvesting is somewhat outside a farmer's control (e.g., due to weather, local soil conditions, or availability of harvesting labor). In general, it is desirable to go to market as early as possible. Therefore, high volume is a market advantage, and large farmers and coordinated farmer groups benefit from this. After being assigned a market selection probability, each seller is randomly selected, one at a time, to market its inventory to distributors and customers ("buyers"). The current seller must determine which of the potential buyers will yield the greatest profit. It is assumed that sales occur on the "spot market" rather than through contracts. Therefore, to make this decision, the seller first needs to negotiate a unit price and a sales volume with each potential buyer, which tells the seller how much revenue each buyer will provide. The seller then subtracts the associated transport cost from each buyer's revenue value to determine the profit that would be earned from selling to that buyer. Finally, the seller simply selects the buyer that provides the greatest profit and sells the agreed-upon volume to that buyer at the negotiated unit price. If the seller has inventory remaining after this transaction, he will reevaluate the remaining unselected buyers as before, and will repeat the negotiation and sale process until either he runs out of inventory or there is no remaining demand for the seller's crop at a price that the seller and buyer will accept. The unit price negotiation process is described in detail in the next two sections. Table 1 provides a summary of the parameters and variables that will be described in these sections.

Table 1: Summary of crop distribution sub-model parameters and variables

Parameters			
b	current number of negotiation iterations between the buyer and seller	r	current buyer (distributor/customer)
B	max allowable value for b before negotiations terminate unsuccessfully	t_{fr}	cost of transporting v units of crop c from the seller f to buyer r ($)
c	crop type, $c \in \{0,1,2,3\}$	u_c	expected unit wholesale price for crop c ($/crop unit)
f	current farmer/farmer group (the seller)	U_{min}	customer utility threshold
$g_{f(min)]}$	minimum allowable gross margin for seller f	α	transport cost per unit distance
j	crop class, $j\epsilon\{0,1\}$	δ	max difference between farmer's and buyer's bids to reach agreement ($/crop unit)
q_r	coefficient on buyer r's pricing function	λ_{fr}	distance from seller f to buyer r (distance units)
Variables			
d_c	current customer demand for crop type c	$x_{f(b)}$	current seller f bid at bid b ($/crop unit)
D_c	overall system demand for crop c (crop units)	$x_{f(b-1)}$	previous seller f bid at bid (b – 1) ($/crop unit)
D_{cr}	buyer r's overall demand for crop c this season (crop units)	$x_{r(b)}$	current buyer r bid ($/crop unit)
h_{cf}	total harvest cost of crop c for seller f in a given season ($)	$x_{r(b-1)}$	previous buyer r bid at bid (b-1) ($/crop unit)
i_{cj}	current customer inventory of crop type c and crop class j	y_{cf}	seller f's actual total yield for crop c in a given season (crop units)
k	current count of negotiations that have occurred this season	z_{clr}	buyer r's lower bound for crop c unit price ($/crop unit)
m_{cfvr}	net return to seller f from selling v units of crop c to buyer r ($)	z_{cur}	buyer r's actual upper bound for crop c unit price ($/crop unit)
p_{cf}	total production cost of crop c for seller f in a given season ($)	$z_{cur(max)}$	buyer r's current maximum upper bound for crop c unit price ($/crop unit)
r_f^*	buyer providing winning bid to seller f	$z_{cur(min)}$	buyer r's minimum upper bound for crop c unit price – a constant ($/crop unit)
S_c	overall system supply of crop c (crop units)	z_{clf}	seller f's lower bound for crop c unit price ($/ crop unit)
U_c	current customer utility for crop type c	z_{cuf}	seller f's upper bound for crop c unit price ($/crop unit)
v_{cfr}	max volume of crop c that the seller f can sell to buyer r	z_{cfrv}	agreed-upon unit price buyer r pays seller f for volume v units of crop c ($/crop unit)
w_j	current customer utility weight for crop class j		

2.4 Calculation of Lower and Upper Price Bounds

Seller *f*'s initial lower bound (z_{clf}) on the unit price for volume v_{cfr} units of crop *c* (z_{cfrv}) is the unit cost of producing, harvesting, and transporting crop *c* to buyer *r*, plus a markup based on the seller's minimum allowable gross margin ($g_{f(min)}$). The calculation of z_{clf} is based on the equation for calculating gross margin:

$$gross\ margin = \frac{revenue - cost\ of\ goods\ sold}{revenue} \tag{1}$$

The unit transport cost is determined by first calculating the total cost of transport from seller *f* to buyer *r*:

$$t_{fr} = \alpha \times \lambda_{fr} \tag{2}$$

where α is the transport cost per unit distance and λ_{fr} is the distance from seller *f* to buyer *r*. The total transport cost is then divided by the buyer's bid quantity (v_{cfr}) to yield the unit transport cost. The unit cost of producing and harvesting is calculated by dividing the sum of the total seller production cost (p_{cf}) and harvest cost (h_{cf}) for crop *c* by the seller's total yield of crop *c* (y_{cf}). The equation for gross margin can then be rearranged to solve for z_{clf}, which is the revenue per unit required to earn the desired gross margin ($g_{f(min)}$), given the unit costs of production, harvest, and transport:

$$z_{clf} = \frac{\frac{p_{cf}+h_{cs}}{y_{cf}} + \frac{t_{fr}}{v_{cfr}}}{1 - g_{f(min)}} \tag{3}$$

The initial upper price bound for seller *f* (z_{cuf}) on z_{cfrv} is the current market wholesale unit price (u_c), which is assumed to be known by both the seller and the buyer, and is the same for all buyers in the system.

$$z_{cuf} = u_c \tag{4}$$

The buyer's lower bound on z_{cfrv} is the same for both distributors and customers: it is equal to the seller's costs before markup. It is assumed that the buyer knows this value and assumes that the seller would not sell below it.

$$z_{clr} = \frac{p_{cf}+h_{cs}}{y_{cf}} + \frac{t_{fr}}{v_{cfr}} \tag{5}$$

If the buyer is a customer, his upper bound is simply the current market wholesale unit price (u_c). In contrast, the distributor's upper bound (z_{cur}) is dynamic throughout the selling subroutine. It is initialized as follows. First, the maximum value of z_{cur} is calculated. This value $\left(z_{cur(max)}\right)$ depends on the overall system supply-demand ratio for crop c. If the system supply of crop c is greater than or equal to system demand ($S_c \geq D_c$), the distributors need not worry about being competitive and simply set their maximum upper bound at the start of the selling season to a predetermined minimum value ($z_{cur(min)}$, where $z_{cur(min)} > z_{clr}$), which is a fraction of the wholesale unit price (u_c). However, if the system supply is less than system demand ($S_c < D_c$), then distributors must account for with larger upper bounds to remain competitive. In this case, $z_{cur(max)}$ is a linear function of the supply-demand ratio, with a maximum value of u_c when the supply-demand ratio equals zero, and a minimum value of $z_{cur(min)}$ when the supply-demand ratio equals 1.

$$z_{cur(max)} = \begin{cases} \left(z_{cur(min)} - u_c\right) \times \frac{S_c}{D_c} + u_c, & \frac{S_c}{D_c} < 1 \\ z_{cur(min)}, & \frac{S_c}{D_c} \geq 1 \end{cases} \tag{6}$$

The distributor's upper bound (z_{cur}) is a percentage of $z_{cur(max)}$, and this percentage depends on the seller's volume (v_{cfr}). Specifically, z_{cur} increases as the percentage of the distributor's overall demand for crop c that can be filled by the seller $\left(\frac{v_{cfr}}{D_{cr}}\right)$ increases, reflecting distributors' preferences for large volumes. The rate at which z_{cur} increases with volume depends on q_r, which represents the strength of the distributor's preference for large volumes. When q_r is large, the relationship between volume and price is strong (i.e.,, the unit price that the distributor is willing to pay becomes directly proportional to the volume as $q_r \rightarrow 1$). It is assumed that z_{cur} is an exponential function of $\frac{v_{cfr}}{D_{cr}}$, with a lower bound of zero (when $v_{cfr} = 0$) and an upper bound of $z_{cur(max)}$ (when $\frac{v_{cfr}}{D_{cr}} = 1$). If z_{cur} is less than the distributor's lower bound (z_{clr}), then z_{cur} is set to z_{clr}.

$$z_{cur} = \max\left(z_{clr}, \left(\frac{1-e^{-\frac{v_{cfr}/D_{cr}}{q_r}}}{1-e^{-\frac{1}{q_r}}}\right) \times z_{cur(\max)}\right) \tag{7}$$

This upper bound z_{cur} is the maximum value that the distributor is willing to pay for a unit of crop c, and this value becomes a basis for the distributor-seller negotiation process. Because customers' upper bounds do not depend on volume, the unit price that a seller receives from a customer will often be higher than the price offered by distributors.

2.5 Buyer-Seller Negotiation Process

The negotiation process initializes with seller f offering z_{cuf} (so $x_{f(0)} = z_{cuf} = u_c$), and buyer r counteroffering z_{clr} to the seller. The iterative negotiation process then begins with the seller response of bidding a unit price that is the midpoint between his previous bid, $x_{f(b-1)}$, and the maximum of z_{clf} and $x_{r(b-1)}$; that is,

$$x_{f(b)} = \frac{x_{f(b-1)} - \max(z_{clf}, x_{r(b-1)})}{2} + \max(z_{clf}, x_{r(b-1)}) \tag{8}$$

Buyer r counteroffers with a unit price that is the midpoint between its own previous bid, $x_{r(b-1)}$, and the minimum of z_{cur} and $x_{f(b)}$; that is,

$$x_{r(b)} = \frac{\min\left(z_{cur}, x_{f(b)}\right) - x_{r(b-1)}}{2} + \min\left(z_{cur}, x_{f(b)}\right) \tag{9}$$

The absolute value of the difference between the seller's offer and the buyer's counteroffer is calculated and compared with the constant δ; if the difference is greater than δ, the bid counter b is incremented by 1. If b does not exceed B (where B is the maximum allowable value of b before negotiations terminate unsuccessfully) , then bid values are updated and another iteration of the negotiation proceeds, but if b exceeds B, then the negotiation terminates without price agreement being reached, and z_{cfrv} is set to zero. However, if the difference between the seller's and buyer's offers does not exceed δ, the seller accepts buyer r's most recent counteroffer and the negotiation terminates, with the agreed-upon price z_{cfrv} set to $x_{r(b)}$. Regardless of the outcome, once the negotiation terminates, seller f moves on to the next buyer (setting r to $r + 1$). The values v_{cfr} and t_{fr} are recalculated for buyer ($r + 1$), and negotiations for $z_{cf(r+1)v}$ begin, using the same negotiation process previously described.

Once seller f has negotiated prices with all available buyers, he will calculate the net return (revenue minus transport cost) from selling to each buyer:

$$m_{cfvr} = \left(z_{cfrv} \times v_{cfr}\right) - t_{fr} \tag{10}$$

The seller selects the buyer with the largest return (buyer r_f^*) and sells v_{cfr} units of crop c to that buyer:

$$r_f^* = \left\{r \middle| m_{cfvr} = \max\left\{m_{cfvr}\right\} \forall r\right\} \tag{11}$$

If the seller has any remaining inventory, the entire negotiation process starts again. This cycle continues until there are no worthwhile transactions available (i.e., $m_{cfvr} \leq 0 \ \forall \ r$).

After each seller has completed negotiations with the entire buyer set and has selected a buyer, each distributor will adjust $z_{cur(max)}$ depending upon whether he won or lost the sale, in order to stay competitive. If a distributor won the current sale k, it will reduce its current maximum upper bound for the next round of negotiations. The amount by which it reduces this value depends on the supply-demand ratio – if demand is greater than supply, it will reduce it by a small amount; otherwise, it will feel confident enough to reduce it by a larger amount. Regardless, it will never reduce it below $z_{cur(min)}$.

$$z_{cur(max)_{k+1}} = z_{cur(max)_k} - \Delta \tag{12}$$

On the other hand, if a distributor lost the current sale k, it will increase its current maximum upper bound for the next round of negotiations, in hopes of attracting the next sale with a better offer. It is assumed that the losing distributors do not know how much the winning sale price is, so they must blindly adjust their own prices. The amount by which a distributor increases this value depends on the supply-demand ratio – if supply is greater than demand, it will increase it by a small amount; otherwise, it will increase it by a larger amount. Regardless, it will never increase it above u_c.

$$z_{cur(max)_{k+1}} = z_{cur(max)_k} + \Delta \tag{13}$$

2.6 Distributor-to-Customer Inventory Allocation

The next step for distributors is the allocation of inventory among its regional customers. Each distributor ranks its customers by total demand over all crops, with the largest customer receiving the highest rank. The distributor then works its way down the ranked list of customers, filling each customer's demand for all crop types as best as possible. That is, the distributor will supply each customer with his most preferred crop class, if it is available in inventory. If conventional crops are available, the distributor will allocate these to its Class 0 customers, thereby saving inventories of regional crops that Class 1 customers will prefer. If regional crops are not available, the distributor will provide its Class 1 customers with conventional crops. Given the distributors' preference for large size, it is likely that larger customers will be allocated their most preferred crop classes and full demand quantities, while smaller customers are less likely to have their demand fully satisfied. As distributors allocate inventory to customers, each customer's own inventory (i_{cj}) updates, where c is the crop type and j is the crop class. After a customer receives his allocation, he calculates the utility he receives from each crop type (U_c), which is the weighted sum of its conventional and regional inventories, divided by the customer's demand for that crop type (d_c) . The weights for each crop type depend on the customer's class: for Class 0 customers, $w_0 = w_1 = 1$, whereas for Class 1 customers, $w_0 = 0.5$ and $w_1 = 1$.

$$U_c = \frac{\sum_{j=0}^{1} w_j i_{cj}}{d_c} \tag{14}$$

The customer uses his utility to evaluate his purchasing strategy for crop c in the next time-step. The customer has two different strategies to choose from: Strategy 0, in which the customer depends solely on his distributor to fulfill his demand for crop c, or Strategy 1, in which the customer will attempt to fill his demand through direct purchases from farmers, and will rely on the distributor only when he is unable to obtain sufficient inventory from farmers. At the start of the simulation, all purchasing strategies are initialized to Strategy 0. In each time-step, each customer compares his current utility for crop c (U_c) with a threshold (U_{min}). His strategy selection process is as follows:

- If the customer's current strategy is Strategy 0:
    - If $U_c \geq U_{min}$, maintain Strategy 0.
    - Else if $U_c < U_{min}$, change to Strategy 1.

- Else if the customer's current strategy is Strategy 1:
  - If $U_c \geq U_{min}$:
    - If the customer did not purchase any crop *c* from farmers, change to Strategy 0.
    - Else if the customer purchased some of crop *c* from farmers, maintain Strategy 1.
  - Else if $U_c < U_{min}$:
    - If the customer did not purchase any crop *c* from farmers, maintain Strategy 1.
    - Else if the customer purchased some of crop *c* from farmers, change to Strategy 0.

3. Results and Discussion

The model was used to run experiments to test the impact of different marketing channels, distributor pricing functions, and transport costs on the emergence of overall FSC structure over time, as well as economic, social, and environmental measures. For each experimental set of parameter values, 30 replications of 50 time-steps (i.e., growing seasons) each were run. In all experiments, half of the small- and medium-sized customers were designated as Class 1 customers. All possible combinations of input parameter values were included, for a total of 18 different experiments. Experimental input parameters in the model included:

- **Set of agents enabled to purchase (c):** This binary parameter determines whether farmer agents are allowed to sell to distributors only ($c = 1$), or to both distributors and regional customers ($c = 1$).
- **Distributor pricing coefficient (q):** This factor is the coefficient on distributors' pricing function (as shown in Equation 7), which relates volume to unit price. For small values of *q*, a seller that is offering a small volume (relative to the distributor's demand) can get a large percentage of the wholesale price (u_c). However, when *q* is large, a seller with a low volume will only receive a very small percentage of the wholesale price. Experimental values of *q* are: 0.05, 0.20, and 0.70.
- **Transport cost per unit distance (t):** This parameter represents the cost of transporting crops from farmers to buyers, assuming that transport cost is fixed and does not depend on volume, crop type, or transport mode (i.e., regional vs. long-haul). It has three experimental levels: $0.10, $0.50, and $1.00.

At the end of each replication, the final values of four output metrics were captured, including:

- **Percentage grouped farmers (pg):** This is the percentage of all farmers in the system that are members of a coordinated farmer group. A farmer's decision to coordinate is based on how much the farmer believes he will benefit from the resulting economies of scale. The percentage of grouped farmers provides information about the extent of farmer coordination, which partly describes the FSC structure.
- **Number of farmers in system (nf):** This output metric is the overall number of farmer agents in the system. At the start of each replication, there are 200 farmers, but over the course of the replication, farmers may go out of business, causing the number of farmers in the system to be reduced. Thus the number of farmers in the system captures an important aspect of economic and social FSC sustainability (i.e., farmer employment), and, because the out-of-business farmers disappear from the system (rather than being absorbed by other farmers), the number of farmers also has implications for customer utility (i.e., with fewer farmers, less food is produced, and customer demand might go unfilled).
- **Average customer utility (cu):** This metric captures the average utility value over all 200 customers in the system (based on Equation 14). Each customer's utility contributes the same weight in the calculation of the overall average. This metric provides information about customers' satisfaction.
- **Average transport distance per farmer (td):** This system metric is captured in the 50th time-step. Because the energy for transportation is typically supplied from fossil fuels (which are non-renewable and produce greenhouse gases when consumed), transport distance is an important environmental sustainability metric.

Figure 2 shows the main effects plots for the four output metrics for all experimental parameter values, and Tables 2, 3, 4, and 5 show the related ANOVA output. The output values represent the average values at the end of the 50th time-step, over 30 replications. In general, the percentage of grouped farmers (*pg*) value behaved as expected. When customers are allowed to purchase directly from farmers ($c = 1$), the percentage of farmers in groups is significantly less (at a 95% confidence level) than when customers are only allowed to purchase from their distributors (37.3% and 24.6% grouped, respectively). This result reflects the fact that when farmers can sell directly to customers (who do not value economies of scale), they can typically receive a high unit price for their crops. As a result, their profits are sufficient, and their utilities are high enough that there is no incentive to form coordination groups. Unsurprisingly, *pg* increases with increasing distributor pricing coefficient values (16.1%, 24.7%, and 52.2% for low, medium, and high levels of *q*, respectively) – when distributors place greater value on large volumes, farmers are more likely to form coordinated production groups to achieve greater aggregated volumes. As Table 2 shows, of all three input parameters, *q* has by far the strongest effect on *pg* (F = 963.0). Although the impact of transport cost (*t*) is not as strong, increasing its value results in increased coordination (23.2%, 31.4%, and 38.3% for low, medium, and high transport costs, respectively). This outcome may be a result of farmers' increasing desire to consolidate transport with other farmers as costs increase, and/or it may be a response to decreasing utility as profits are eroded by transport cost.

In all of the experiments, the total number of farmers in the system (*nf*) remaining at the end of each replication was not greatly reduced from the original number (200), indicating that most farmers were sufficiently profitable to stay in business under all experimental conditions. Table 3 shows that the availability of a direct farmer-customer marketing channel has no significant impact on farmer survival (p = 0.7). In contrast, *q* and *t* significantly affect *nf*, with fewer farmers on average surviving 50 time-steps when *q* is high (*nf* = 190.9) compared with low *q* (*nf* = 199.7), and there are similar effects when *t* is high (*nf* = 191.6) and low (*nf* = 199.6). These results indicate that fewer farmers can survive when operational costs are high and revenues are low, which is intuitive.

Average customer utility (*cu*) is significantly higher when direct farmer-customer transactions are allowed (*cu* = 0.88) than when only the distributor-customer channel is available (*cu* = 0.74), which suggests that Class 1 customers have better access to regionally-produced crops when they are able to purchase directly from farmers. The degree of farmer coordination is also a factor – Figure 2 shows that *cu* decreases significantly as *q* increases (*cu* = 0.90, 0.81, and 0.73 at low, medium, and high levels of *q*, respectively), and Figure 3 shows that as the percentage of grouped farmers in the system increases, *cu* tends to decrease. Increased farmer coordination likely decreases Class 1 customer utility by reducing the availability of direct farmer-customer transactions – coordinated farmer groups can take advantage of consolidated transport and aggregated volumes, and they therefore prefer to sell to distributors. Additionally, because farmer groups produce a single crop type, the formation of large groups leads to regional crop specialization, increased interregional trade, and reduced intraregional trade. These outcomes result in decreased availability of regionally-produced crops, thereby reducing the utility of customers who value local food.

When the direct farmer-customer channel is available, the average farmer transport distance (*td*) increases slightly. It is likely that an increase in direct farmer-customer transactions leads to an increased number of farmer delivery trips (based on the assumption that a separate trip is made for each customer, i.e., there are no "milk runs"), but does not result in a large overall increase in distance since fewer interregional trips are made. This outcome suggests that in order for localized food systems to meet the environmental sustainability goal of reducing "food miles," transport coordination among regional farmers and customers will be necessary. Unsurprisingly, *td* decreases significantly as *q* increases (*td* = 2293, 2009, and 1309 for low, medium, and high levels of *q*) and as *t* increases (*td* = 2201, 1843, and 1567 for low, medium, and high levels of *t*), as farmers tend to join groups and consolidate their shipments.

4. Conclusion

In response to quality, health, and sustainability concerns, consumers are becoming increasingly interested in knowing where their food comes from, which has led to recent dramatic increases in demand for locally- and regionally-produced food. New market channels will be necessary to efficiently and effectively support this demand, while supporting the values (e.g., sustainability) that consumers seek. In this paper we have described an agent-based methodology for studying the impact of the availability of a direct farm-to-institution market channel, as well as varying volume-price relationships and transport cost, on overall FSC structure and sustainability metrics. The results of our experiments indicate that the availability of farm-to-institution market channels and the emergence of decentralized FSC structures increase the availability of regionally-produced food, leading to greater customer satisfaction, but they also lead to increased total transport distances, which suggests that farmer and customer coordination will be required for such a scheme to be sustainable. Future work will focus on the development of these types of coordination mechanisms and will also allow for coordinated farmer groups to produce a diverse range of crop types, in response to customer demand. The effects of differences in regional and long-haul transport costs will also be included. The model will also be modified to consider institutional customers' preference for convenience in their sourcing decisions, and to enable the development of relationships and trust among customers, distributors, and farmers. Additionally, the distributors' purchasing and order-fulfillment strategies will be enhanced, allowing them to dynamically adapt to better meet customers' preferences. Using an agent-based approach allows us to capture the adaptations and interactions among the autonomous members of an FSC, and it is the complex combination of these individual-level behaviors that leads to overall emergent FSC structure and outcomes. Gaining a better understanding of the types of agent-level decisions and behaviors that lead to long-term food system sustainability is critical.

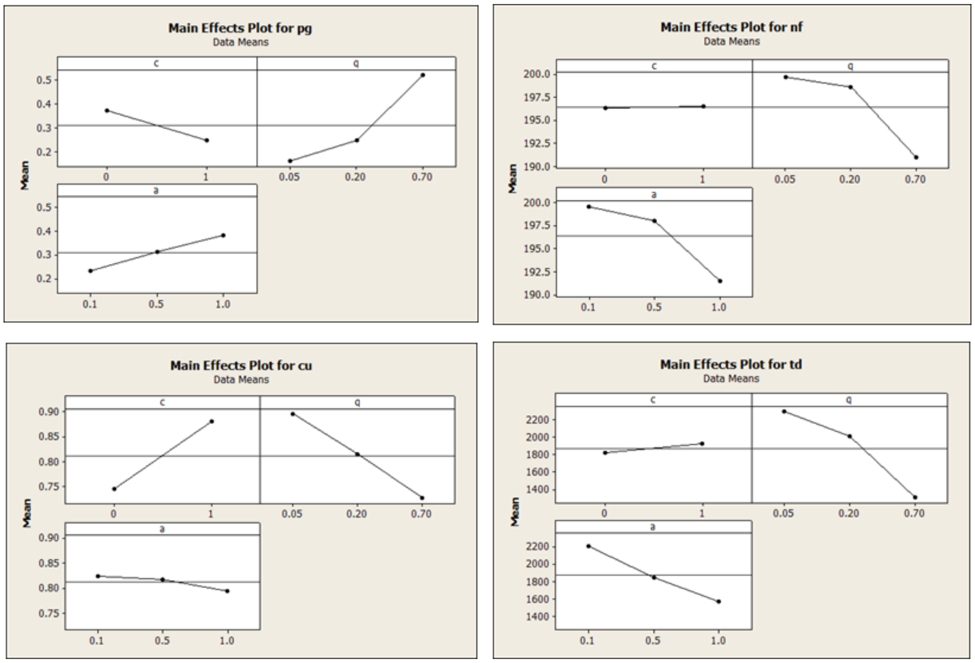

Figure 2: Main effects plots for experimental outputs

Table 2: ANOVA output for percentage of grouped farmers in the 50th time-step

Source	DF	SS	MS	F	P	S	R-Sq	R-Sq(adj)
c	1	2.2	2.2	328.5	0.0			
q	2	12.8	6.4	963.0	0.0			
a	2	2.1	1.0	155.0	0.0			
Error	534	3.5	0.0					
Total	539	20.5				0.1	82.8%	82.6%

Table 3: ANOVA output for total number of farmers in the 50th time-step

Source	DF	SS	MS	F	P	S	R-Sq	R-Sq(adj)
c	1	3.3	3.3	0.2	0.7			
q	2	8204.2	4102.1	187.8	0.0			
a	2	6597.7	3298.8	151.0	0.0			
Error	534	11664.2	21.8					
Total	539	26469.4				4.7	55.9%	55.5%

Table 4: ANOVA output for average customer utility in the 50th time-step

Source	DF	SS	MS	F	P	S	R-Sq	R-Sq(adj)
c	1	2.5	2.5	808.2	0.0			
q	2	2.6	1.3	418.7	0.0			
a	2	0.1	0.0	15.2	0.0			
Error	534	1.6	0.0					
Total	539	6.8				0.1	75.8%	75.6%

Table 5: ANOVA output for average distance traveled per farmer in the 50th time-step

Source	DF	SS	MS	F	P	S	R-Sq	R-Sq(adj)
c	1	1315636	1315636	51.42	0.0			
q	2	92425247	46212624	1806.05	0.0			
a	2	36363404	18181702	710.56	0.0			
Error	534	13663819	25588					
Total	539	143768106				160.0	90.5%	90.4%

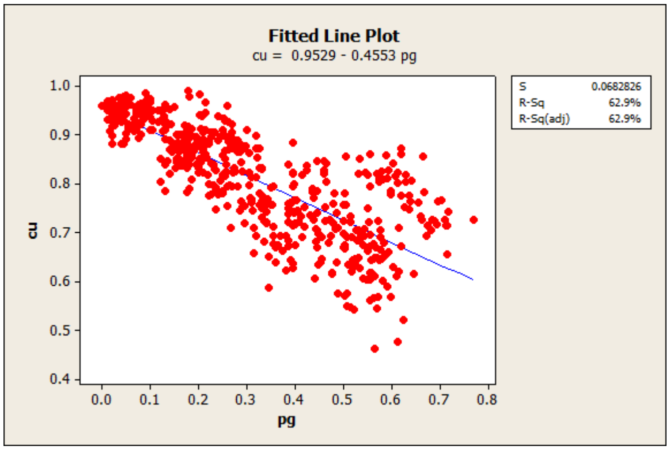

Figure 3: Scatterplot of the percentage of grouped farmers vs. average customer utility in the 50th time-step

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