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Multi-agent simulation modeling of supplier selection for local food systems

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Abstract

Consumer demand for regionally-produced food has increased dramatically in the past decade, in response to concerns over food safety and quality, as well as the serious environmental, economic, and social equity issues that pervade the modern industrial food supply system. As demand grows, distributors of regionally-produced food (i.e., food hubs) face many challenges in their efforts to scale up, particularly with supply chain management. They must find ways to operate more efficiently without undermining their support for the regional farming community. In this paper we describe a multi-agent simulation model of a theoretical regional food system in which multiple farmer-agents produce food, negotiate with a regional food-hub-agent, and try to sell their food at the best possible price. Using this model, we compare the effects of various food hub supplier selection policies on system outcomes, in terms of food hub profitability, the cost of quality, transaction costs, the number of farmers required to satisfy demand, and the size distribution of these farmers. Results suggest that the food hub's selection policy significantly impacts long-term system performance.

Keywords
Multi-agent simulation, supply chain management, regional food system, supplier selection policies

1. Introduction

Demand for regionally-produced food has increased tremendously in the past decade as consumers have become increasingly aware of the benefits of supporting regional food systems. Consumers' reasons for buying regional food vary widely. Typical reasons include: a desire to save money on groceries, a belief that regional food is fresher, safer, and/or more nutritious than conventionally-produced food, concerns about the environment and the treatment of farm workers, and a desire to support the local economy and establish connections with the people who produced their food [1-3]. This demand growth has been a boon to small- and medium-scale farmers, who can benefit from higher prices and fewer restrictions on volume, compared with sales through mainstream distributors. However, they have also begun to discover that new market and distribution channels will be necessary to efficiently and effectively support this demand, while continuing to support the values that consumers seek [4]. In particular, many farmers are challenged by a lack of distribution infrastructure which would provide them with better access to retail, institutional, and commercial food service markets where demand for regional food is substantial [5].

In response to these challenges, the concept of a regional aggregator, or "food hub" has emerged. A food hub provides smaller-scale farmers a platform for aggregating their products and distributing them to institutional and retail buyers who would like to buy regional food at larger volumes than traditional farmers' markets can support. By providing a single point of sale, a food hub can reduce farmers' operational costs and enable them to be more profitable. Although their missions, strategies, and structures can vary widely, nearly all food hubs offer a combination of production, distribution, and marketing services that allows smaller-scale farmers to gain entry into new and additional markets that would be difficult or impossible to access on their own [5]. Food hubs also benefit customers by providing them with a single point of purchase for consistent and reliable supplies of source-identified products from regional producers.

Although regional food hubs are a great idea and have become very popular (there are currently over 200 food hubs in the U.S. [6], many of them have struggled to make ends meet. Some of the most commonly-cited challenges faced by food hubs are insufficient infrastructure for efficient distribution, an inability to successfully match supply and demand, and an inability to meet customer requirements for consistent year-round volumes and high quality [7-10]. Efficiently meeting customer requirements is of particular importance, and food hubs must rely heavily upon their suppliers to make this happen. Therefore, a robust supplier selection and assessment strategy is critical to food hubs' long-term success.

There are many studies in the domains of manufacturing and service industries that recommend that distributors periodically and systematically evaluate supplier performance in order to retain those suppliers who meet their requirements in terms of multiple performance criteria that are aligned with the organization's values and objectives [11]. Although there is very little research on the problem of supplier selection and evaluation for regional food hubs, it would seem that they should be able to follow the same guidelines as those that are recommended for other industries. In reality, however, food hubs tend to use ad-hoc heuristics to select and evaluate their suppliers, and they do not systematically track supplier performance over time. A major reason for this is that food hubs typically lack the infrastructure, personnel, and financial resources to support a supplier management program. However, they also face challenges that are unique to the regional food domain. For example, regional food systems are typically supported by a large number of small, independent producers who have widely variable objectives, preferences, and abilities, and they greatly value their autonomy. Another challenge is that regional food hubs are typically motivated not only by traditional supply chain metrics (i.e., maximizing profits), but also by social concerns (e.g., supporting regional employment). This concern for overall social welfare of regional producers is typically rooted in personal values, a desire to maintain a strong and diverse regional supply base, and/or government incentives in support of regional economic development. One of the many challenges that food hubs face is determining appropriate policies for supplier management that balance these two (often conflicting) objectives. For example, food hub managers would like to know how to determine the ideal number of producers they should work with for each product type to minimize risk, provide customers with sufficient selection, and provide sufficient revenues for the producers. These managers also have concerns about developing and managing quality assurance policies that satisfy their customers but are not overly burdensome to the producers.

As a result, the supplier selection and evaluation problem in regional food systems is very complex. Traditional modeling tools are inadequate for the analysis of complex systems like food supply networks [12]. Multi-agent simulation is a particularly appropriate modeling methodology for studying the dynamics among the many autonomous, heterogeneous, and interacting agents the regional food chain [13]. In this paper, we describe a multi-agent simulation model of a regional food supply network, in which farmer agents and a food hub agent interact, gather feedback, and adapt accordingly over time. This virtual system can be used to test the impact of various supplier selection policies on the performance of the system and its structural development over time.

2. Methodology

In this section we describe a multi-agent simulation model of a theoretical regional food supply chain, which was developed using NetLogo (5.0.5). A typical regional food supply chain has three echelons – farmers, a distributor, and consumers. This model is focused on the relationships between farmers and a regional distributor (i.e., a food hub). The model consists of two different types of agents: farmers and a regional food hub. The model contains 100 farmer agents and one food hub agent. The food hub is located at the center of the region, and the farmers are distributed randomly throughout the region. In each time-step, the farmers interact with the food hub to sell the food that they have produced. The objective of the farmers is to increase their profits, and the objective of the food hub is to ensure that farmers produce good quality food at a reasonable price.

2.1 Farmer Agents

Each farmer's farm size is classified as being small, medium, or large. The ratio of size classifications (shown in Table 1) is based on data from the 2012 Census of Agriculture, USA [14]. The location of the food hub and farmers is fixed for all experiments. The distance of each farmer to the food hub is calculated using the Euclidian formula. The farmers are autonomous and work independently to produce food in each time-step, where a time-step represents a transaction cycle, which is equivalent to one week. Farmers do not communicate with one another, nor are they capable of observing other farmers' behaviors and outcomes. Farmers' profits are earned via sales to the food hub and/or other customers (e.g., farmers' markets, mainstream distributors). Since the focus of our model is to study the relationship between the farmers and the food hub, the other customers are exogenous to the model (i.e., they are not represented as agents). It is assumed that the farmers prefer to sell to the food hub because it offers a better prices and more efficient transactions than other customers. However, the literature suggests that farmers are generally risk-averse [15, 16]. That is, they do not want to put all their eggs in one basket. Although the food hub is the preferred market channel, a farmer typically will not sell all of his yield to the food hub, in order to maintain his autonomy and not be wholly dependent on a single customer for his business.

Table 1 : Classification of farmer agents

Size Category	Minimum Size (acres)	Maximum Size (acres)	Number of Farmer Agents per Category
Small	1	50	43
Medium	50	500	31
Large	500	2000	26

To capture the farmers' process of deciding how to allocate their business in each time-step, a weighted aggregated utility function *U(x)* is constructed for each farmer. This function is based on the work of Hildreth and Knowles [16], who develop the sum of constant absolute risk aversion (SCAR) function to estimate utility functions of farmers in Minnesota. This function represents farmer utility as an exponential function. *U(x)* is the weighted sum of two components: the utility the farmer gains through sales to the food hub ($U(x_1)$) and the utility he gains from selling to other customers ($U(x_2)$). $U(x_1)$ represents the farmer's utility when x_1 percent of his total sales are through the food hub. Similarly, $U(x_2)$ is the farmer's utility when x_2 percent of his total sales are to other customers. x_1 and x_2 always sum to 100%, based on the assumption that all of a farmer's yield is either sold to the food hub or to other customers. $1/R$ represents the farmer's degree of risk preference and is positive for all farmers (based on the assumption that they are risk-averse), where *R* is the profit that the farmer would receive by selling all of his yield at the lowest possible price.

$$U(x_1) = 1 - e^{\left(\frac{-x_1}{R}\right)} \tag{1}$$

$$U(x_2) = 1 - e^{\left(\frac{-x_2}{R}\right)} \tag{2}$$

w is a weighting parameter that represents the importance of other non-food hub customers to the farmer, where the value of *w* increases with increasing farm size. It is assumed that large farmers have more market options and access to customers and hence would not be dependent on the food hub as their main source of business ($w = 4$). For small-sized farmers, both the food hub and the other customers are assumed to be equally important ($w = 1$). For medium-sized farmers, maintaining business with other customers is slightly more preferred than the food hub ($w = 2$). *U(x)* is the overall utility of the a farmer and is a weighted average of $U(x_1)$ and $U(x_2)$:

$$U(x) = \frac{U(x_1) + wU(x_2)}{1 + w} \tag{3}$$

Lyons [17] provided some insights on estimates of ranges of values for x_1 (from $x_{1(\min)}$ to $x_{1(\max)}$) for farmers of different sizes. For small farmers the supply of food to the food hub would be expected to range from 30 to 80% of their total yield, while medium-sized farmers prefer to supply 10-50% of their output to the food hub, and large farmers target 1-20%. Figure (1) shows the utility values (*U(x)*) for a small farmer for different possible values of x_1. It can be seen that the minimum value of *U(x)* over the expected range of x_1 (30-80%) is 0.50. This value is the threshold utility value for a small farmer to be "satisfied" with his current state. Similarly, on solving Equation (3), the threshold values for medium and large farmers are 0.45 and 0.50, respectively.

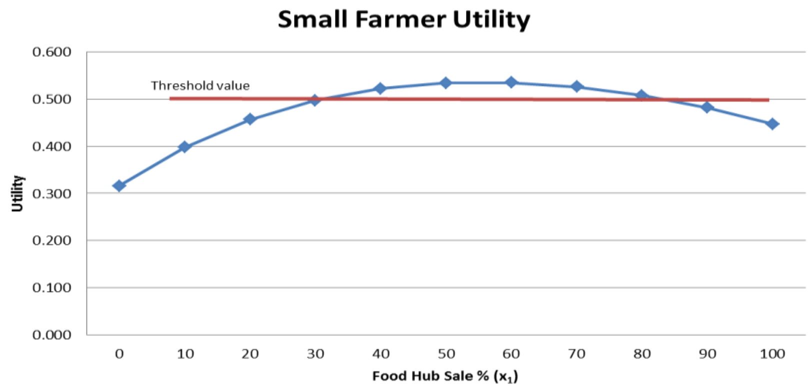

Figure 1: Utility values for a small farmer

2.2 Food Hub Agent

The main objective of the food hub is to ensure that regionally-produced food of the highest quality is supplied to its customers. However, the food hub also seeks to support small and medium-sized farmers [17, 18]. In fact, one of the defining characteristics of a regional food hub is its commitment to buy from small to mid-sized regional producers whenever possible [5]. The food hub must determine the policy by which it selects its farmer suppliers. It is possible for the food hub to simply select its suppliers randomly; however, it is more typical to follow a policy that is based on the outcomes of previous interactions. Some examples of common supplier selection polices include performance-based selection , the vendor profit sharing model, and a relationship-based model [19, 11, 20]. With performance-based selection, a supplier is evaluated on predetermined measures (e.g., quality) and the top-performing suppliers are selected for future business. In the vendor profit sharing model suppliers are considered to be partners, and profits earned by the buyer are shared with suppliers to improve the relationship with supplier. In the relationship-based model a supplier is selected based on its relationship which is based on trust, commitment, and customer satisfaction with the buyer. In our model the food hub can apply one of two different policies to select a farmer: either random selection or performance-based selection.

Good supplier performance is essential for a robust and sustainable supply chain[21]. For the food hub to achieve its objective of supplying good quality food at reasonable prices, it must rely on its suppliers' performance. Farmer performance (P) is the weighted sum of four key metrics: food quality (Q), food cost (C), the status of the buyer-supplier relationship (A), and farm size (S). These are commonly-used parameters for supplier evaluation [11, 19]. The weights of these parameters were determined based on a discussion with the manager of the Iowa Food Cooperative, a food hub in central Iowa [18]. The food hub values the quality of produce very highly; therefore, food quality (Q) is weighted at 50%. The purchase cost of the food (C) is another major attribute of supplier performance – lower costs are preferred, but it is essential that costs are not too low such that it affects quality. It is essential that the food hub and the farmers have a cordial and healthy relationship for continuous, efficient and timely supply in order to satisfy consumer demand. Cost and relationship are viewed as equally important and are weighted at 25% each. The buyer-supplier relationship metric (A) is based on supplier performance and is equal to the performance of the supplier in the previous time-step . Since one of the principal objectives of the food hub is to promote small- and medium-sized farmers, to represent this preference, an additional bonus is given to these farmers during their performance evaluation. A bonus of 10% is added to the supplier performance if the farmer size (S) is small or medium (i.e., S = 0 for large farmers and S = 1 for small and medium farmers). Farmer performance (P) is the weighted sum of these four measures:

$$P = 0.5Q + 0.25C + 0.25A + 0.1S \tag{4}$$

Table (2) provides an overview of the performance metrics.

Table 2 : Farmer performance metrics

Measure	**Most Preferred**	**Least-Preferred**
Quality (Q)	No defects	Defects produced
Cost (C)	Less than selling price	More than selling price
Farm Size (S)	Small and medium	Large
Relationship (A)	P_{max}	P_{min}

2.3 Model Overview

At the beginning of each time-step, the following values are initialized: unit production costs and prices, each farmer's yield, the food hub's demand, , and the percentage farmers supplying defective food. Although the model is based on a theoretical food-producing system, the demand parameters are based on actual USDA [14] data for fresh produce with regular demand and year-round availability. Jones [22] state that potatoes, carrots and onions are available across the country, throughout the year, irrespective of the season. For our analysis we have used data for carrots.

According to USDA [14] data, the average production cost of carrots is $0.262/lb. The price at which farmers can sell carrots to customers other than the food hub is $0.59/lb. Huber [18] states that the price of regional food is typically comparatively higher than the average conventional retail price. Food hubs use product differentiation strategies to command a premium price for the producers [5]. Therefore, in the model the price that the food hub will pay for carrots is fixed at $1.00/lb. However the price could vary by ±10% after negotiation.

In the literature, a farmer's yield is typically assumed to follow a normal distribution [23-26]. In the model, each farmer's yield in each time-step is assumed to be normally distributed, with a mean of 575 pounds per acre and lower and upper bounds of 500 and 600 pounds per acre, respectively [25]. It is difficult to predict demand in general [23, 24]. The triangular distribution is often used as an input distribution to simulation models when the data is limited. Therefore, food hub demand in this model is assumed to follow a triangular distribution, with minimum and maximum values of 500,000 lbs. and 700,000 lbs., respectively, and a mode of 626,550 lbs.

The data on the rejection of food due to poor quality is not readily available in the literature. However, Huber [18] reveals some insights on defective food supplied to his food hub by farmers, stating that in his experience, the probability that a farmer would supply defective crop is 10%. Defective carrots are those that have been deemed unfit for consumer to buy due to their deformation and irregular shape and size [27]. In order to eliminate this defective supply, farmers must incorporate quality control processes, such as 100% inspection, sample checks, proper packaging and handling, which will require an additional cost. Ensuring quality through quality control activities is assumed to cost the farmer $0.05/lb produced.

After initialization, the model simulates each time-step (i.e., transaction cycle). Figure (2) depicts an overview of the model sequence. Depending upon the supplier selection policy of the food hub, a search for a farmer is initiated. Once a farmer is selected, the food hub and the selected farmer will determine whether or not they need to negotiate prices, sales quantities and/or quality requirements. If the negotiation is successful, or if they decide that they don't need to negotiate, the food hub will purchase the food from the farmer, update its attribute values (cost, quantity and quality) and search for new farmers if demand is yet to be satisfied. The food hub will continue to search for farmers until its demand is satisfied. At the end of each time-step, each farmer's utility value *U(x)* is calculated, which will inform the negotiation decision in the next time-step.

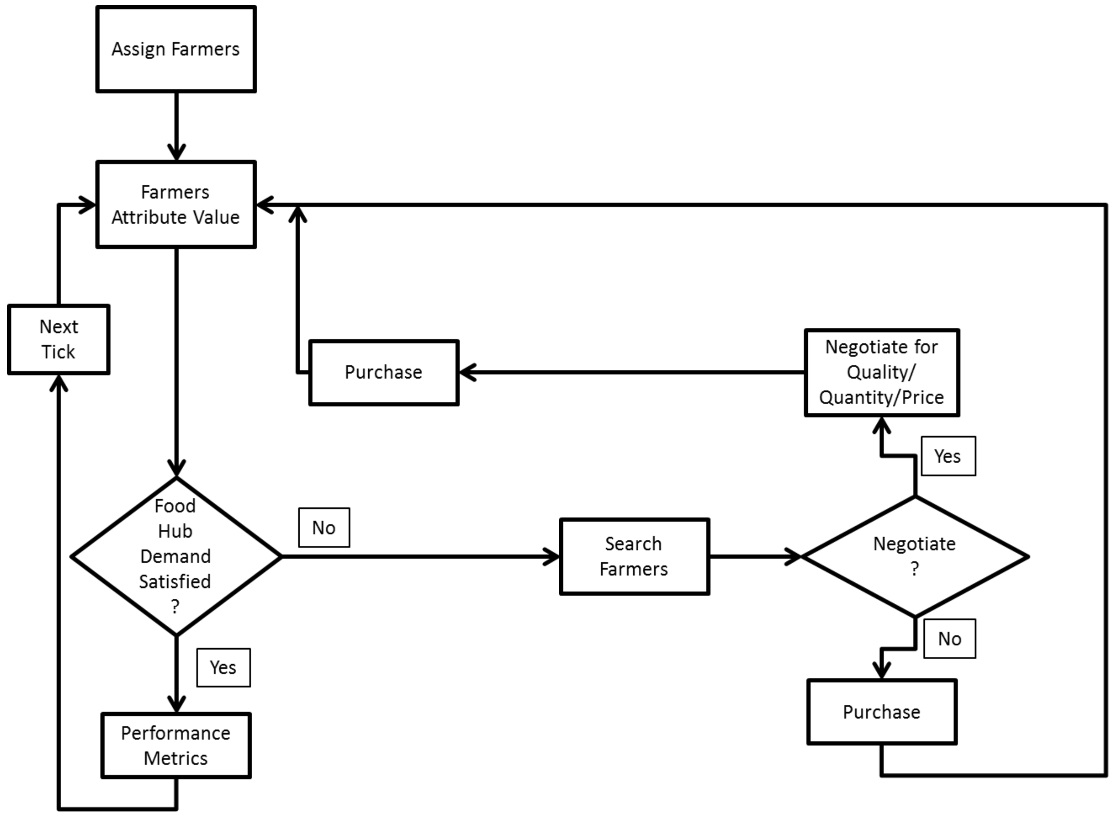

Figure 2: Model overview

2.4 Agent Negotiation

Negotiation is based on prices, quantities, and food quality. For model initialization in the first five time-steps, irrespective of its supplier selection policy, the food hub purchases 10%, 5% and 1% of its demand from small, medium and large farmers, respectively. After five time-steps, purchase quantities becomes subject to the negotiation process.

Negotiation between the food hub and a selected farmer will occur if any of the following three conditions are met:

- *The farmer supplies poor-quality food to the food hub*. If this occurs, the food hub will ask the farmers to introduce quality control methods in their production processes. Examples of quality control techniques include improving packaging, performing sample inspections, and using statistical tools to verify and monitor quality. The farmer's reaction to this request depends upon his current utility value. If this value is below the threshold value, the farmer will agree to implement quality control methods in order to do business with the food hub and increase its profit. If the utility value is higher than the threshold value, the farmer is satisfied with his business and would not want incur additional costs of quality control and therefore would not impose quality control methods in his process.
- *The farmer is dissatisfied with his level of sales to food hub (i.e., the utility of farmer-agent is less than the threshold utility value)*. If the farmer is dissatisfied with its level of sales to the food hub (x_1), he will enter into negotiations with the food hub in an effort to increase his utility value. Farmers will increase the percentage of food to be supplied to foodhub if their utility value is less than their threshold value. The increment will be by 5%, 2% and 0.1% for small, medium and large farmers, respectively. The farmers will decrease the percentage supplied to the food hub when it exceeds the limits of its range ($x_{1(max)}$).
- *The farmer offers a price to the food hub that is more than the expected price*. It is assumed that the price at which the food hub would like to purchase carrots to the farmers is fixed at $1.00/lb (the "expected price"). If the price offered by the farmer is greater than this expected price, the food hub will initiate negotiation with the farmer to reduce its cost. In response, the farmer will reduce the price by 10%. However, if

after this price reduction the cost is still greater than the expected price, the food hub will purchase from the farmer. However, the performance value (P) of the farmer will be reduced by 25%.

3. Simulation Results and Analysis

The model was used to run experiments to test the impact of two different supplier selection policies on a variety of supply chain metrics. The two policies for selecting suppliers are as follows:

- Policy A: Random selection of farmers
- Policy B: Selection of farmers based on their performance ranking (*P*)

The output metrics that were captured for each time-step include: the number of farmers selected, farmer size distribution, cost of quality control, average farmer performance, and the number of farmers negotiating. These metrics help us understand the key performance parameters which will help food hub achieve its objectives and support small and medium size farmers. For each of the policies, 10 replications of 100 time-steps each were run.

Figure (3) provides a graphical summary of the experimental results, comparing the impact of the two different supplier selection policies on the five output metrics. On average, the number of farmers selected (Figure 3(a)) to satisfy demand under Policy A (48 farmers) is slightly (but significantly) greater than under Policy B (41 farmers). Policy A requires more suppliers to fulfill demand because a policy of random selection forces the food hub to continuously rotate its set of suppliers, whereas with performance-based selection (Policy B), the food hub consistently works with the same group of suppliers from one time-step to the next, and as relationships develop between the farmers and the food hub, each farmer increases his supply the food hub.

Every consumer would like to have defect-free food; however it is producers who control the quality of their supplies. The cost of implementing quality control by itself means nothing unless it results in improvement in the performance of the supplier. Between the two policies used by the food hub, we see that there is no significant difference in the cost of quality (Figure 3 (b)). However, the performance of the suppliers (Figure 3 (c)) improves significantly (by 6.4%) under Policy B. This big change in performance of the farmers is due to the increase in the frequency of interactions and negotiations between the food hub and its suppliers: Under Policy B, the percentage of farmers negotiating with the food hub is 43%, compared to 26% under Policy A (Figure 3 (d)).

The most interesting experimental outcome is the size distribution of the selected farmers. As Figure 5(e) shows, more small and medium-sized farmers are selected under Policy B, while more large suppliers are selected under Policy A. Thus we can infer that the 10% bonus on performance (*P*) that is given to small and medium farmers has an impact.

Overall, Policy B results in better system outcomes in terms of farmer performance and size distribution, but the tradeoff is that it requires more negotiation. A t-test was performed on the mean values for each output metric to determine whether the observed differences between the two policies were statistically significant ($\alpha = 0.05$). As shown in Table (3), the test revealed that the policies are significantly different for all output metrics except for “Cost of Quality Control”, which further emphasizes why selecting policy B is better in order to achieve the food hub’s objectives.

4. Conclusion

This paper describes a multi-agent simulation model of a food-producing region in which farmers of various sizes negotiate with and sell food to a regional food hub. This model was used to assess the impact of two different supplier selection policies on performance and structural metrics of the regional food system, which is an area of significant interest to food hub managers and other regional food chain participants. The use of multi-agent simulation to study this problem allows us to capture agent autonomy and heterogeneity, in terms of objectives, attributes, and behavior. It also enables us to represent food hubs as decision makers that apply multiple different criteria (including non-traditional social metrics) in their evaluation of supplier performance, as they do in the real world.

The results of our experiments indicate that food hubs should anticipate that an up-front investment of time and resources will be necessary to provide adequate assistance to smaller-scale farmers to help them meet performance requirements. However, once these relationships have been established, food hubs, regional farmers, and consumers

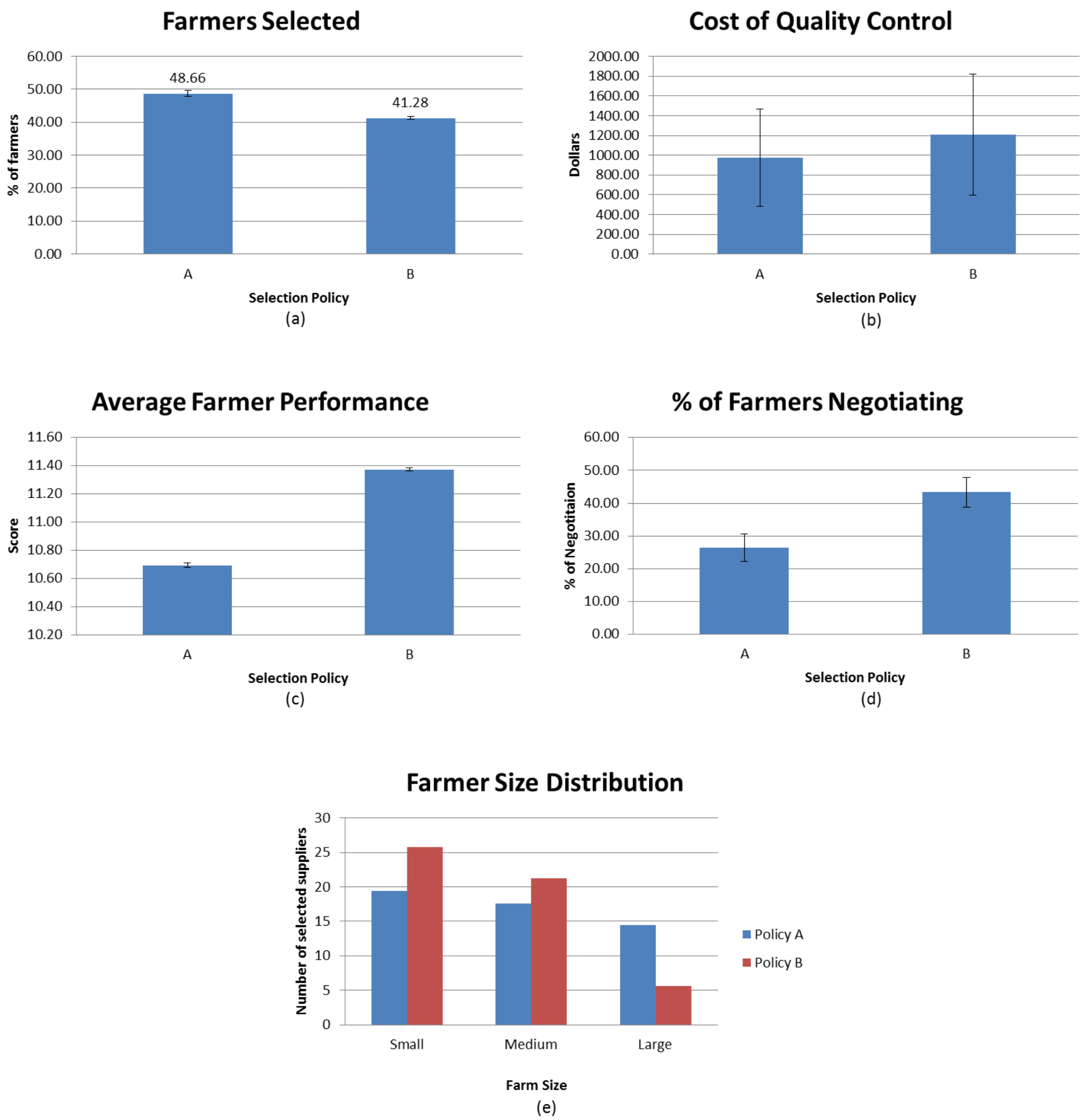

Figure 3 : Graphical comparison of policy A and policy B

Table 3: Statistical comparison of policy A and policy B

	Policy A		Policy B			
Output Metrics	**Mean**	**Std.Dev**	**Mean**	**Std.Dev**	**t statistic**	**p-value**
Farmers Selected	48.66	0.91	41.28	0.39	-16.57	0.00
Average Farmer Performance	10.69	0.02	11.37	0.01	83.55	0.00
Cost of Quality Control	975.53	495.20	1209.96	613.17	0.94	0.19
% of Farmers Negotiating	26.40	4.14	43.28	4.42	8.81	0.00

can greatly benefit from this partnership. Future work will focus on understanding the impact of more complex supplier selection policies and negotiation practices in which farmers are aware of and can communicate with neighboring farmers. The outcomes of this research will provide guidance to food hubs as they develop their supply chain management policies to support profitable, efficient, and sustainable regional food chains.

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