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ARTICLE

More competitive than you think? Pricing and location of processing firms in agricultural markets

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Abstract

The spatial distribution of production is a defining characteristic of agriculture, and the location choice in geographic space and the spatial pricing policies adopted by agricultural processing/packing firms are key determinants of the competitiveness and efficiency of agricultural product procurement markets. Spatially distributed buying firms in the presence of costly transportation of farm products creates natural oligopsony procurement markets. Although several studies have contributed to our understanding of price and output determination and the distribution of welfare in these markets, all are limited in that they address buying firms' locations or their choices of spatial pricing strategy in isolation, holding the other factor fixed, even though both would be chosen jointly in reality to comprise a firm's product-procurement strategy. Here we overcome this limitation by using computational methods (including genetic algorithms) to study duopsony firms' joint choices of location and pricing policy. Our results differ considerably from those presented in prior literature. In general, we find that, when buyers have the flexibility to jointly choose their locations and pricing strategies, market outcomes are much more competitive and locations more efficient in terms of cost minimization than has been predicted by prior studies viewing location choice or pricing strategy in isolation.

KEYWORDS

genetic algorithm, oligopsony, price discrimination, spatial competition

JEL CLASSIFICATION

Q13, L13, R32, C63, C72

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1 | INTRODUCTION

The spatial dimension of agricultural production is a key distinguishing feature relative to other industries. It is a key determinant of the structure of markets for the procurement of farm products, the competitiveness of these markets, the efficiency with which farm products are assembled, and the determination of prices, outputs, and distribution of welfare in them (Hamilton & Sunding, 2020; Jung et al., 2022).

Although the economic importance of the spatial dimension of agricultural markets has been studied at least since von Thünen (1826),[1] study of the implications of spatially dispersed farm production and processing/packing firms for the nature of competition in farm-product procurement is of much more recent vintage. Stripped to its essence, the issue is that costly transport of farm products incentivizes processing/packing firms to locate in close proximity to producing areas and limits farmers' access to spatially distributed buyers, creating procurement markets that are natural oligopsonies (Faminow & Benson, 1990; Hamilton & Sunding, 2020; Rogers & Sexton, 1994).

Researchers have sought to understand two questions that are fundamental to determining prices and outputs, and the competitiveness of these markets: (i) Where within the producing region will buying firms choose to locate, and (ii) what spatial-pricing strategies will they adopt? A spatial-pricing strategy involves more than merely setting an offer price. It also concerns what share, if any, of the transport costs from farm to the buyer's location that the buyer bears. Common examples are to bear none, that is, free-on-board (FOB) pricing; bear all, that is, uniform delivered (UD) pricing; or bear some fraction $1-\alpha \in (0,1)$ of these costs.

Contributions in recent decades to addressing questions of location and pricing strategy in agricultural markets have addressed one question or the other while treating the unaddressed question as a given, even though the two decisions are interrelated and chosen jointly by a firm as defining elements of its product-procurement strategy. For example, studies of buying firms' choice of spatial pricing policy have located buying firms exogenously at the endpoints of Hotelling's line (Graubner et al., 2011; Zhang & Sexton, 2001), whereas studies of firm location have typically assumed free-on-board (FOB) pricing (Fousekis, 2015).[2]

The goal of this paper is to surmount this central limitation of the literature and study firms' geographic-location and pricing-strategy decisions jointly. In so doing, we hope to contribute to understanding of the efficiency of farm-product assembly, and processing and of the importance of

[1]The study of optimal processing plant locations has a rich history in agricultural economics, with key examples being Stollsteimer (1963), King and Logan (1964), Polopolus (1965), and Hilger et al. (1977). These studies utilized programming models to derive least-cost plant locations, given plant economies of scale and shipment costs for both the farm and processed products. Studies tended to find significant economies of scale in processing, leading to few plants in the least-cost configuration. Although some authors noted the implications of number and location of processing firms for possible market power (e.g., Stollsteimer et al., 1975, p. 113), none made any attempt to account for it in their analysis. See Lucas and Chhajed (2004) for a review of this literature.

[2]The same limitation applies to a parallel set of studies that have examined location and pricing by duopoly sellers operating on Hotelling's line. Key early examples include Hotelling (1929) himself, who believed erroneously that FOB-pricing firms would each locate at the market center (a result known as minimum differentiation), and d'Aspremont et al. (1979), who corrected Hotelling, demonstrated the nonexistence of pure strategy equilibrium in Hotelling's base model and established maximum differentiation (location at the market endpoints) as the location equilibrium with FOB pricing and quadratic transport costs, instead of linear costs as assumed by Hotelling. Others have tweaked different aspects of the base Hotelling model to establish existence of pure-strategy Nash equilibria under specific conditions. Examples include Anderson et al. (1997), who relaxed the assumption of uniform distribution of consumers on Hotelling's line; Hinloopen and van Marrewijk (1999), who added a finite reservation price to the inelastic consumer demands of Hotelling; and Meagher and Zauner (2005), who introduced seller uncertainty regarding consumer tastes into the d'Aspremont et al. (1979) model. In general these extensions of the FOB pricing model establish that equilibria may exist with locations intermediate to the extremes of maximum or minimum differentiation. Other work has addressed seller location assuming a specific form of price discrimination (e.g., Lederer & Hurter, 1986; Hamilton et al., 1989). None have studied both location and choice of pricing strategy, such as FOB, UD, or something intermediate between these polar cases. Summaries of this literature are provided by Thisse and Norman (1994), Greenhut and Norman (1995), and Biscaia and Mota (2013).

buyer power in agricultural product procurement markets, topics of longstanding and ongoing interest in both western and developing economies.[3]

2 | BACKGROUND AND RELATED LITERATURE

The essential reason for the failure of the prior literature to address location and pricing decisions jointly is the analytical complexity involved in introducing spatial considerations into a model of market competition. The goal of such models is to determine Nash equilibrium strategies for firms. However, these models are plagued by problems of nonexistence of equilibrium in pure strategies in many cases (Dasgupta & Maskin, 1986; d'Aspremont et al., 1979; Schuler & Hobbs, 1982; Zhang & Sexton, 2001)[4] and a multiplicity of asymmetric equilibria in others (Mérel & Sexton, 2010).[5] Thus, these models quickly become intractable and analytical solutions and pure-strategy Nash equilibria are attainable only if supported by strong assumptions that limit the generality of inferences derived from them.

We eschew the quest for analytical solutions in favor of a framework that relies upon computational economics methods. In particular, we identify firms' decisions regarding location and price policy by genetic algorithm (GA) learning of equilibrium strategies within an agent-based model (ABM). The use of ABMs in agricultural economics has gained a foothold in the last 25 years, with Balmann (1997) and Berger (2001) representing prominent early applications. Kremmydas et al. (2018) and Huber et al. (2018) provide recent reviews of agent-based approaches in agricultural economics.

Although most ABMs have been based on mathematical programming or ad-hoc decision rules, some authors have employed flexible and powerful optimization techniques, including the application of artificial intelligence methods, to study decision problems of high complexity within ABMs (Boyer & Wade Brorsen, 2013; Feil et al., 2013; Zhang & Wade Brorsen, 2010). We follow this approach, in particular Graubner et al. (2011), and combine an ABM structure with an artificial intelligence technique (GAs), which enables us to investigate spatial competition between buyers of an agricultural product as a noncooperative game and to surmount the aforementioned analytical difficulties. This approach leads to surprising results that contrast with standard assumptions and prior findings in the spatial economics literature.

Our model follows most previous studies of firm location decisions by focusing on duopsony/duopoly competition and location along Hotelling's line or street. However, instead of assuming a particular pricing policy, we allow buying firms to adopt any linear pricing strategy consisting of paying a fixed "mill" price at the processing-plant gate, minus some fraction, $\alpha \in [0,1]$ of the costs of transporting the product from farm gate to plant gate. Although most studies of spatial agricultural markets have assumed $\alpha = 1$, so-called free-on-board (FOB) pricing wherein sellers are responsible for all transport costs, departures from FOB pricing are common in reality (Sesmero, 2016), including full buyer absorption of transport costs, $\alpha = 0$, known as uniform-delivered (UD) pricing (Alvarez et al., 2000; Durham et al., 1996; Tribl et al., 2017). Instances of pricing policies between the extremes of FOB and UD pricing, $\alpha \in (0,1)$, are also common and easy for buying firms to implement through offering farmers hauling allowances (Ali, 2004; Meyer, 2005), operating receiving stations at intermediate locations,[6] or directly providing the farm-to-plant transportation and billing farmers for only a fraction, $0 < \alpha < 1$, of the cost.

[3]Arguably intermediaries' buyer power over farmers has become the central market structure policy issue in agricultural supply chains for most countries, supplanting in importance concerns about food manufacturers' and retailers' abilities to raise prices to consumers (Nes et al., 2021; Sexton & Xia, 2018).

[4]Nonexistence of pure-strategy equilibria is due to "market stealing," the phenomenon whereby, with linear transport costs and symmetric pricing strategies, one buying firm, by offering a price sufficiently higher than its rival, can capture the entire market area it is willing to serve at that price, causing discontinuity in the payoff functions and failure of pure-strategy equilibria to exist (Dasgupta & Maskin, 1986).

[5]Mérel and Sexton (2010) show that a continuum of asymmetric Nash equilibria exist with FOB pricing in market settings that they termed "weak duopoly."

[6]Receiving stations are especially common in the developing world for commodities such as coffee and milk (Dries & Noev, 2006; Ndahetuye et al., 2020).

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Our model also conforms to important real-world settings, especially in developing countries, where buyers (e.g., traders) procure farm product at seller (e.g., village) locations and pay costs to transport the product to processing, packing, or export locations (Kopp & Brümmer, 2017; Schipmann & Qaim, 2010). Such buyers are able to offer an unique purchase price at each location, with price decreasing in distance to the processing facility or export terminal, so as to conform in practice to our pricing schedule and an $\alpha \in (0,1)$.

FOB pricing is nondiscriminatory because, although all sellers obtain a differentiated net price based upon their location relative to the buyer, the price differences equate the transport cost differences between locations. Any departure from FOB pricing represents a form of third-degree price discrimination against farmers located nearby the processing or packing facility, with UD pricing representing a particularly extreme form of price discrimination.[7]

Although the choice between FOB and UD pricing for duopoly sellers located at the endpoints of Hotelling's line had been studied for the case of inelastic-demand consumers arrayed uniformly along the line (Espinosa, 1992; Kats & Thisse, 1989), Zhang and Sexton (2001) were the first to study the problem in a procurement market, where farmers had (unit) elastic supply functions. They found that mutual FOB pricing emerged as equilibrium strategies when spatial competition was intense (i.e., transport costs were low relative to the value of the farm product), and mixed pricing strategies (UD for one firm, FOB for the other) emerged under moderate competition, with mutual UD pricing emerging only when relative transport costs were high and competition was weak. Fousekis (2011) revisited the problem in a mixed duopsony setting, with one investor-owned firm and one cooperative.

Using GA optimization, Graubner et al. (2011) were able to study a richer set of spatial pricing options than just UD and FOB pricing for buying firms located at the endpoints of Hotelling's street. They adopted the aforementioned linear pricing schedule and showed that price discrimination in the form of either UD pricing or partial freight cost absorption emerge as equilibrium pricing strategies in the duopsony case with maximum differentiation, but FOB pricing does not.

The infrequent emergence of FOB pricing as equilibrium behavior in these studies might call into question the relevance of the many studies of farm-product procurement that invoke FOB pricing as a foundational assumption. However, the policy relevance of these conclusions may itself be challenged by the restrictive assumption that buyers are located at the market endpoints and the fact that casual empiricism reveals frequent examples of FOB pricing in farm product procurement markets (e.g., Jung et al., 2022).

Although maximum differentiation minimizes price competition between firms, such locations are inefficient from the perspective of minimizing transport costs, and some authors have considered alternative market structures. Examples include Alvarez et al. (2000), who investigated a milk market duopsony under UD pricing and an unbounded line market; Faminow and Benson (1990) and Sesmero et al. (2015), who considered a third buyer at the market center in models of FOB pricing; and Wang et al. (2020) who analyzed alternative market structures in a two-dimensional FOB pricing model of procurement markets for corn ethanol plants. In each of these contributions, however, firm locations and price policies were treated as exogenous.

Neither FOB pricing nor maximum differentiation maximize buyer profits for most spatial competition settings, raising the question of how behavior is affected if firms are able to choose both their location and pricing policy, especially if the denizens along Hotelling's street, whether they be consumers or farmers, have elastic responses to price. We seek to answer this question in the following sections. Key findings are that neither maximum nor minimum differentiation ever represent equilibrium behavior in the generalized setting of our model and locations and pricing strategies that are chosen tend to result in greater competition and economic efficiency than is found in prior work. Pricing strategies close to FOB pricing re-emerge as equilibrium strategies in this generalized

[7]The nondiscriminatory character of FOB pricing has caused competition authorities to regard it (incorrectly) as competitive pricing and to view UD pricing with suspicion (Zhang & Sexton, 2001).

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framework in settings where competition is intense because FOB pricing limits direct price competition to the market boundary (Zhang & Sexton, 2001), a key consideration once firms are no longer constrained to locate at the competition-stifling endpoints of Hotelling's line.

3 | MODEL FRAMEWORK

Two buyers, denoted as A and B, choose a plant location on a line market of unit length ($x = [0,1]$), with $x_A = [0,1/2]$ and $x_B = [1/2,1]$ indicating the location of A and B, respectively. For example, locations $x_A = 0$ and $x_B = 1$ would represent maximum differentiation, whereas minimum differentiation would be represented by $x_A = x_B = 1/2$.[8]

We assume a fixed rate of conversion from the farm input into the final product output, and without further loss of generality set that conversion rate to one through appropriate choice of measurement units so that one unit of the farm input is needed to produce one unit of the processed output. Input buyers sell the final product in a perfectly competitive market, where Φ is the constant price of the finished good.[9] Processing/packing costs, exclusive of farm-product costs, are constant, c, per unit, and we set the net price $\phi = \Phi - c = 1$ via normalization. ϕ is thus the "gross" marginal value product of the farm input, that is, the marginal value prior to accounting for shipment costs.

Farmers are perfect competitors and uniformly distributed in the geographic space such that each location x accommodates exactly one seller of the farm product. Each has a common price-elastic supply function, and the quantity of each input seller is determined by the price, p, at the seller's location, x:

$$q(x) = \max\{p_i(x), 0\} \text{ with } \; i = \{A, B\}. \tag{1}$$

This supply function is unit elastic, and the absence of any slope parameter is simply a unit-of-measurement choice and achieved without any further loss of generality.[10] As Zhang and Sexton (2001) noted, including price responsiveness of farmers in a product-procurement model (consumers in a selling context) is important because otherwise pricing decisions are made primarily from a competition perspective and without regard for their impact on farmer sales (consumer purchases in the selling context), so long as the farmer (consumer) participates in the market at all.

Transport costs are linear in distance with given transport rate t per unit of product and unit of distance. Given the normalization of monetary units based on gross value of the finished product, that is, $\phi = 1$, the value of t is interpreted relative to ϕ. For example, if $t = 1$ and the farm product is transported distance $|x - x_i| = 0.25$, then the transport costs represent 25% of the gross value of the farm product.

In the prototype model with maximum differentiation and the market size normalized to one, t represents the differentiation between the buying firms, which, in turn, is a pivotal factor in determining the intensity of competition in the market, with $t = 0$ representing undifferentiated buyers and perfect competition (i.e., Bertrand's paradox) and sufficiently high values of t enabling the buyers to act as isolated monopsonists (e.g., Zhang & Sexton, 2001). Intermediate values of t characterize different intensities of oligopsony competition. Importantly, however, when firms are free to choose locations within the market area, the product of t and the distance, $x_B - x_A$, between them

[8]Buyers incur a fixed capital cost of locating a plant, but we assume this cost is not a function of the specific location chosen. Such costs, thus, play no role in our analysis, in that we assume implicitly that the variable profits from operating in the market exceed the fixed entry costs.

[9]The assumption of perfect competition in output sales, while allowing buyer power in farm product procurement, is realistic given that the finished product is typically much less bulky and perishable than the farm product and, thus, sold in a geographic market that is much larger and subject to more competition than the procurement market. Empirical studies have tended to find limited seller power in the food industries—see for example the recent surveys by Perekhozhuk et al. (2017), Sexton and Xia (2018), and Deconinck (2021).

[10]Assuming a unit elastic supply function is no more general than assuming a perfectly inelastic function but is undoubtedly much more realistic, especially over the length of run at issue in this paper wherein we study buying firms' joint location and pricing-strategy decisions.

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determines the differentiation between firms, which, together with the pricing strategies chosen, determine intensity of competition in the market.

We define the price $p_i(x)$ offered by buyer i to the seller at location x as a function of the mill price m_i and the portion α_i of the transport costs between i's location, x_i, and the seller's location, x, that is borne by the seller. Accordingly, we denote the triple $\gamma_i = (m_i, \alpha_i, x_i)$ as the spatial price and location strategy of buyer $i = \{A, B\}$. The linear price schedule is:

$$p_i(x) = m_i - \alpha_i t \,|\, x_i - x \,|\,. \tag{2}$$

We define the local breakeven price, $b_i(x)$, as the price at each location that yields zero profits to the buyer:

$$b_i(x) = \phi - t \,|\, x_i - x \,|\,. \tag{3}$$

Figure 1 illustrates $p_i(x)$ and $b_i(x)$. Given the supply function (1), i's profit at seller location x is:

$$\pi_i(x) = \left[b_i(x) - p_i(x)\right] p_i(x), \tag{4}$$

and is represented on a per-unit basis by the vertical distance between $b_i(x)$ and $p_i(x)$ in Figure 1. However, importantly, profit is also a function of the amount of farm product supplied, $p_i(x)$, at the location, a factor ignored in the spatial models that assume inelastic consumer demands or farmer supplies.

We model the choice of the elements in γ_i as simultaneous decisions. This approach departs from the simpler decision problems studied in the analytical models wherein location and price (given an assumed FOB or UD pricing regime) are set sequentially, with the game solved recursively, meaning that the pricing game is solved for arbitrary locations in stage 2 and then the stage 1 location choice is studied, given rational anticipation of the subsequent pricing game. The simultaneous-choice game is comparably general with the sequential-choice game and is more tractable in terms of our computational framework.

A buyer's profit is zero if the local price is zero, so no product is supplied, or if $b_i(x) = p_i(x)$. Accordingly, the buyer will not serve locations outside the market radius r where:

FIGURE 1 Touching equilibrium ($t = 4$) with OD pricing ($m = 1/2$ and $\alpha = 1/2$) and location at the quartiles

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$$r = \min\left\{\left.\frac{m_i}{\alpha_i t}\right|_{\alpha_i > 0}, \left.\frac{1-m_i}{(1-\alpha_i)t}\right|_{\alpha < 1}\right\}. \tag{5}$$

The optimal price strategy for the monopsonist is $(m_M, \alpha_M) = (1/2, 1/2)$, a result that can be found analytically (see, e.g., Norman, 1981) and involves price discrimination, with partial freight absorption (Löfgren, 1986). This result is known as optimal discriminatory (OD) pricing, and under OD pricing there is a unique location equilibrium known as the "touching equilibrium" for $t = 4$, where firms locate at the quartiles of the market, $x_A = 1/4$ and $x_B = 3/4$, and market areas "touch" at the market center, $x = 1/2$, with $p_A(0) = p_B(1) = p(1/2) = 0$.[11] This equilibrium is illustrated in Figure 1. OD pricing maximizes both the market radius and the local profit (4). Location at the market quartiles is also efficient in the sense of minimizing the total cost of transporting the farm product.

Complications arise, however, for lower transport costs because the potential market areas of both buyers will overlap. Unless further restrictions are imposed on the price or location strategies of the buyers, a variety of possible competition scenarios emerge, which may require alternative formulations of the buyers' profit functions. This, in turn, can cause discontinuous payoff functions and nonexistence of Nash equilibrium in pure strategies (d'Aspremont et al., 1979), multiple Nash equilibria with asymmetric buyer strategies (Mérel & Sexton, 2010), or inability to obtain closed-form solutions (Osborne & Pitchik, 1987).

4 | SIMULATION MODEL

We surmount these analytical complications by studying the spatial competition problem using an agent-based framework that is able to capture the interactions among many heterogeneous players (Tesfatsion, 2006). In particular, we build upon the Spatial Agent-based Competition Model (SpAbCoM) developed by Graubner (2011). Within this model, genetic algorithms (GAs) are applied to solve the decision problem of the buyers. GAs have proven to be successful in identifying equilibrium strategies in complex games and have been used over a broad range of disciplines (Foster, 2001). Economic applications include Alemdar and Sirakaya (2003), Arifovic (1994), Axelrod (1997), Balmann and Happe (2001), Dawid and Kopel (1998), Feil et al. (2013), Graubner et al. (2011), Haruvy et al. (2006), and Price (1997).[12]

A GA is a stochastic, heuristic search method to find optimal or close-to-optimal solutions in large decision or strategy spaces. In analogy to biological evolution, the GA is based on the principle of the survival of the fittest (Dawid, 1999) in that good strategies are more likely to be selected within the optimization framework, while bad strategies become extinct. During optimization, through "mutation" and "crossover", the GA enables new and potentially superior strategies to emerge, making solutions from the GA process efficient and robust. Specifically the GA minimizes the dependency on the initial conditions and vulnerability to lock-in toward local optima than other numerical methods (Son & Baldick, 2004). In general, a GA converges over a sufficient number of iterations towards an equilibrium in evolutionary stable strategies—a NE of the game if one exists (Dawid, 1999; Price, 1997; Riechmann, 2001).

We use this approach and model the decision making of each buyer by the application of an individual GA within a spatial competition setting. In adapting the simulation to fit the case at hand, we explicitly consider the spatial dimension of a market by an array of $n = 400$ equidistant locations, each occupied by one farmer $j = \{1, \ldots, n\}$. Given that the size of the market is normalized to 1.0, the distance between two neighboring farm locations is $x_{j+1} - x_j = 1/(n-1)$. Each competitive farmer's

[11]The touching equilibrium is derived for the seller case under FOB pricing by Economides (1984) and Hinloopen and van Marrewijk (1999).
[12]Detailed discussions of GAs can also be found in Goldberg (1989) and Mitchell (1996).

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profit-maximizing strategy is to select the higher net price at her/his own location and set quantity according to the supply function (1), given this price.

Buyers can choose to locate at any of the equidistant points. Given the normalizations of monetary and spatial units, all buyer strategy variables $\gamma_i = \{m_i, \alpha_i, x_i\}$ are in the interval $[0,1]$. Each buyer's decisions must incorporate the strategic interaction with its rival and the competitive responses of farmers.

4.1 | Modeling buyer decision making with a GA

To illustrate how the GA operates and to demonstrate its ability to identify NE, we begin by replicating the touching equilibrium $\gamma_A = (1/2, 1/2, 1/4)$ and $\gamma_B = (1/2, 1/2, 3/4)$ via simulation. The first step to initialize a GA is to generate a pool of possible solutions—the so-called population. In our case, such a population consists of an arbitrary number of triples. Each represents a random combination of the decision variables m, α, and x within their feasible ranges to comprise a buyer's strategy $\gamma_i = (m_i, \alpha_i, x_i)$, $i = \{A, B\}$. Although the triples bear information in terms of real numbers (the phenotype), GA commonly work on encoded representations as binary strings (the genotype). Thereby, a single piece of information (e.g., the mill price m) is called a gene, and the chaining of genes (the strategy γ) is the chromosome. Because we consider strategic interactions among processors, we use a co-evolving simulation structure (Price, 1997; Son & Baldick, 2004), that is, each buyer $i = \{A, B\}$ has an individual GA with an individual population $\Gamma_{i,g}$ that is optimized over a given number $g_{\max}$ of so-called generations. Throughout the simulation procedure, we used $v = 25$ chromosomes to form the initial population $\Gamma_{i,0} = \left\{\gamma_{i,0}^k | k = 0, \ldots, v\right\}$ of each buyer $i = \{A, B\}$.

The second part of the GA is a fitness function, which measures how well a particular strategy γ_i solves a problem. We use the sum of i's local profits, that is, Equation (4), over all seller locations x_j where firm i has a higher local price than its rival $-i$ to evaluate performance:

$$\Pi_i(\gamma_i, \gamma_{-i}) = \sum_{j=1}^{n} \pi(x_j) \qquad \forall x_j \in [0,1] : p_i(x_j) > p_{-i}(x_j). \tag{6}$$

Because the profit to a specific buyer, A, depends on the strategy chosen by the other buyer, B, we evaluate A's profit (fitness) for each $\gamma_{A,0}^k$ relative to a randomly selected strategy $\gamma_{B,0}^{k'}$ of firm B. Clearly, if we select a different strategy, $\gamma_{B,0}^{k''}$, for firm B the profit of $\gamma_{A,0}^k$ is likely to change. Hence, we conduct a tournament, where all of A's strategies are tested repeatedly and in different combinations with the competitor's strategies to approximate the expected profits of A's strategies for the given set of B's strategies. This process yields an average profit $\overline{\Pi}_A^k\left(\gamma_{A,0}^k, \boldsymbol{\gamma}_{\mathbf{B,0}}\right)$ of strategy $\gamma_{A,0}^k$, with $\boldsymbol{\gamma}_{\mathbf{B,0}} \subset \Gamma_{B,0}$ being a vector of randomly selected strategies out of buyer's B strategy pool. The repeated test of all $\gamma_{A,0} \in \Gamma_{A,0}$ assigns an average profit value ($\overline{\Pi}_{i,0}^k$) to each strategy k of buyer A, as well as buyer B.

Given the evaluation of the fitness function, we identify the best strategy $\gamma_{i,0}^*$ for $i = \{A, B\}$ within $\Gamma_{A,0}$ and $\Gamma_{B,0}$. Of course, the best strategy of the initial generation $g = 0$ is not likely to be the optimal strategy overall. Therefore, the last step within a GA's generation g is to apply genetic operators: selection, crossover, and mutation. These operators are used to generate a new pool of potentially improved strategies $\Gamma_{i,g+1}$ for the next generation $g + 1$.

In our GA simulation, *selection* picks a predefined number $\dot{v} = 20$ of the best chromosomes (based on the fitness evaluation) in each generation. The difference between the previous and the new population is filled up by $v - \dot{v} = 5$ copies of already selected strategies. The probability of copying a strategy increases with its fitness, that is, the greater the fitness of a strategy, the more likely $\Gamma_{i,g+1}$ contains a copy of this strategy.

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Although selection reduces the variability of the population, crossover and mutation expand it. Crossover (or recombination) splits up two (parent) chromosomes, for example, $\gamma^1 = (m^1, \alpha^1, x^1)$ and $\gamma^2 = (m^2, \alpha^2, x^2)$, with given probability at a random locus. The exchange of the fragments yields two offspring, for example, $\gamma^1 = (m^1, \alpha^1, x^2)$ and $\gamma^2 = (m^2, \alpha^2, x^1)$, representing (with high probability) new strategies. Mutation randomly alters the information carried by a chromosome and generates a mutant strategy, for example, from $\gamma^1 = (m^1, \alpha^1, x^1)$ to $\gamma^{1'} = (m^1, \alpha^{1'}, x^1)$. In our simulations the probability of mutation is 4%, and the rate of crossover is 10%. After selection, crossover, and mutation are applied, each buyer has a new pool of 25 strategies $\Gamma_{i,g+1}$ mostly consisting of retained strategies from the prior generation but also some newly created chromosomes. An unaltered copy of the best strategy of the previous generation is always part of the next generation.

Figure 2 shows the composition of the initial strategy pool and the population after $g = 5$ as well as $g = 1000$ generations with respect to the location variable x for replication of the touching equilibrium. The figure highlights that the algorithm needs a number of generations to adapt to the problem but ultimately yields a variable distribution that is very close to the expected solution.

To improve the precision of the GA's outcome and avoid effects based on the initialization, we repeat the GA simulation 40 times, each with $g_{\max} = 2500$.[13] The best out of $v = 25$ strategies for each player of the last 5% of repetitions, that is, the $g = \{2375, \ldots, 2500\}$, are retained for analysis. Thus, we analyze $125 \cdot 40 = 5000$ games for each value of t for the duopsony pricing and location game.

In our example, the average outcome (over the last 5% of generations and all repetitions, denoted by $\overline{g}$) is $\gamma^*_{A,\overline{g}} = (0.500, 0.500, 0.248)$ and $\gamma^*_{B,\overline{g}} = (0.500, 0.500, 0.751)$, which shows that the GA is able to approximate the analytical solution with high precision. The deviations from 1/4 and 3/4 of the location variables are due to the discrete nature of locations within the simulation.

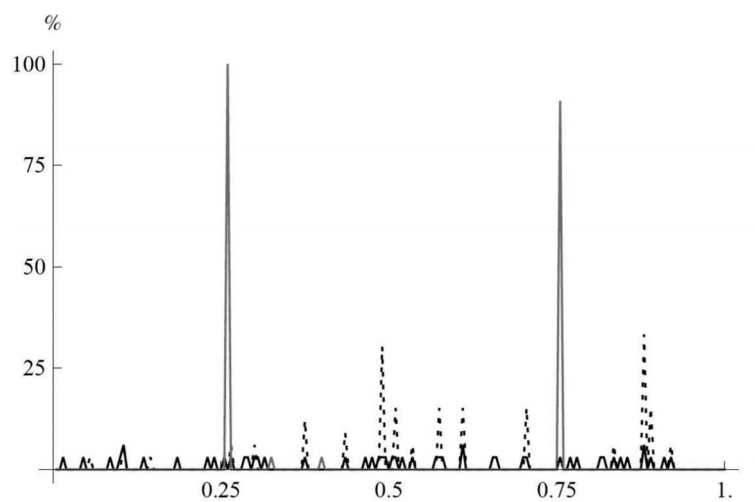

FIGURE 2 Distribution of the buyers' location parameter x in the initial population (solid, black), after five (dashed, black), and 1000 generations (solid, gray), respectively

[13]The maximum number of generations $g_{\max}$ is set based on our experience regarding the convergence of the GA. If a unique Nash equilibrium in pure strategies exists (for a given initialization), the GA approximates it with high precision over the course of 2500 generations and frequently even faster. If, however, there are multiple or no Nash equilibria in pure strategies for the initialized game, the GA does not converge towards a single stable strategy population, and different runs of the simulation can yield distinct strategy populations. Hence, the repetition of the simulation in such situations is critical to reveal the set of Nash equilibria when multiple of them exist or approximate the probability distribution function in the case of mixed-strategy equilibria.

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Given that nonexistence of pure strategy Nash equilibria is a significant phenomenon in simpler spatial markets settings than ours due to market-stealing incentives (see footnote 4), it is highly likely that pure strategy Nash equilibria fail to exist for some values of t in our more complex model environment. Thus, the GA's ability to depict mixed-strategy equilibria is a central aspect of this paper. The solution for a mixed-strategy equilibrium is a probability distribution for the decision variables. The GA does not directly yield the equilibrium probability distribution in any particular simulation, but across a large number of simulations the GA does a very good job of approximating distribution functions for known mixed-strategy equilibria as illustrated in Appendix S1: Section A, where we present applications of the simulation to other spatial competition models in input and output markets that have been investigated in the literature, including those involving mixed (Shilony, 1981; Zhang & Sexton, 2001) and asymmetric (Mérel & Sexton, 2010) price strategies, and games involving choice of both location and FOB price (Hinloopen & van Marrewijk, 1999). These replication exercises further demonstrate the ability of the GA to closely approximate known analytical price and location equilibria in both pure and mixed strategies.

As leading game theorists have observed (e.g., Rubinstein, 1991), the idea of mixed strategies involving randomization or players executing a lottery is unappealing in economics applications, but, outside of simple games of chance, such interpretations are naive and unnecessary. An alternative interpretation, which is appropriate in the present case, is what is known as the *large population case* (Oechssler, 1997; Rubinstein, 1991), wherein a game is viewed as an interaction involving large populations, and each occurrence of the game takes place after a draw of players from these populations. Each player implements a pure strategy, with the mixed strategy equilibrium viewed as the resultant distribution of pure strategies across the repetitions of the game. This interpretation aptly describes the process undertaken by the GA. Each iteration within a simulation represents a draw from the population, and across a large number of draws or replications the distributions for the strategy variables are revealed.

5 | SIMULATION EXPERIMENTS AND RESULTS

We present results of simulations where two buyers choose optimal location, x_i, and pricing regime, (m_i, α_i), given the strategy $\Gamma_{-i} = (m_{-i}, \alpha_{-i}, x_{-i})$ of the competitor. Results are reported for t in increments of 0.05, ranging from perfect (Bertrand) competition to two spatially separated monopsonies for each value of $t = \{0.0, 0.05, \ldots, 5.0\}$.[14] For each simulated value of t, Figure 3 reports median values for the mill price, $\widetilde{m}$, share of transport costs borne by farmers, $\widetilde{\alpha}$, and median distance separating the two firms, $\widetilde{x}_{AB}$, where $x_{AB} = x_B - x_A$. Median values and standard deviations for each of the strategy variables and each value of t are reported in the Appendix S1: Table B.1.

5.1 | Equilibrium behavior

For high transport costs (i.e., $t \to 4$), results are consistent with the touching equilibrium discussed previously. Firms locate at or very near the market's quartiles (i.e., at distance $|\widetilde{x}_i - 1/2| \approx 1/4$ symmetrically right and left of the market center, and $\widetilde{x}_{AB} \approx 1/2$). Given the flexibility to do so, the firms adopt pricing strategies close to optimal monopsony price discrimination, with $(m, \alpha) \approx (1/2, 1/2)$. As Figure 3 illustrates, the pricing and location equilibrium closely resembles the touching equilibrium for values of $t \in [3, 4)$, where active but weak head-to-head competition exists between the firms at the market center.

[14]Although primary interest lies in the range of t values where head-to-head competition prevails between the buying firms, we include results of interest for values of $t \in [4, 5]$ to show firm behavior under monopsony Appendix S2.

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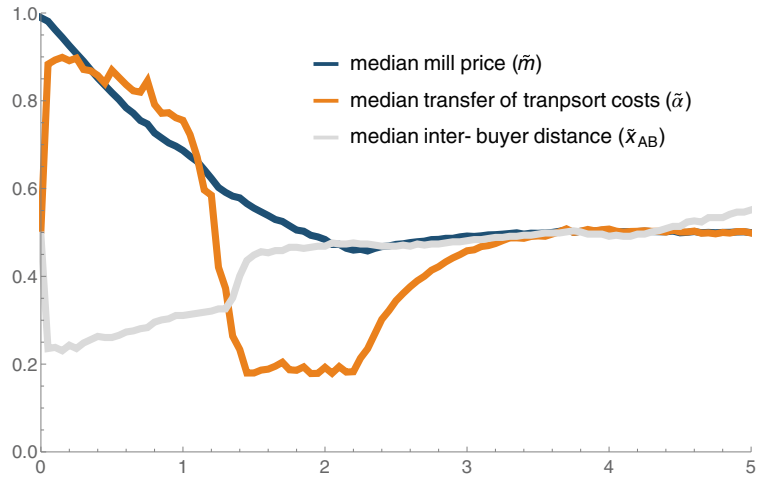

FIGURE 3 Simulation results for price strategy and location in the generalized Hotelling model

The OD price strategy also prevails throughout the monopsony range of $t > 4$. As t increases above 4.0, however, x_{AB} increases, reflecting buyers' locations at the midpoints of their shrinking market areas. These markets feature two spatially separated monopsonies, and "subsistence" regions around the market center and at the region's border(s) that are unserved by either buyer.

At the other extreme, as $t \to 0$, we find the classic Bertrand-Nash equilibrium with mill price m converging to the marginal value product of the farm input, $(m = \phi = 1)$. The choice of x and α is irrelevant if $t = 0$. Because all decision variables are randomly initialized according to a uniform distribution within $[0,1]$, the expected median values of $\tilde{\alpha} = 1/2$ and $\tilde{x}_{AB} = 1/2$ (with $\tilde{x}_A = 1/4$, $\tilde{x}_B = 3/4$) are obtained.

The results depicted in Figure 3 represent the central tendency over 5000 games for each level of t. The initial set of strategies available to each buyer is randomly assigned and hence varies for each repetition. Because of this and the very nature of the GA simulation, which is based on stochastic processes including the random match of strategies, the full outcome of the simulation for each value of t is a distribution for each of the three decision variables. If there is a unique NE in pure strategies, the distribution is degenerate, with the only source of variation being the numerical error which is inherent to any numerical method. For example, for $t = 4$ and the touching equilibrium the standard deviations of α and m are 0.0151 and 0.0093, respectively (see Appendix S1: Table B.1).

Figure 4 shows the cumulative distribution functions (CDFs) for m, α, and x_{AB} for $t = \{0.5, 1.0, 1.5, 2.0, 3.0\}$ and illustrates that the distributions of the decision variables change considerably over the parameter range of t.[15] For small but positive values of t, Figures 3 and 4 highlight a rich and complex set of relationships between firms' price policies and location choices. In these settings, differentiation between firms is minor, creating the potential for intense price competition, including market stealing and nonexistence of pure strategy Nash equilibria.

The total economic surplus available in the market is also highest for low values of t. A firm that locates near the center of the production region positions itself well to capture the supply available in the market, and this is a dominant incentive for low t. However, if both buyers chose to locate directly at the market center (i.e., minimum differentiation), competition between them would dissipate their profits as in a Bertrand paradox setting.

[15]The CDFs represent a smooth kernel distribution based on simulation results. The density functions that accompany the CDFs are provided in the Appendix S1: Section C.

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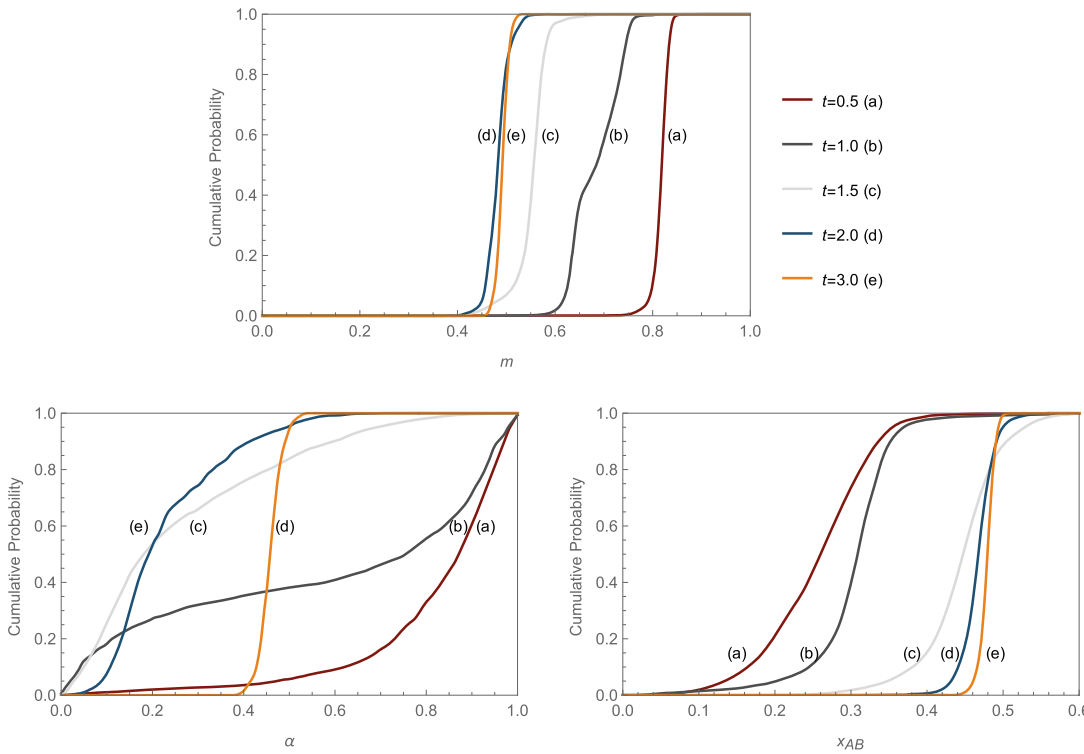

FIGURE 4 Cumulative distribution functions of the decision variables for selected values of the normalized transport costs, t

The simulation results show, however, that firms are able to avoid competing profits away completely for positive but low t by (a) each locating some distance from the market center and (b) using close-to FOB pricing, thereby limiting competition to the market boundary. Although $\widetilde{\alpha}$ is consistently large for $t < 1$, reflecting near FOB pricing, $\widetilde{m}$ declines monotonically in t, reflecting the lessening competitive pressure caused by higher values of t. Separation of firms x_{AB} under low t, although critical to their profitability, is nonetheless modest and rises only gradually from 0.24 to 0.33 over the interval $t \in (0, 1.3]$ (see Appendix S1: Table B.1).

The results for $t \in (0, 0.8)$, exemplified by the CDFs of $t = 0.5$ in Figure 4, are consistent with prior findings that a Nash equilibrium in pure strategies does not exist for low t due to market stealing. Hinloopen and van Marrewijk (1999) derive this result for FOB pricing and inelastic demand, whereas (Beckmann, 1973) and (Zhang & Sexton, 2001), respectively, provide similar results under UD pricing with price inelastic demand and price elastic supply. In this regard, the distribution of the decision variables from the simulation can be interpreted as an approximation of the mixed strategy distribution function over this range of t.

5.2 | Asymmetric equilibria

A different type of result emerges for $t \in [0.80, 1.25]$. Here firms adopt asymmetric strategies. One buyer locates near the center of the market and uses FOB or near-to FOB pricing, whereas the other buyer locates within the first or fourth quartile of the market and uses UD or near-to UD pricing. This behavior is reflected in the bimodal CDF for m and α for $t = 1$ in Figure 4, and is illustrated in Figure 5, where firm A (B) utilizes FOB (UD) pricing. The market boundary is at location $\widehat{x}$.

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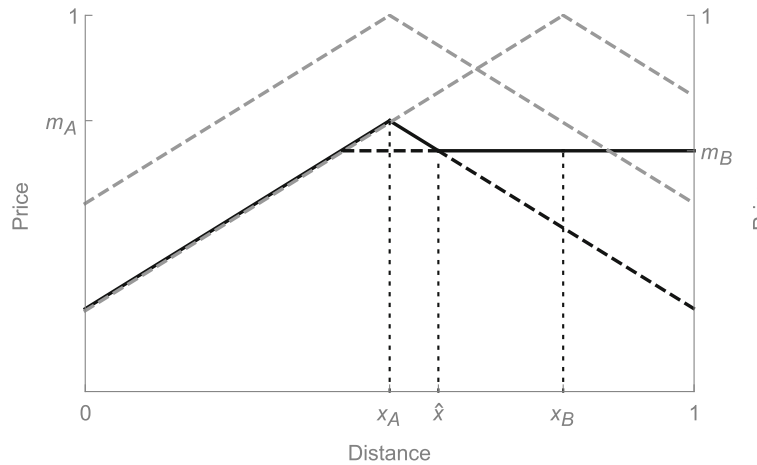

FIGURE 5 Firm locations and market areas under asymmetric pricing strategies. The figure depicts equilibrium price schedules (black lines) with FOB-pricing firm A located at x_A and UD-pricing firm B located at x_B, with endogenous market boundary $\widehat{x}$. The dashed, gray lines show the breakeven prices of both buyers.

Section C of the Appendix S1 shows the combinations of the decision variables by means of density plots. Such asymmetric strategies are consistent with the Zhang and Sexton (2001) analytical result that for moderate values of t one firm chose FOB pricing and the other chose UD pricing in the equilibrium.[16] This combination of pricing strategies limits competition to the market boundary $\widehat{x}$. The firms' locations under the asymmetric equilibrium also result in greater separation between them compared to lower values of t (e.g., compare the CDFs for $\widetilde{x}_{AB}$ for $t = 0.5$ and $t = 1$). The UD-pricing firm thus also contributes to reduced head-to-head competition by locating away from the market center. This apparent locational disadvantage is obviated by the firm utilizing UD pricing, which makes its offer competitive over a large geographic area.

Indeed it has commonly been argued that high price discrimination in the form of UD pricing is superior to FOB pricing in settings with intense spatial competition because UD pricing makes a firm's price competitive over a broad market area (Espinosa, 1992; Graubner et al., 2011; Greenhut et al., 1987; Thisse & Vives, 1988). Firms choosing close-to FOB pricing for low values of t and choosing asymmetric UD and FOB pricing strategies for moderate t is not consistent with these results and beliefs but is consistent with the idea that firms in intensively competitive market environments will find ways to mutually forbear from severe price competition to some degree.

With mutual UD pricing, a firm has a strong unilateral incentive to overbid its rival in order to capture the entire market within the area it is willing to serve. In contrast, FOB pricing restricts direct price competition to the market's boundary, making it a tool to mitigate competition. A FOB-pricing firm that increases its mill price m only captures incremental sales at the market border regardless of the pricing strategy employed by its rival and, meanwhile, loses profits from all infra-marginal sellers.[17] Choice of asymmetric pricing strategies also works to limit direct competition to the market boundary and to limit market-stealing opportunities.

The second strategic tool to moderate competition, which is unexplored when firms are exogenously located at the market's endpoints, is for one or both firms to forbear from operating directly at the center of the production region despite the advantages of a central location in terms of farm-product procurement. For given t, separation in space increases differentiation between the firms,

[16]Li et al. (2018) describe use of asymmetric UD and FOB feedstock pricing strategies for the two major cellulosic biofuel manufacturers in Iowa.

[17]The exception is the aforementioned "market stealing" case wherein a FOB-pricing firm overbids its FOB-pricing rival sufficiently to capture the entire market area that receives a positive net price.

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mitigating the pressures of pure price competition. Indeed, when a model endows firms with the full set of tools they would ordinarily possess in the real world, it is apparent that some of them broadly substitute for each other.

Choice of location and share of freight charges to pay is a key example. Both FOB pricing (or near to it) and location away from the market's center are tools to mute price competition with a rival. Similarly, location near the market's center and adoption of UD or close-to UD pricing are also substitute tools to access product over a broad geographic area. Thus, the combination of locating within the first or fourth quartile to limit price competition and adopting UD or close-to UD pricing to facilitate access to farm product can be roughly equivalent to a strategy of locating near the market's midpoint to facilitate access to product and implementing FOB or close-to FOB pricing to limit direct price competition.

The simulation results show that minimum differentiation does not occur for any $t > 0$. If the distance between both firms is too small, market stealing is easily possible (see footnote 17). The potential for market stealing, however, decreases with the inter-buyer distance x_{AB} because market stealing for i requires that $m_i - \alpha_i x_{AB} \geq m_{-i}$. As long as the distance between a buyer's location and the market center $|x_i - 1/2|$ is sufficiently large, the competitor is better off by locating away from the market center (close to the quartiles) and using close-to UD pricing.

5.3 | Equilibrium spatial differentiation

As t rises we see a sharp increase in spatial price discrimination; $\widetilde{\alpha}$ decreases rapidly in t, approximating UD pricing for both firms for a range of values in the vicinity of $t = 2$. We also see an increase of spatial differentiation, $\widetilde{x}_{AB}$, representing a movement of both firms towards the efficient location at the market quartiles ($x_A \approx 0.25, x_B \approx 0.75$). Further increases in t have little impact on the location choice of the buyers. Spatial price discrimination, however, begins to dissipate for larger values of t, and converges upon OD pricing.

The median mill price $\widetilde{m}$ decreases with t for low and intermediate market competitiveness before it increases under low and decreasing competitiveness to converge upon $m = 0.5$, also consistent with OD pricing. This non-monotonic relationship between m and t corresponds to the "weak duopsony" case described by Mérel et al. (2009). For relatively large values of t, competition is weak but given $\alpha > 0$, increases in t reduce grower supplies and buyer profits for a given value of m, and, if t is sufficiently large, the market would no longer be covered. Buyers rationally respond to increases in t in this range by raising price to maintain supplies of the product, including full market coverage.

A particularly important result illustrated in both Figures 3 and 4 is that neither maximum nor minimum differentiation ever appear as part of the equilibrium strategy for buyers regardless of the value of t. Even when t is low and location at the market center maximizes a buyer's access to valuable farm product, each buyer limits direct price competition by locating strictly within the second and third quartiles.

The incentive to maximally differentiate to reduce competition does not ever dominate the other incentives at work in the generalized market environment studied here. Thus, despite many studies of spatial markets exogenously locating firms on the endpoints of Hotelling's street,[18] and some analytic results supporting maximum differentiation as an equilibrium strategy in special cases (e.g., d'Aspremont et al., 1979; Kats, 1995), firms do not choose those locations when confronted with elastic consumer demands or farmer supplies, costly transport of product, and the freedom to adopt flexible pricing schedules.

To understand the reasons behind this divergence in results, note that the location of the buyer within its own market area does not affect the firm's profit under FOB pricing and inelastic farm

[18]Examples on the farm-product procurement side include Zhang and Sexton (2000), Mérel et al. (2009), Fousekis (2011), and Graubner et al. (2011).

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supply (or consumer demand), as in the base Hotelling model. When $\alpha = 1$ and supplies are inelastic (and normalized to 1), profit in our model at each seller location as defined in Equation (4) reduces to $1 - m$ and is hence constant irrespective of the distance to the seller. The incentive for firms to locate at the market boundaries to minimize direct competition becomes dominant in these cases.

However, if supply is elastic, buyer profits earned at each farm location decrease with increasing distance to the buyer's location because nearby sellers obtain a high local price and supply more, thus yielding greater local profit to the buyer compared to more distant sellers. We denote this as the *supply effect* of a location decision. As a result, elastic demand functions in the selling case or input supply functions in our input-buying case create an incentive, ceteris paribus, for firms to choose central locations within the own market area when operating under a price policy with $\alpha > 0$.

To illustrate the importance of the supply effect, we computed the ratio, $R_1(t)$, of supply received by a seller located at the end point of its market area to the supply received by a seller located at the midpoint (i.e., quartile) under competitive FOB pricing ($m = 1$) and unit-elastic supply functions. Performing the calculations yields the following:

$$R_1(t) = \begin{cases} \dfrac{2t-8}{t-8} & \text{if } 0 \le t < 2, \\ \dfrac{8}{(8-t)t} & \text{if } 2 \le t < 4, \\ \dfrac{1}{2} & \text{if } 4 \ge t. \end{cases} \tag{7}$$

Figure 6 illustrates the results. $R_1(t) < 1$ for all $t > 0$ and declines monotonically in t, before becoming constant at $R_1(t) = 0.5$ for $t \ge 4$. For example, $R_1(2) = \frac{2}{3}$.[19] Once elastic response to price by the farmers along Hotelling's street is introduced, the supply effect creates a strong incentive for firms to locate in the center of their market area, with the importance of the effect increasing in t.

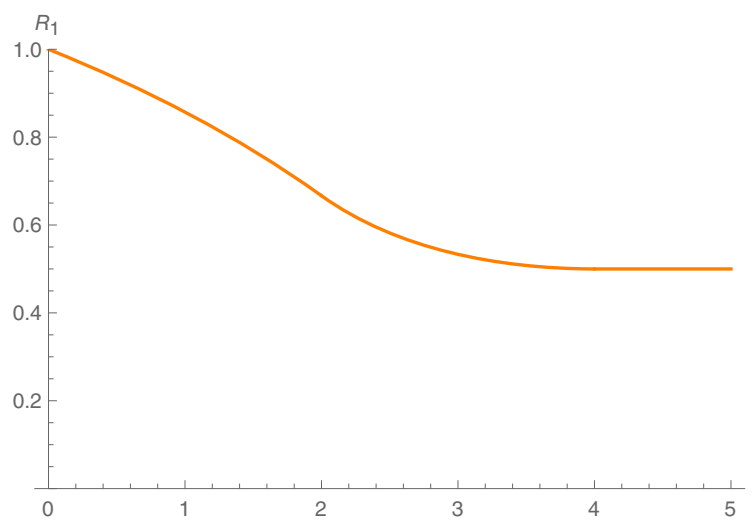

FIGURE 6 Illustration of the supply effect, $R_1(t)$. R_1 is the ratio of total supply for buyer A using competitive FOB pricing ($m_A = 1$ and $\alpha_A = 1$) and located at the market endpoint ($x_A = 0$) relative to the same buyer located at the quartile ($x_A = 1/4$) over the relevant range of spatial competition

[19]The FOB-pricing buyer located at the market's endpoint has a market radius less than one half for $t > 2$.

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Independent of the elasticity of the supply function, any price strategy that involves the buyer paying some portion of the transport costs, that is, $0 \le \alpha < 1$, also creates the incentive to choose a central location within the procurement area because the buyer's per unit transport costs are minimized if the firm locates in the center of its own market area.

The importance of this *cost effect* in firm location decisions is illustrated by the ratio $R_2(t)$ of per-unit transport cost paid by a buyer located at the endpoint and engaging in OD monopsony pricing (thus, bearing half the transport cost) to per-unit transport cost paid by a buyer located at the quartile and also engaging in OD pricing as in the touching equilibrium:

$$R_2(t) = \begin{cases} 2 & \text{if } 0 < t \le 2, \\ \dfrac{4}{t} & \text{if } 2 < t \le 4, \\ 1 & \text{if } t > 4. \end{cases} \tag{8}$$

$R_2(t)$ is illustrated in Figure 7. Per-unit transport costs are twice as high for a buyer at the endpoint compared to a buyer at the quartile for $0 < t \le 2$, that is, as long as the end-point buyer can profitably buy at all locations up to the market's midpoint. $R_2(t)$ decreases with t for $t > 2$ because the buyer at the endpoint serves a market area less than one half, which reduces its unit transport costs relative to a buyer located at the quartile. If $t = 4$, both buyers have identical market radii and per-unit transport costs, although the quartile buyer has twice the supply.

Both the supply and cost effects of the location choice are relevant to any pricing strategy outside of the polar cases of UD and FOB pricing, but the powerful incentives they create are missed in analyses that assume one of these polar forms of spatial pricing or that locate firms exogenously. The supply effect is also missed for any analysis that assumes inelastic response to price for the residents of Hotelling's street. Both effects incentivize firms to locate at the center of their respective market areas.

Offsetting forces are the already noted incentive to maximally differentiate in location from the rival firm to lessen price competition and an opposite incentive to locate near the center of the total production region to maximize access to farm production. For low values of t the cost and supply effects are not powerful enough relative to the incentive to choose a central location in the total

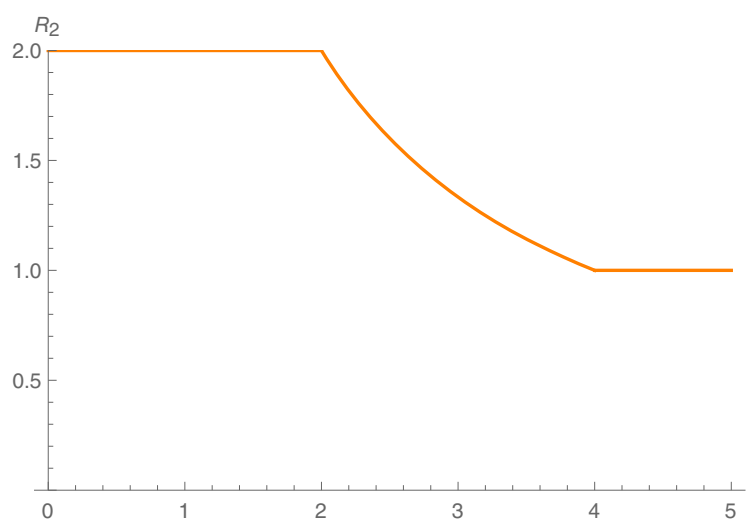

FIGURE 7 Illustration of the cost effect, $R_2(t)$. R_2 is the ratio of per-unit transport costs paid by the OD-pricing buyer located at the endpoint ($x_A = 0$) relative to cost borne by the same buyer when located at the quartile ($x_A = 1/4$)

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production region to pull the firms to the market's quartiles. Firms' locations drift towards the quartiles as t increases above 1.1, with convergence to the quartile locations for all $t \approx 1.5$ and greater (see Appendix S1: Table B.1).

5.4 | Welfare distribution

Figure 8 shows the distribution of economic surplus among producers, processors, and deadweight loss as a function of t. The outcomes of each game (i.e., m_i, α_i, and x_i) were used to calculate total buyer profit (Π) and producer surplus (PS) in the market, based on Equations (1) and (4), and with

$$\Pi = \int_0^1 (\pi_A + \pi_B)\mathrm{d}x \quad \text{and} \quad \mathrm{PS} = \frac{1}{2}\int_0^1 q(x)^2 \mathrm{d}x. \tag{9}$$

Deadweight loss (DWL) is computed relative to a setting where buyers operate at the quartiles and set the competitive FOB price, that is, $(m,\alpha) = (1,1)$, thereby eliminating surplus loss due to inefficient transportation and imperfectly competitive pricing[20]:

$$\mathrm{DWL} = \mathrm{PS}_C - \Pi - \mathrm{PS}, \text{with } \mathrm{PS}_C = 2\int_{\max[0,(t-4)/4]}^{1/4} 1 - t(r - 1/4)\mathrm{d}x. \tag{10}$$

Farmers capture the lion's share of the available market surplus in PS for $t \in [0, 1.1]$, reflecting the competitiveness of these market structures. Whereas PS declines monotonically in t, total processor profits increase over the range of low values of t and actually reach their maximum at $t \approx 0.9$. Larger

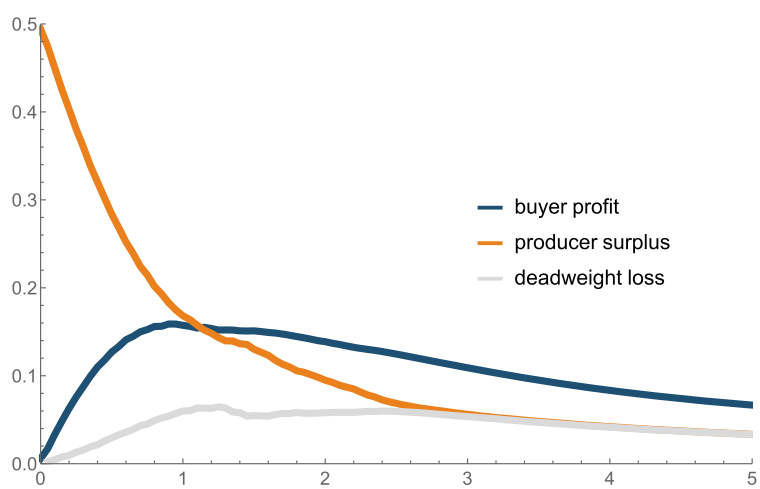

FIGURE 8 Buyer profit, producer surplus and deadweight loss as a function of the normalized transport cost t. The graph depicts median values from 5000 simulations for each value of t.

[20]In the competitive setting, producers capture the entire market surplus (i.e., $\Pi = 0$), and because of symmetry this surplus is identical for each market quartile. Therefore, PS_C in Equation (10) is formulated for the first quartile and incorporates the case of $t > 4$ when the competitive buyers do not cover the market.

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values of t dissipate the available economic surplus in the market, causing processor profit to decrease in t for values of $t > 0.9$, despite processors' market power increasing as a function of t.

DWL is present and increasing in t because of suboptimal firm location relative to minimizing transport costs for low t and departures from competitive pricing for all $t > 0$. However, DWL does not rise monotonically in t, as might be expected. Although the portion of DWL due to the exercise of oligopsony power increases in t, the inefficiency cost of suboptimal buyer locations decreases in t as firms move to the efficient locations at the market quartiles for larger values of t.

We illustrate this point by constructing a location inefficiency index, LII $\in [0, 0.5]$, as the sum of each firm's deviation from its efficient location at the market quartile, that is, $\text{LII} = |x_A - 0.25| + |x_B - 0.75|$. For example, firm locations at the market's endpoints generates LII $= 0.5$. Figure 9 illustrates LII. The index is roughly constant at LII ≈ 0.25 for $t \in (0, 1.3]$, and then declines rapidly in t to converge upon zero. Inefficient locations are chosen only for low values of t when the costs of such inefficiency are low.

As noted, firms' locations also affect the differentiation between them and the competitiveness of procurement markets. The less the interfirm distance, x_{AB}, the less differentiation between firms and the more intense the competition. Figure 9 also illustrates this point by constructing a firm-differentiation index, DI, as the product of normalized transportation cost, t, and $\widetilde{x}_{AB}$. DI $= t$ in the standard models with exogenous location at market endpoints and market size normalized to 1.0 and DI $= t \cdot \widetilde{x}_{AB}$ in our general model. Firms are less differentiated and markets are more competitive for all relevant values of t in the general model because firms do not ever maximally differentiate. Indeed for low values of t, geographic dispersion is minor, and firms only retreat to near the market quartiles for larger values of t.

5.5 | Market competition and producer welfare

Spatial separation among buying firms in the presence of costly transportation creates horizontal differentiation among them. Therefore, many farm-product procurement markets feature an oligopsonistic structure, which is a key reason behind concerns of buyer power in farm product markets (Faminow & Benson, 1990; Hamilton & Sunding, 2020; Jung et al., 2022; Rogers & Sexton, 1994; Sexton & Xia, 2018; Sheldon, 2017). Most of the theory supporting significant oligopsony distortions

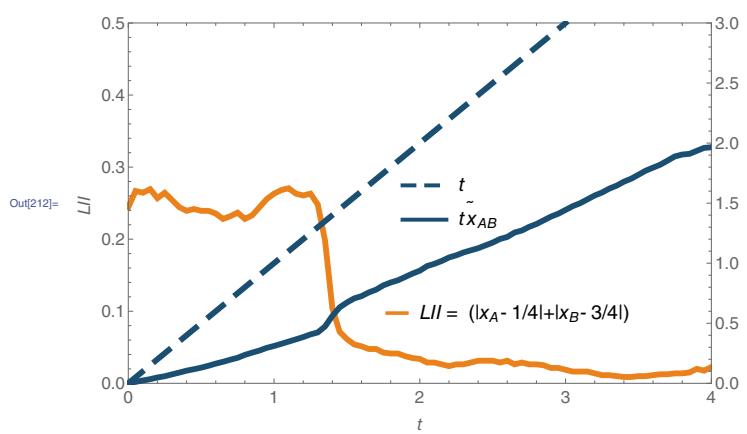

FIGURE 9 Location inefficiency index (LII) and firm differentiation index (DI) as a function of the normalized transport cost t. LII is the sum of differences of each firm's median location for each value of t and its efficient location at the market quartile. DI measures the differentiation between firms in the market. Under maximum differentiation DI $= t$ (dashed line), while DI $= t \cdot \widetilde{x}_{AB}$ (solid line) with endogenous location.

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in these markets is, however, based on models with restrictive assumptions, including locating firms exogenously at the market boundaries, assuming FOB pricing, and specifying inelastic farm supplies.

How are conclusions about market competition and producer welfare impacted by the results found here for firm locations and pricing strategies? A natural basis for comparison is the analytical result of Zhang and Sexton (2001) (ZS) for FOB-pricing firms located at the boundaries of Hotelling's line, given the frequency with which these assumptions are made in the literature (e.g., Fousekis, 2011; Mérel et al., 2009; Mérel & Sexton, 2010; Sesmero et al., 2015). ZS incorporate the unit elastic farm supply function utilized here, which induces more competitive behavior and a higher mill price than under inelastic farm supply (e.g., Mérel et al., 2009).

Location and price policy are both endogenous in our model. To distinguish between competition effects due to firms' choices of location versus choices of price policy, we formulated a simplified version of the simulation model that restricts pricing to FOB but allows endogenous buyer location. Table B.2 in the Appendix S1 provides the median equilibrium values and standard deviations for the FOB mill price $\widetilde{m}$, distance, $\widetilde{x}_{AB}$, separating the two firms, buyer profit $\widetilde{\Pi}$, and producer surplus $\widetilde{\mathrm{PS}}$ for each value of $t \in [0,5]$ in increments of 0.05. Figure 10 depicts the equilibrium FOB price of ZS and $\widetilde{m}$ from the simulation and also the median interfirm distance $\widetilde{x}_{AB}$ from this simulation ($x_{AB} = 1$ by construction in ZS).

The FOB-pricing simulation reveals many similarities to the results from the general model. Interfirm distance is small for low values of t and competition is intense, but firms avoid the worst of it by maintaining some geographic separation and (by assumption) using FOB pricing. As t increases, the FOB prices decline and firms retreat gradually to the market quartiles, reflecting the increasing importance with increasing t of choosing central locations within their respective market areas due to both the cost and supply effects.

We compared the value of PS from ZS's analytical model for each value of t to $\widetilde{\mathrm{PS}}$ from the simulation models by computing the ratio $R_3(t)$:

$$R_3(t) = \frac{\widetilde{\mathrm{PS}}_{\mathrm{Sim}}(t)}{\mathrm{PS}_{\mathrm{ZS}}(t)}, \tag{11}$$

where $\widetilde{\mathrm{PS}}_{\mathrm{Sim}}(t)$, $\mathrm{Sim} = \{\mathrm{PD}, \mathrm{FOB}\}$ is the median value across 5000 simulations for each t for both the general simulation model with price discrimination (PD) and the restricted model with FOB

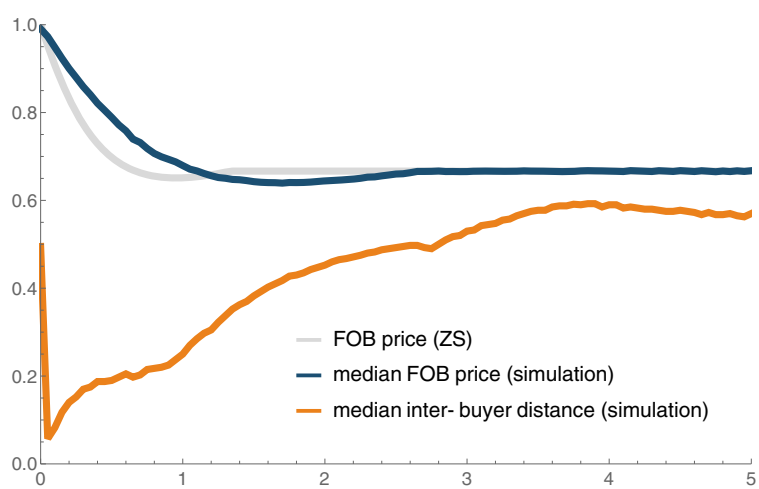

FIGURE 10 The equilibrium FOB price $m(t)$ in the ZS model and median FOB price and interfirm distance in the restricted simulation model. For each value of t the graph depicts ZS's analytical result for FOB price (gray), and median values from the simulation model for FOB price, $\widetilde{m}$ (blue) and inter-buyer distance $\widetilde{x}_{AB}$ (orange).

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pricing. Results are illustrated in Figure 11. Corresponding figures for profit and deadweight loss can be found in the Appendix S1: Section D.

The monopsony FOB price in ZS is $m = 2/3$, and the two buying firms operate as monopsonies for $t \geq 4/3$, that is, each firm's desired market radius is $r = 0.5$, for $t = 4/3$ and $r < 0.5$ for all $t > 4/3$. However, if firms operate at the market quartiles, oligopsony competition prevails until $t = 8/3$, at which point $r = 0.25$. This is the equivalent of the aforementioned "touching equilibrium" when firms are restricted to use FOB pricing. Thus for all values of $t \geq 8/3$, the firms are isolated monopsonies in both models and pay the monopsony price $m = 2/3$, but the model with endogenous location results in product acquisition over twice the market area as in ZS, meaning that $\widetilde{PS}_{\mathrm{FOB}}/\mathrm{PS}_{\mathrm{ZS}} = 2$, that is, endogenous firm location results in twice the value of PS as in ZS for high values of t.

For low values of t, the FOB price in the endogenous-location model is higher than in ZS because the firms locate near to the market center, intensifying price competition relative to the endpoint locations of firms in ZS. PS is solely a function of m as long as the market remains covered under both settings (i.e., for $t \leq 4/3$), so $\widetilde{PS}_{\mathrm{FOB}} > \mathrm{PS}_{\mathrm{ZS}}$. For $4/3 < t < 8/3$ we have monopsony markets in ZS but full market coverage in the simulation model. Thus, $R_3(t)$ is a function of both the difference in market coverage and mill prices between the two models. As Figure 10 illustrates, the ZS monopsony price, $m = 2/3$ is greater than the simulation price over a range of values of t which correspond to the "weak duopsony" case of Mérel et al. (2009), that is, settings in the simulation model where the market is covered but competition is weak. Nonetheless the greater market coverage in the simulation model relative to ZS causes $R_3(t)$ to increase monotonically in t until reaching $R_3(t) = 2.0$ at $t = 8/3$.

$R_3(t) > 1$ for all $t > 0$ for the general model as well. Figure 11 shows that $\widetilde{PS}_{PD}$ is about double the value of $\mathrm{PS}_{\mathrm{ZS}}$ for intermediate values of t. Eventually the ratio converges to $R_3(t) \approx 1.7$ for $t \geq 8/3$. $\widetilde{\mathrm{PS}}_{\mathrm{PD}} > \widetilde{\mathrm{PS}}_{\mathrm{FOB}}$ for low and intermediate values of t. As has been noted, FOB pricing is a way for buying firms to forbear from the most intense price competition because it limits competition to the market boundaries. For low to moderate values of t, total economic surplus in the market is high, and, given the opportunity to do so, profit-seeking firms have unilateral incentive to price discriminate by paying increasing portions of freight costs as a way to expand their market areas (see Figure 3), thereby intensifying competition and creating greater PS than in the FOB case. However,

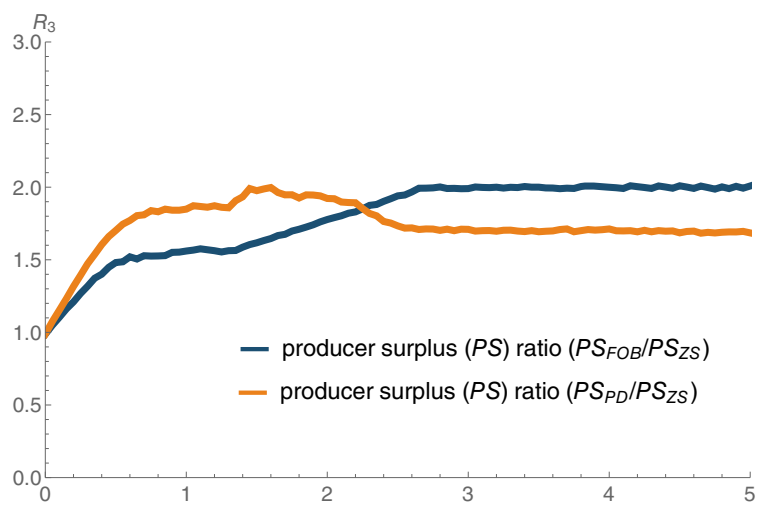

FIGURE 11 Illustration of ratio $R_3(t)$. $R_3(t)$ is the median producer surplus as a function of the normalized transport cost t from the simulations where buyers are free to choose location and (i) any linear price strategy ($\mathrm{PS}_{\mathrm{PD}}$) or (ii) are restricted to use FOB-pricing, $\mathrm{PS}_{\mathrm{FOB}}$ relative to the producer surplus, $\mathrm{PS}_{\mathrm{ZS}}$, from the analytical model of Zhang and Sexton (2001)

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for larger values of t, direct competition is weak and firms converge upon the optimal monopsony price discrimination scheme $(m,\alpha) = (0.5,0.5)$, thereby enabling them to extract greater profit and reduce PS relative to firms restricted to use of FOB pricing.

In sum, our results suggest that farm product procurement markets are considerably more competitive and enable farmers to obtain a greater share of the total market surplus than the conventional theory would lead us to believe. The increase in producer welfare in the simulation results relative to the base analytical model exemplified by ZS is driven by the dual facts that firms do not maximally differentiate, as they do by assumption in ZS, and for considerable ranges of t do not employ symmetric FOB pricing.

A decrease in x_{AB} always intensifies price competition between firms and leads to full market coverage over a considerably larger range of t relative to ZS ($t \leq 4$ in our general model and $t \leq 8/3$ in the model restricted to FOB pricing versus $t \leq 4/3$ in ZS). In addition, firms' tendency to locate near the market quartiles for larger values of t in our model reduces transport costs and, for $\alpha < 1$, causes greater farm supplies, increasing the total surplus in the market relative to buyer location at the endpoints. Flexible pricing strategies that depart from FOB pricing may also intensify competition between buyers and contribute to higher *PS*, as Figure 11 shows for low values of t. However, price discrimination can also enable buyers to extract more of the available market surplus from sellers, as Figure 11 shows for higher values of t when buyers adopt optimal discriminatory pricing and reduce PS relative to the FOB-pricing case.

6 | CONCLUSION

Locations of agricultural processing/packing firms and the pricing strategies they adopt are critical determinants of the efficiency of farm-product assembly and the competitiveness of farm-product procurement markets. Although significant contributions to addressing these issues have been made, studies have encountered severe challenges due to the analytical complexities created by introducing the spatial dimension into models of farm-product procurement. Studies to date have been able to move forward only by imposing strong assumptions on economic models, with corresponding limitations on the generality of results derived from them.

This paper has utilized a computational economics framework with use of genetic algorithms to study processing/packing firms' decisions on location and pricing strategy in a more general setting than predecessor papers. Our results differ considerably from the prior literature regarding these decisions. Specifically, we find that maximum differentiation, that is, location on the endpoints of Hotelling's line, although often assumed as the starting point in models of spatial pricing, is never part of an equilibrium location and pricing strategy. Nor is minimum differentiation (location at the same point) part of equilibrium behavior, although firms locate closest to each other for low values of normalized transport costs, t, when competition is most intense. As transport costs become more important with rising t, firms gravitate to the efficient locations at the market quartiles, that is, in the center of their market areas.

We also find a rich diversity of pricing strategies depending on the importance of the spatial dimension in the market. Many of the pricing strategies involve price discrimination, with absorption of some or all freight charges by the buyer. This diversity of pricing strategies is broadly consistent with what is observed in the real world, where firms have access to readily implementable mechanisms to absorb farm-to-plant shipping costs when it is optimal to do so.

The seemingly paradoxical result that firms locate closest to their rivals for low values of t when competition is most intense is understood in terms of firms' quest to locate accessibly to farm production in these settings when it is most valuable, and their use of pricing strategies to mute the otherwise-intense competition. The factors that motivate firms to locate in the centers of their market areas are less important for low t. Firms avoid the most intense price competition by not locating in direct proximity to each other, that is, minimum differentiation does not emerge in equilibrium,

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and by at least one firm choosing a pricing strategy close to FOB pricing, which limits direct price competition to the market boundaries.

Although maximum differentiation has the desirable property from a buyer's perspective of minimizing price competition with its rival, it is a poor strategy in a generalized market environment where farmers have an elastic response to price and that allows flexible pricing strategies such that buyers can absorb any portion of the costs of transporting product from farm gate to plant gate. It is often optimal for buyers to absorb some portion of transport costs and in that setting to locate at the midpoint of their market areas to minimize those costs—what we termed the cost effect. Similarly, with elastic farm supplies a supply effect creates the same incentive—supplies are maximized when firms locate at the midpoint of their market areas whenever the pricing strategy involves farmers bearing some portion of the transport costs.

Competition issues have been at the forefront of policy discussions regarding food supply chains in both Western and emerging economies in recent years, with serious concerns raised about farmers' position in supply chains amid rising concentration and consolidation of sectors downstream from the farm (AMTF, 2016; Deconinck, 2021; U.S. General Accounting Office, 2009; Nes et al., 2021). Our results are relevant to these discussions in that they suggest that farm product procurement markets are both more competitive and more efficient than has been predicted based on conventional wisdom. As the possible market power exercised by buyers of agricultural products from farmers has risen to primacy among competition issues in agriculture, we hope these results can contribute to ongoing debates regarding optimal competition policies and structure of supply chains.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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