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Feasibility Assessment for a Pecan Shelling Cooperative

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Abstract

Demand for pecans in U.S. is rising, yet small/midsize growers remain price takers. Capturing value requires converting in-shell pecans into value-added shelled products like snack-halves and meal, which demands capital-intensive facilities and compliance systems. We assess whether a producer-owned shelling cooperative can deliver this value. Using a stochastic capital-budgeting model linking prices, kernel yields, and patronage, we estimate cooperative and member Net Present Value (NPV), Internal Rate of Return (IRR), and an end-of-horizon cash-flow solvency check. Baseline results show viability: cooperative NPV is $0.75 million; IRR is 33%; member IRR is 31%. Ending cash-flow is positive in 95% of simulations.

Keywords: cooperative, internal rate of return, Monte Carlo simulation, net present value, pecan, stochastic feasibility

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Introduction

The pecan industry in the United States is experiencing increased demand, due primarily to expanding international markets and recognized health benefits. Domestic consumption remains strong, supported by clinical evidence of cardiometabolic benefits, while export demand continues to drive utilization and prices (McKay et al., 2018; Sidharthan, 2025; USDA-ERS, 2025). In the 2023–2024 marketing year, U.S. shelled-basis pecan exports were estimated to be 61% higher than the previous year (USDA-ERS, 2025). Much of this growth reflects the influence of markets such as China and India (United States Senate, 2025). These trends present substantial opportunities for producers but also underscore the growing need for consistent, high-quality shelled products.

Even with growing domestic and international demand, many small and medium-scale growers remain price takers. They often sell in-shell pecans through accumulators, local brokers, or truckers, losing per-unit value in the process (Texas Pecan Growers Association, 2025). During peak harvest, shellers operate at or near capacity, so delivery slots are scarce. Growers without scheduled intake must either hold inventory or sell quickly into the spot market, which raises costs or forces discounts and leaves them exposed to short-term price drops (Wells, 2024). Although USDA Agricultural Marketing Service (USDA-AMS) reporting on prices, inventories, and trade flows has improved transparency, the advantage still leans toward well-connected buyers and processors, sparking greater interest in producer-owned shelling capacity (Capps Jr, and Williams, 2019).

Modern commercial shelling facilities are capital intensive. They require cracking equipment, possibly an optical sorting to remove shell fragments and defects, a validated sanitation or "kill step" for pathogen control, food-grade space with appropriate environmental controls, and a documented Quality Assurance (QA) system with trained staff (Grocery Manufacturers Association and Peanut and Tree Nut Processors Association, 2016; Peanut and Tree Nut Processors Association, 2022). Under the Food Safety Modernization Act of 2011, shelling plants that are not otherwise exempt must comply with 21 CFR Part 117, which requires current good manufacturing practices, a written hazard analysis plan, preventive controls for sanitation and allergens, and verification and recordkeeping (Electronic Code of Federal Regulations [eCFR], 2025; U.S. Food and Drug Administration, 2025). Pecans are on FDA's "rarely consumed raw" list. That means the Produce Safety Rule in 21 CFR Part 112 does not apply at the farm level (eCFR, 2025). However, facilities that manufacture, process, pack, or hold pecans are still covered by Part 117. Some states also specify sanitizing steps for tree-nut shellers; for example, Oklahoma requires a bactericidal process and recognizes hot-water or hot-air treatments, which can add cost for smaller operators (Bowser, 2017; Oklahoma Administrative Code, 2025). Collectively, these equipment, validation, and documentation requirements raise the bar for individual growers considering a shelling operation and justify the consideration of a shared, cooperative infrastructure.

Given the capital and regulatory requirements for a commercial shelling operation, one question emerges: Can a regionally based pecan shelling cooperative enable local producers to achieve sufficient economies of scale in processing to create a feasible and stable business that can capture

value at the next stage of the value chain? This study addresses that question by conducting a stochastic feasibility assessment of a producer-owned shelling cooperative. The model evaluates whether a cooperative-scale plant could operate effectively, allowing members to retain more value through in-shell deliveries processed into snack-halves, pecan meal, and cracked shells.

The study presents a feasibility analysis that links process yields, operating costs, and financing choices to assess cooperative performance under stochastic member deliveries and market prices. From these simulations we report expected net present value (NPV), internal rate of return (IRR), member-level returns, cumulative cashflow, and the probability that NPV is positive to identify conditions under which a cooperative is financially viable. As with any feasibility analysis, an important step is to identify and understand market opportunities for final products. The financial viability of a value-added processing opportunity is then evaluated under prevailing market conditions.

Our contribution to pecan economics literature is a set of rudimentary but transparent economic findings that producer groups, lenders, and extension professionals can apply across producing regions to guide investment decisions related to the shelling and marketing of pecans. The remainder of the paper describes the cooperative framework, model, and data; presents results with robustness checks; and concludes with managerial and policy implications.

Materials and Method

Cooperative Framework

The study models a producer-owned shelling operation organized as a closed membership cooperative and follows a purchase model. Under a purchase model, the cooperative purchases in-shell pecans at delivery based on the posted grower price and assumes title to the crop at intake, thereby bearing subsequent processing, inventory, and marketing risk. The term "closed membership cooperative" is used in the strict sense that membership shares in the cooperative are limited, and all throughput and patronage arise from member deliveries. Each share of stock has an associated usage right with the total usage rights matching the total processing volume. Under the closed membership structure there is no non-member volume. Members must purchase shares with associated usage rights during the initial equity drive, and after that period a share can only be obtained by purchasing it from an existing member. That structure provides the potential for the shares/usage rights to appreciate in value if individuals want to be able to deliver to the cooperative for the patronage benefits. The closed membership structure also provides a measure of liquidity to the members because they could sell their shares to another qualifying member if they exit pecan production.

Growers become members by purchasing membership common shares, which are nonrevolving, and each share has an associated 1-ton usage (delivery) right. Under the cooperative structure, profits are distributed in proportion to use, so the share does not directly create a return on investment. However, because usage rights are associated with the shares, the member's share of the total patronage will be proportional to their share of the total membership stock investment.

The membership stock also creates a governance right that confers one member, one vote. If a member desired to sell their shares with associated usage rights, the cooperative would not have an active role in that process, but the member purchasing the shares would have to be approved by the board. That approval would generally just require that they are an agricultural producer with the ability to deliver pecans.

The board approves intake and quality rules for member deliveries and annual budgets. The board also adopts a patronage allocation policy that sets the mix of cash and written notices of allocation and a revolvement policy that specifies when patronage equities are redeemed for cash. The baseline allocation of net return is 5% to unallocated reserve (UR), 50% as cash patronage refund (CP), and 45% as nonqualified stock (NQS) patronage refund (see Table 1). Patronage is allocated in proportion to pounds of in-shell pecans delivered by members. This basis is simple to administer and transparent to members. The cooperative is assumed to operate under a 5-year revolvement period, so patronage equities are redeemed on that schedule, subject to cash and loan agreements.

This patronage mix is chosen for tax and cash flow reasons. Both qualified and nonqualified stocks retain cash inside the cooperative, but they differ in tax timing. Qualified stock is deductible to the cooperative and taxable to the member at issuance, which forces members to pay tax without receiving cash and has been unpopular. Since the 2017 tax reform, the corporate rate is often below producers' effective rates once self-employment taxes are included, so it is more efficient to park the tax at the cooperative by issuing nonqualified stock, which is taxed to the member and deductible to the cooperative at redemption. Pairing nonqualified stock with a cash refund provides member liquidity while maintaining tax efficiency and internal capital, so we set qualified stock to zero.

Tax treatment for patronage follows Subchapter T of the U.S. Internal Revenue Code (26 U.S.C. §§ 1381–1388). Cash patronage is deductible to the cooperative and taxable to members in the year declared. Profits retained as unallocated reserves are not designated (allocated) to specific members but are instead collectively owned by the entire membership. Unlike revolving equity, unallocated reserves are never redeemed but instead create a permanent cushion fund. The function of unallocated reserves is to create a category of equity that could be reduced if the cooperative experienced a loss without having to write down the value of the revolving stock or membership stock. Unallocated reserves and nonqualified notices are not deductible at issuance; the cooperative pays income tax on these amounts at the modeled 30% rate. As discussed, members will be taxed on cash patronage when it is issued and the nonqualified stock patronage when it is redeemed. The cooperative will be able to deduct the cash patronage when issued and the nonqualified when it is redeemed, which implies that the cooperative's taxable income in any particular year will include the amount retained as unallocated reserves plus the amount retained as nonqualified revolving stock, less the amount of any previously issued nonqualified equity redeemed. In an actual pecan shelling cooperative, the board of directors would make decisions on the patronage mix each year after considering the cooperative's cash flow situation. They could therefore improve cash flow by reducing the cash patronage percentage or improve member return by issuing a greater proportion of cash. They could also switch from issuing qualified revolving equity patronage to nonqualified or vice versa. For the purposes of our simulation, we maintain

the profit distribution mix at the level logical for the baseline scenario. In doing so, we slightly overstate the probability of negative cash flow in unfavorable conditions because the board could have slightly moderated that condition by decreasing cash patronage. Similarly, we slightly overstate the impact of favorable conditions on member returns because the board could have increased the cash patronage percentage in response to more than adequate cash flow. It would be very difficult to model those flexibilities in profit distribution without complex decision rules. The decision to maintain a constant profit distribution mix across scenarios is therefore defendable.

Shelling Facility and Capacity Assumptions

The cooperative operates one shelling line, a single continuous train of equipment laid out for linear flow from receiving to packaging (see Figure 1). At receiving, each delivery is weighed and assigned a lot identity that links the load to the member, date, and variety class for traceability and settlement. Pre-cleaning removes foreign material, such as sticks and leaves, followed by a validated sanitation step. Drying is used as needed to bring moisture into the target range for clean cracking. Products then pass through cracking, shelling, and separation with aspiration and screens, sizing into halves and pieces on the inspection table and packaging. Kernel pieces are routed to meal grinding and sieving. Shells septum (internal partition) are collected along with shell pieces at the separation stage and prepared for bulk sale, primarily for mulch. The overall facility layout and process flow from receiving to packaging are illustrated in Figure 1.

Facility capacity is stated on an in-shell basis in pounds (lbs). The line uses two Savage Equipment pecan crackers, "238C cracker," rated at 750 lbs per hour each, giving a nameplate throughput of 1,500 lbs per hour. Planned operation is 12 hours per day over a 75-day season. Allowing 10% of available time for sanitation, changeovers, and minor stops yields 810 operating hours and an effective seasonal capacity of 1,215,000 lbs. This effective capacity represents the maximum in-shell intake the plant can process in a season. The 75-day operating assumption is based on the seasonal nature of pecan harvests, which occur primarily from October to December. During this period, member deliveries peak, and shelling facilities typically run at high utilization. Limiting the modeled season to 75 days captures this concentrated activity.

A baseline requirement of 1 horsepower (HP) per pound per hour of throughput is assumed as a simplifying engineering approximation to represent aggregate power demand across the shelling line. At the design scale of 1,500 lbs per hour, the line requires 1,500 HP, equivalent to approximately 1,120 kW using a conversion of 0.746 kW/HP. With 810 hours of operation annually, this calculation results in an estimated total energy demand of 972,000 kWh. Because actual equipment-level power requirements vary across processing components and operating conditions, this assumption serves as a planning approximation and may over- or under-estimate realized operating energy costs. To evaluate the robustness of this assumption, a sensitivity analysis was conducted by varying energy requirements from 50% below to 25% above the baseline level to assess the effect on feasibility results (see Results and Discussion section).

Finished goods, specifically snack-halves, pecan meal, and cracked shells, are derived from this intake using percentage coefficients specified in the next section. These coefficients define kernel yield by variety class and the share of kernels routed to snack-halves versus meal. Shell output equals the complement of kernel yield and is modeled as a by-product.

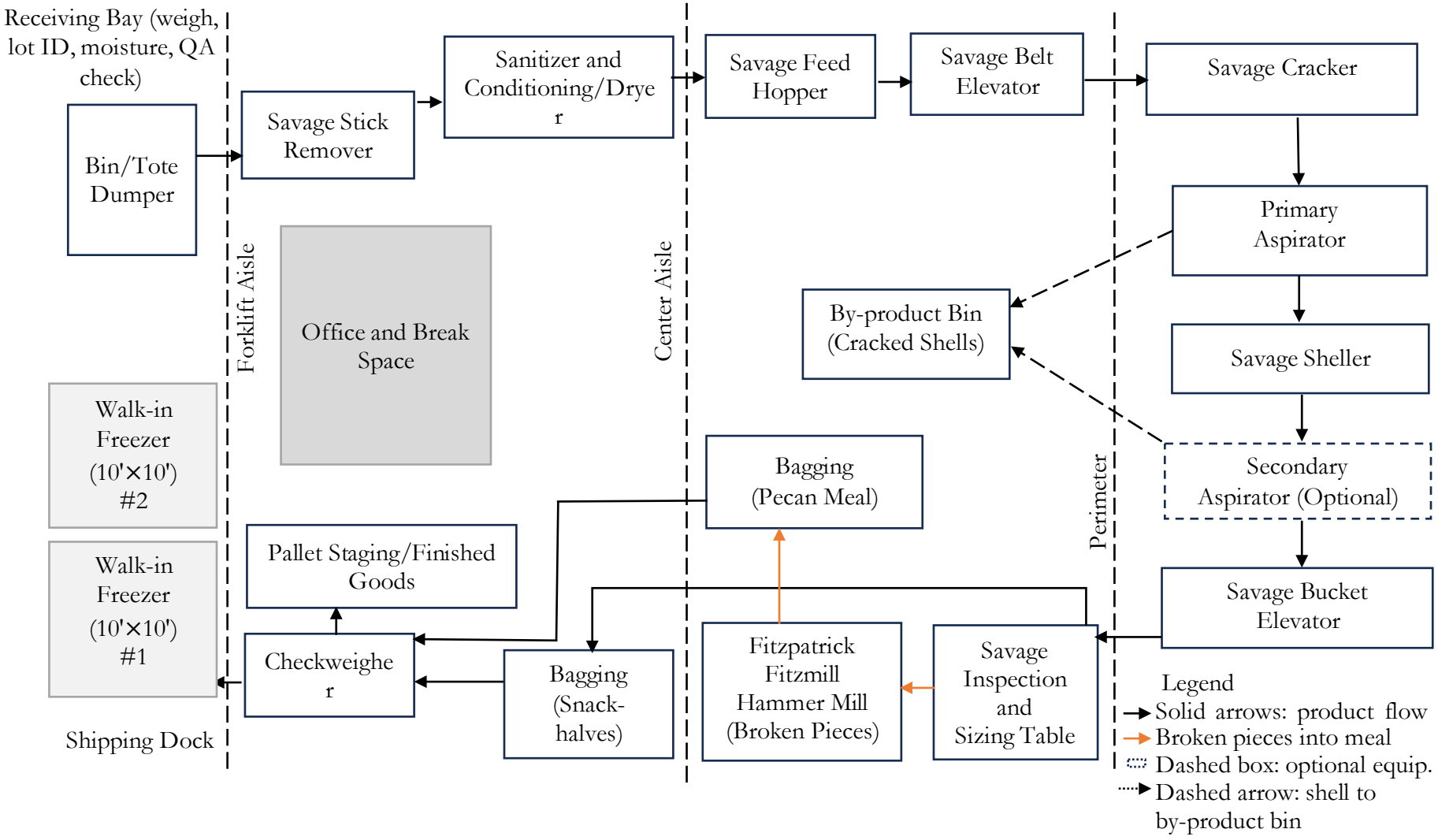


Figure 1. Process Schematic of the Cooperative Pecan Shelling Line

Note: At the inspection and sizing table, 15% of kernels are assumed to be broken pieces and routed to the hammer mill for processing into pecan meal. The remaining 85% are collected as snack-halves. Cracked shells are routed to the by-product bin.

Kernel Yields and Outputs

This section states the baseline assumptions that convert in-shell deliveries into kernels and shells and that allocate kernels between snack-halves and meal. The goal is to mirror common commercial practices while keeping the model transparent. The cooperative facility assumes a baseline mix of 90% improved varieties and 10% native varieties. This assumption imitates prevailing commercial patterns in which improved cultivars dominate planted acreage and marketed volume because they offer larger nut size, more uniform quality, and better crack out (USDA-NASS, 2024). Sensitivity analysis varies the mix to test how results change when native shares are higher (see the Sensitivity Analysis section).

Kernel yield generally varies by cultivar, orchard conditions, moisture, and maturity, and may fluctuate annually. For modeling clarity, the baseline assumes an average kernel yield of 56% for improved varieties and 42% for native pecans, with these figures subject to sensitivity analysis in subsequent sections. These assumptions align with lower yield ranges reported for native pecans and with higher kernel percentages typical of improved cultivars in industry and extension literature (Stein, Nesbitt, and Kamas, 2015; Caroll and Smith, 2017).

Within edible kernels, 85% are assumed to be recovered as snack-halves and 15% as meal from broken pieces. This allocation captures the facility's objective to maximize whole pecan halves, while acknowledging that a proportion of broken pieces is unavoidable and contributes to secondary product streams. The assumption is further supported by the high efficiency of modern Savage shellers, which are engineered to minimize breakage and recoverable halves (Savage Equipment, 2019). In practice, not all snack-halves would be sold directly to consumers. To reflect prevailing marketing channels, the model apportions edible snack-halves among wholesale and retail outlets, with 60% assumed to be sold at wholesale prices and the remaining 40% marketed at retail prices. This adjustment recognizes both bulk transactions typical of sheller operations and the cooperative's retail objectives.

Table 1. Baseline Financing and Working-Capital Inputs

Parameter	Value with Description
Debt load	50% of land, plant property and equipment ($461,496)
Loan term (LT) and rate	10-year loan at 7.50% fixed (amortizing)
Annual debt service	$67,233 (constant payment)
Year-1 interest (LT)	$34,612
Year-1 principal (LT)	$32,621: year-1 ending balance $428,875
Working capital	10% of annual sales, with 6% short-term interest rate
Aggregate member common stock	$461,496 (governance stock; see cooperative framework)
Property tax	0.50% of land, plant property and equipment
Insurance	2.00% of plant property and equipment
Routine maintenance	3.00% of plant property and equipment
Expense inflation rate (annual)	1.00%
Co-operative's income tax rate	30.00%
Unallocated reserve (UR)	5.00%

Table 1 (cont.)

Cash Patronage (CP)	**50%**
Nonqualified stock patronage (NQS)	45%
Revolving period	5 years
Discount rate	10%

Capital Investment and Depreciation

The cooperative must undertake a set of fixed investments to establish a commercial-scale shelling line and meet food-processing standards. This section specifies assets, states the basis used to value them, and documents the depreciation rules used in the financial model. The cooperative assumes a 2-acre (87,120 ft^2) land space to accommodate truck access, stormwater or septic, fire lanes, employee parking, and allows future expansion to a second line without major site rework.

Land is parameterized at $175,000 for the 2 acres (see Table 2). The basis for this value is industrial-zoned listings compiled on "LandSearch," a website that aggregates current asking prices from multiple U.S. brokers. A modelled 6,000ft^2 pre-engineered metal building (PEMB) with concrete slab is used and valued at $204,960, inclusive of interior retrofitting costs (BuildingsGuide, 2025). The office space takes about 1,600ft^2 of the PEMB. Table 2 shows the breakdown for the PEMB cost. This space comfortably fits one shelling line, a modest office core, quality assurance rooms, and pallet staging, which preserves forklift aisles and egress (see Figure 1). A $25,000 salvage value is assigned to the PEMB to capture recoverable steel and reusable components. The PEMB has an annual building depreciation of $4,614, and it's computed on a 39-year straight-line schedule for nonresidential real property.

The study accounted for two indoor walk-in freezers (10′ × 10′ × 8′) at an installed cost of $36,167 each based on published unit pricing and installation service add-on (Katom, 2025). Each unit is treated as a special purpose building and depreciated on a straight-line basis over 10 years. The combined annual depreciation expense is $7,233 for both units.

Table 2. Capital Outlays by Asset

Description	**Value ($)**	**Salvage ($)**	**Depreciation per Year ($)**
Buildings			
Steel building kit (6,000 ft^2)	96,960	15,000	
Concrete slab (6,000 ft^2)	54,000	2,000	
Retrofitting of interior (6,000 ft^2)	54,000	8,000	
Total cost of buildings	204,960	25,000	4,614 (39 years straight line)
Special purpose buildings (SPB)			
Walk-in freezer (10′ × 10′ × 8′ :2 units)	72,334	-	7,233 (10 years straight line)
Light trucks and vehicles (LTV)			
Semi-truck	100,000	-	
Forklifts	25,000	-	

Table 2 (cont.)

Description	Value ($)	Salvage ($)	Depreciation per Year ($)
Total cost of LTV	125,000	-	25,000 (5 years MACRS with half-year convention)
Equipment and heavy rolling stock (EHRS)			
Savage 3918 feed hopper	7,135	-	
Savage 1312 - 12' belt elevator	4,238	-	
Savage 238C cracker (2 units)	48,670	-	
Savage 704S bucket elevator (4 units)	24,540	-	
ME & E aspirator/cyclone head blower	18,556	-	
Savage 410S sheller (2)	39,670	-	
Savage 520S inspection table	16,835	-	
ME & E chlorine bath sanitizer	87,994	-	
ME & E batch meat dryer	58,560	-	
Used Fitzpatrick Fitzmill hammer mill, Model M5A	19,500	-	
Miscellaneous	20,000	-	
Total cost of EHRS	345,698	-	49,400 year 1 (7 years MACRS with half-year convention)
Land	175,000	-	-
Total cost of land, plant property, and equipment	922,992		

The shelling line is composed of a feeder and conveyor, a validated kill-step batch dryer, a cracker, an aspirator for shell removal, bucket elevators and screens, a sheller, an inspection and sizing table, packaging equipment, and a Fitzpatrick M5A hammer mill for producing pecan meal from broken pieces. These core shelling lines total $345,698, based on supplier quotations from Savage Equipment and modern electronics and equipment (ME & E). The Fitzpatrick M5A for processing broken pieces into pecan meal is not sourced from Savage. It is sourced from a used-equipment dealer, with specifications cross-checked against the manufacturer's brochure. The study obtained a quote of $19,500 for the hammer mill (Federal Equipment, 2025). A budget of $125,000 is allotted for one semi-tractor plus one forklift, consistent with national listing ranges (Forklift Trader, 2025; Truck Paper, 2025).

Depreciation follows the Internal Revenue Service Modified Accelerated Cost Recovery System (MACRS) (Internal Revenue Service, 2024). The shelling train and heavy rolling stock are treated as 7-year property under the half-year convention, yielding $49,400 in first-year depreciation. The semi-tractor and forklift are 5-year property (half-year convention), yielding $25,000 in first-year depreciation.

Financing, Working Capital and Profit Distribution

The basic financing assumption for the model is a loan for 50% of the total cost of land, plant, property, and equipment. This cost is financed with an amortizing term loan acquired at an interest rate of 7.5% for a term of 10 years. The 10-year period is also considered as the project timeframe. Working capital was estimated at 10% of annual sales with a short-term interest rate of 6% (Kenkel et al., 2008). Equity complements debt through $461,496 in membership common stock. This investment would imply a per share investment of $760, with each share of stock providing the usage right to deliver 1 ton of in-shell pecans. Patronage allocations follow the baseline policy described previously with 5% to unallocated reserve, 50% as cash patronage, and 45% nonqualified stock patronage. Table 1 presents a summary of this section.

Economic Model

Determining whether the cooperative shelling facility is financially viable and worth member investment requires an appropriate economic and financial metric. This study adopts the Expected Net Present Value (ENPV) as the primary measure of feasibility, because it evaluates whether projected returns are sufficient to offset costs and risks. The Net Present Value (NPV) is a standard capital budgeting technique used to discount simulated cash inflows to their present value (Zapata, Ribera, and Palma, 2017; Cowley, Brorsen, and Hamilton, 2019; Adom, Bir, and Lambert, 2023; Coleman et al., 2024). It accounts for both the time value of money and the magnitude of cash flows over the project's lifespan. In addition to NPV, the internal rate of return (IRR) is reported as a complementary measure, defined as the discount rate that sets the net present value of projected cash flows equal to zero. In this study, an IRR greater than or equal to the assumed discount rate is interpreted as indicating financial viability. To incorporate risk and variability, the model was implemented stochastically using Excel @Risk software, which generates probability distributions of results through Monte Carlo simulation (Lumivero, 2022). The estimated ENPV is calculated as:

$$E(NPV_s) = \sum_{t=1}^{T} \frac{E(R_{ts})}{(1+r)^t} \Bigg| s, \tag{1}$$

where $E(R_{ts})$ is the expected annual net return in year t under scenario s, and r is the discount rate (10%). The 10% discount rate is consistent with values commonly used in agricultural feasibility analyses and reflects a risk-adjusted cost of capital for cooperative investment decisions (Adom, Bir, and Lambert, 2023; Coleman et al., 2024). The scenarios (s) in this study vary according to alternative patronage allocation policies and kernel yield assumptions for improved and native varieties, which are further detailed in the sensitivity analysis. The expected annual net return $E(R_{ts})$ was estimated as:

$$E(R_{ts}) = E(Revenue_t) - E(Cost_t) | s, \tag{2}$$

where $E(R_{ts})$ is the Revenue$_t$ in year t under scenario s, less the corresponding cost incurred in that year. The expected annual revenue under scenario s is expressed as a function of snack-halves, cracked shells, pecan meal, and their respective retail prices:

$$E(Revenue_t) = \sum_{i=1}^{2}(W_{it} * PW_{it}) + \sum_{i=1}^{2}(V_{it} * PV_{it}) + C_t * PC_t + M_t * PM_t \Big| s, \quad (3)$$

where $i = 1$ denotes improved varieties and $i = 2$ denotes native varieties. PW_{it} and PV_{it} are the respective wholesale and retail price of snack-halves for variety i in year t. W_{it} and V_{it} are the quantity of 1-pound snack-halve bags of variety i sold at the wholesale and retail level in year t. The variables C_t and M_t are the quantities of cracked shells and pecan meal sold in year t, with retail prices PC_t and PM_t, respectively. Unlike snack-halves, which are priced separately for improved and native varieties, cracked shells and pecan meal from both varieties are pooled and sold at a uniform retail price. During the shelling process, we collect all snack-halves as H_{it}, which is the summation of wholesale quantities (W_{it}) and retail quantities (V_{it}). As illustrated in Figure 1, these quantities correspond to the snack-halves bagging stage. The total quantities of snack-halves (H_{it}) from the shelling line is determined as:

$$H_{it} = Q_t * (S_{it} * Y_{it} * F_{it}), \quad (4)$$

where Q_t is the total in-shell pecan volume in pounds that is fed into the cracking machine in year t. S_{it} is the proportion of in-shell volume for variety i in year t. In the baseline 90% of in-shell volume is assumed to be improved varieties and 10% native. The parameter Y_{it} denotes the kernel yield for variety i in year t. As mentioned in the kernel yields and outputs section, the baseline assumes Y_{it} of 56% for improved varieties and 42% for native pecans. F_{it} represents the proportion of kernels that remain as snack-halves for variety i in year t and has a baseline value of 85%. The determination of pecan meal quantities (M_t) is specified as:

$$M_t = \sum_{i=1}^{2}(S_{it} * Y_{it} * (1 - F_{it}) * Q_t), \quad (5)$$

In Figure 1, this quantity corresponds to the pecan meal bagging stage. Similarly, we specify the determination of cracked shell (C_t) quantities based on delivered in-shell volume and kernel yield assumptions as:

$$C_t = \sum_{i=1}^{2}(S_{it} * (1 - Y_{it}) * Q_t), \quad (6)$$

In Figure 1, this quantity corresponds to the by-product bin (cracked shells). The annual cost under scenario s is:

$$E(Cost_t) = VOC_t + FOC_t + IT_t + CE_t|s, \quad (7)$$

where VOC_t is the variable operating cost in year t, including the raw in-shell pecan purchases, marketing and packaging materials cost, variable labor costs, utilities, and interest on working capital. Typically, the marketing and packaging materials cost for snack-halves and meal were modeled as the unit packaging cost plus 5% of the product's selling price to capture advertising, promotion, and any other retail expenses. Snack-halves considered for wholesale sales and cracked shells incur packaging costs only. The cost from the raw in-shell pecan purchases is the grower price paid to members in year t multiplied by Q_t. The variable FOC_t, denotes fixed operating costs, which capture salaried staff, insurance, property tax, routine maintenance, supplies, and miscellaneous. IT_t is the income tax in year t, computed from taxable income. CE_t is the capital expenditure for land, plant property, and equipment, which are incurred only at the initial investment period ($t = 0$), accordingly, $CE_t = 0$ for all $t > 0$. Under the cooperative business model, the majority of the income tax obligation is passed through to the member, either immediately, as is the case with cash or qualified stock patronage, or with a delay, as is the case with nonqualified stock patronage. For that reason, the income tax payments reflected in the cooperative's NPV and IRR calculations were minimal.

In addition to the NPV and IRR analysis performed at the cooperative level, a similar analysis was performed at the member level, reflecting the members' investment and cash receipts of cash patronage and stock revolvement payments. In a cooperative, the member IRR can be above or below that of the cooperative IRR. The fact that the member is receiving the income tax obligation and the need for the cooperative to retain some profits by issuing revolving stock patronage reduces the member IRR relative to the cooperative IRR. The leverage effect of debt financing can make the member IRR higher than the cooperative IRR since the members' collective initial investment was less than the total (long-term debt and equity) initial investment in the firm. In this model, member IRR and NPV was lower than the measures at the cooperative level.

Data

The data used to parameterize the model were primarily sourced from the U.S. Department of Agriculture's Economic Research Service (USDA-ERS), the U.S. Energy Information Administration (EIA), the U.S. Bureau of Labor Statistics (BLS, 2025), retail shops, and the U.S. Environmental Protection Agency (EPA).

Member Deliveries, Grower and Product Prices

Annual member deliveries are modeled as a uniform draw between 75% and 100% of plant capacity. This amount reflects the operating reality of a closed, member-only cooperative. Pooling across growers, coordinated harvest and intake scheduling, and physical capacity limits reduce extreme year-to-year swings while preserving meaningful variation. A new draw is taken for each year of the planning horizon, treating production as stochastic to emulate real-world variability. Table 3 reports summary statistics for in-shell production volumes and the other variables used in the stochastic analysis.

The USDA-ERS reports 45 years of data (1980–2023) on grower prices for in-shell pecans, measured in dollars per pound ($/lb) and disaggregated by improved and native varieties (USDA-ERS, 2025). These prices were adjusted for inflation to 2023 dollars and modeled stochastically (see Table 3). Because USDA-ERS does not provide data on shelled pecan prices, the study derived shelled-equivalent prices separately for improved and native pecans by dividing in-shell grower prices by the baseline kernel yield values assumed earlier. Following the approach used in a study by Blayney and Gutierrez (2017), these shelled equivalents were used as proxies for wholesale snack-halve prices.

Table 3: Summary Statistics for Data Variables Used in Stochastic Analysis

Variable	Minimum	Mean	Maximum
Improved variety grower in-shell price ($/lb)	1.14	2.29	3.51
Native variety grower in-shell price ($/lb)	0.71	1.45	2.43
Wholesale price for snack-halves (improved)	2.4	4.09	6.27
Wholesale price for snack-halves (native)	1.70	3.45	5.79
Pecan meal price ($/lb)	5.95	13.51	18.95
Cracked shell price ($/50lb)	1.85	3.21	6.40
In-shell production volume (lb)	911,250	-	1,215,000
Packaging costs (50-lb woven polypropylene bags)	0.42	0.71	1.35
Packaging costs (1-lb stand-up pouches)	0.28	0.35	0.47
Retail markup/factor			
Improved variety	4.14		
Native variety	5.47		

Note: All data variables used in stochastic analysis were subject to triangular distribution except for in-shell production volume.

Retail prices for snack-halves were then determined through a markup procedure applied separately to improved and native varieties. Current retail quotes for each variety were collected from pecan shops in 2025, averaged, and adjusted to 2023 dollars (see Table 4). For each variety, a retail markup factor was calculated as the ratio of the adjusted average retail price to the 2023 wholesale proxy price. The markup factor was approximately 4.14 for improved pecans and 5.47 for native pecans. For each project year, retail snack-halve prices were estimated by multiplying the variety-specific markup factor by the simulated, inflation-adjusted in-shell grower price. This approach models retail prices as stochastic while preserving consistency with observed retail margins across varieties.

Historical price data for cracked shells and pecan meal are not available from the USDA. To address this gap, retail price data were gathered through an online search (see Table 5), consistent with approaches used by Adom, Bir, and Lambert (2023) to model quail prices. Summary statistics for cracked shells and pecan meal retail prices used for our stochastic analysis are reported in Table 3. Packaging costs were also modeled stochastically based on online data. The study considered two primary inputs, 50-lb woven polypropylene bags for cracked shells and 1-lb stand-up pouches for snack-halves and pecan meal. The summary statistics used for packaging costs are reported in Table 3.

Table 4: Retail Collected Prices for Snack-Halves

	Retail Price	
Source	**Native Variety ($/lb)**	**Improved Variety ($/lb)**
Houston Pecan Company (2025)	11.00	12.75
York Pecan Company (2025)	13.25	14.00
Miller Pecan Company (2025)	8.59	11.99
Rattlesnake Ranch Pecans Company (2025)	14.99	14.99
Gilbert Pecan Company (2025)	12.00	12.00
The Nut House (2025)	14.99	15.99
Valley View Company (2025)	9.00	10.00
Pecan Producers International (2025)	12.95	13.95
Byrd's Pecans (2025)	14.00	13.00
Hammons Pantry (2025)	17.98	-
Kentucky Nut Corporation (2025)	17.35	-
Azure (2025)	12.96	-
Pecan Shop (2025)	17.05	-
Mean 2025 price	13.29	13.47
Adjusted mean price to 2023	12.63	12.80

Table 5: Retail Collected Prices for Cracked Shells and Pecan Meal

Cracked Shells		**Pecan Meal**	
Source	**Retail Price ($/50lb)**	**Source**	**Retail Price ($/lb)**
Solutions (2025)	6.40	Sunnyland Farms (2025)	15.75
Texas Native (2025)	2.15	Pearson Farm (2025)	12.50
Minick Materials (2025)	4.68	Nuts.com (2025)	17.49
Pete's Landscaping and Materials (2025)	2.45	Young's Premium Foods (2025)	10.95
Clear Fork Materials (2025)	1.85	Shute Pecan Company (2025)	5.95
Strata Landscape Materials (2025)	2.43	The Pecan Pantry (2025)	18.95
Barela Landscaping Materials (2025)	3.00	Millican Pecan (2025)	12.99
Trees That Please (2025)	2.75	-	-

Note: Cracked shell prices are originally provided in dollars per cubic yard. Using a conversion provided by Mexal et al. (2003), we convert $/cubic yard to $/50 lbs (1,000 lbs/cubic yard).

Labor Costs

The Bureau of Labor Statistics reports annual mean wages for general managers, sales managers, and secretaries (BLS, 2025, Table 6). To project labor costs forward, this study applies a 1% annual wage escalation rate over the 10-year horizon as a conservative planning assumption consistent with prior cooperative feasibility analyses (Kenkel, Holcomb, and Hill, 2008). In addition, BLS reports average hourly labor costs for food processing workers and packaging and filling machine operators, serving as proxies for unloading, cracking, shelling, packaging, and shipping. These values were converted to dollars-per-pound basis and multiplied by the facility's stochastic annual in-shell pecan throughput to estimate the stochastic total labor costs over the project period.

Table 6. Labor Cost and Annual Salaries for Full-Time Employees

Category	Estimated Annual Salary ($)
General manager	$146,510
Assistant manager	$137,740
Secretary	$126,390
Sales manager/agent	$157,380
Unloading ($/lb)	$0.012 per pound ($18.12 per hour)
Cracking and shelling ($/lb)	$0.013 per pound ($19.67 per hour)
Packaging and shipping ($/lb)	$0.014 per pound ($21.04 per hour)

Notes: Annual salary estimates are based on Bureau of Labor Statistics Occupational Employment and Wage Statistics (OEWS), food manufacturing industry, and national mean wages. Occupation codes used: Top Executives (SOC 11-1000) for General Manager; Operations Managers (SOC 11-1021) for Assistant Manager; Administrative Services Managers (SOC 11-3010) as a proxy for administrative support staff; and Sales Managers (SOC 11-2022) for Sales Manager/Agent. Reported wages reflect base earnings and exclude fringe benefits, such as insurance and retirement contributions. The facility operates at 1,500 lbs/hr, so the average hourly wages can be converted to $/lb.

Utility Costs

Electricity rates were obtained from the U.S. Energy Information Administration (EIA), with the national average industrial retail price reported at $0.0832 per kWh (EIA, 2023). At this rate, the estimated cost of operating the shelling line in year 1 is approximately $80,870. In addition, the facility incurs year-round electricity expenses for office lighting and support systems. With an office space of 1,600 ft², and using the median consumption of 8.7 kWh per square foot per year for commercial buildings (EIA, 2016), annual office electricity use is estimated at 13,920 kWh, equivalent to about $1,160 per year.

Water usage data were obtained from the U.S. Environmental Protection Agency's Water Sense program, which reports an average combined water and wastewater cost of $12.42 per 1,000 gallons for U.S. commercial users (EPA, 2025). Assuming a baseline consumption of 50,000 gallons annually for cleaning, lavatories, sinks, and drinking, the annual water cost is estimated at $621.

The U.S. Energy Information Administration also reports a national average price of $2.52 per gallon for liquefied petroleum (LP) gas (EIA, 2025). The facility's semi-tractor and forklift are

assumed to consume a combined 800 gallons per year, resulting in an annual fuel cost of approximately $2,016.

Telephone and internet costs include voiceover internet protocol (VOIP) phone service and high-speed internet access. VOIP service averages $25 per user per month (RingCentral, 2025), giving a total monthly cost of $100 for four staff members. To ensure reliable communication and data transfer, a high-speed business internet plan is assumed at $200 per month (Brooks, 2026).

Sensitivity Analysis

The robustness of results was assessed by including a set of sensitivity analyses on key assumptions. First, kernel yields were varied around the baseline of 56% for improved varieties and 42% for native varieties to show annual and orchard-level fluctuations. Second, the allocation of edible kernels between snack-halves and meal (85%:15%) was tested to examine the effect of higher breakage rates on cooperative returns. Third, the percentage share of native and improved varieties in member deliveries was adjusted away from the 10%:90% baseline to evaluate how cultivar mix influences throughput and product values. Because the baseline scenario for snack-halves sales was wholesale-heavy (60%:40%), we tested different scenarios, such as retail-heavy and balanced sales, to verify its robustness. Finally, financial assumptions regarding patronage allocation were varied from the baseline policy of 5% unallocated reserve, 50% cash patronage, and 45% nonqualified stock patronage.

Results and Discussion

The results are summarized in Table 7, Figure 2, and Table 8. For each scenario, the cooperative and member outcomes were evaluated in terms of NPV and IRR. Taken together, the simulation generated 12 distinct mean NPV and mean IRR outcomes that provide a basis for assessing alternative strategies and risk exposure. We also track the cooperative's year-10 cumulative cash balance as a terminal solvency check, reporting its mean and the probability it is positive.

Under the baseline scenario (see Table 7), the cooperative's NPV ranged from -$2,148,865 to $3,596,233, with a mean of $754,064 over the 10-year planning horizon. These values represent the discounted returns from shelling operations after accounting for the time value of money. The cooperative achieved a positive NPV in 83.8% of simulations, indicating that in five out of six runs the discounted revenue stream exceeds the discounted costs. The mean cooperative IRR was 33.36%, with approximately 87% probability of meeting or exceeding the assumed discount rate of 10%. This finding implies that, even under baseline assumptions, the cooperative investment is financially viable and offers a rate of return substantially above typical borrowing costs. The end-of-horizon liquidity is generally maintained, as year-10 cumulative cash averages $113,009 and is positive in 95% of runs.

For individual members, the baseline scenario also yielded favorable outcomes. The mean member NPV was $779,487, with outcomes ranging from -$534,741 to $2,428,924. The mean IRR of 30.79% shows strong profitability potential, and the probability of members achieving an IRR of

at least 10% was nearly 100%. These results indicate that, although the cooperative bears substantial fixed-cost risk, members capture relatively greater benefits once the facility operates at scale. In practical terms, this means that the baseline cooperative structure transfers much of the investment risk to the collective entity, while individual members are positioned to realize high and relatively stable returns.

Overall, the baseline results suggest that the cooperative is financially feasible, though not without risk. The probability of negative cooperative NPV highlights the exposure to downside scenarios, particularly under conditions of low capacity and weaker market prices for snack-halves and pecan meals. However, the relatively high member-level returns indicate that, under the baseline assumptions, the cooperative delivers on its central objective of improving member welfare while pooling investment risk across participants. Subsequent sensitivity analysis identifies the conditions under which cooperative-level viability may be threatened, and to highlight strategies that preserve both organizational sustainability and member profitability.

When the share of native pecans was increased to 30% (with 70% improved), both cooperative and member outcomes weakened compared to the baseline (see Table 7). The mean cooperative NPV dropped to $325,414, and the probability of a positive NPV fell to 68.70%. Members experienced similar effects, with mean NPV reduced to $456,596 and IRR falling to 23.26%. The weaker performance depicts the lower kernel recovery and quality premiums typically associated with native pecans, which limit the value of shelled output even when procurement costs are lower. By contrast, shifting entirely to improved pecans enhanced returns, producing the highest mean cooperative NPV of $966,611 and the strongest member mean IRR of 34.45%. A balanced mix yielded the least favorable results (see Table 7). These patterns reinforce that cooperative profitability is highly sensitive to variety composition. Among the three variety mixes, the all-improved option also delivers the strongest liquidity. Year-10 cumulative cash averages $211,005 and is positive in 67% of runs, indicating a positive ending cash balance in most cases. These results suggest that, for a value-added pecan cooperative, prioritizing improved varieties enhances both profitability and solvency relative to mixes with higher native shares.

Under low kernel yields of 38% native and 52% improved (see Table 7), performance collapses relative to the baseline. The cooperative's mean NPV falls to -$853,454 with only a 14.40% probability of a positive outcome, and member results show a similar decline. Because cash flows are largely negative in this case, IRR values are omitted as they become undefined or unstable. Conversely, when improved-variety yields rise to 60%, the cooperative's mean NPV increases to approximately $2.3 million with a 99.8% probability of being positive. Member outcomes follow the same pattern, with mean NPV reaching $1.9 million. These results demonstrate that kernel recovery is the key driver of financial performance in a pecan shelling facility. Higher kernel yields translate into substantially stronger outcomes, whereas lower yields expose both the cooperative and its members to significant financial risk. These results further indicate that kernel recovery rates near the baseline assumptions define the approximate break-even region for cooperative feasibility, as small reductions below these levels result in negative mean NPV outcomes.

Table 7. Net Present Value and Internal Rate of Return for Baseline Scenario and Sensitivity Analysis on Variety Mix and Kernel Yield

Scenarios		Co-operative			Member	
		Cum. Cashflow (CCF) (Year 10)	NPV	IRR (%)	NPV	IRR (%)
Baseline scenario	Minimum	-$2,327,468	-$2,148,865	-40.55%	-$534,741	-24.8%
	Mean	$113,009	$754,064	33.36%	$779,487	30.79%
	Maximum	$1,769,174	$3,596,233	125.41%	$2,428,924	73.37%
	Prob. of positive CCF/NPV/IRR ≥10%	95.00%	83.80%	86.90%	98.10%	98.30%
Variety mix						
Higher native variety share (30% native; 70% improved)	Minimum	-$2,668,406	-$2,217,246	-68.01%	-$700,484	-34.24%
	Mean	-$132,653	$325,414	22.99%	$456,596	23.26%
	Maximum	$1,315,645	$2,949,517	106.00%	$1,884,269	60.87%
	Prob. of positive CCF/NPV/IRR ≥10%	43.00%	68.70%	75.00%	92.00%	93.00%
All improved variety (0% native; 100% improved)	Minimum	-$2,327,523	-$2,098,931	-32.91%	-$455,462	-12.32%
	Mean	$211,005	$966,611	38.34%	$948,156	34.45%
	Maximum	1,714,839	$4,040,585	150.37%	$2,722,803	77.58%
	Prob. of positive CCF/NPV/IRR ≥10%	67.00%	87.20%	89.70%	99.00%	99.20%
Balanced (50% native; 50% improved)	Minimum	-$2,874,303	-$2,115,935	-64.52%	-$753,903	-37.09%
	Mean	-$458,272	-$108,885	12.66%	$155,648	15.37%
	Maximum	$1,051,275	$1,974,270	82.84%	$1,619,014	47.38%
	Prob. of positive CCF/NPVIRR ≥10%	19.90%	43.10%	54.40%	70.80%%	74.90%
Kernel yield						
Low yield for both varieties (38% native; 52% improved)	Minimum	-$5,039,764	-$4,022,374	-	-$1,260,334	-
	Mean	-$1,544,756	-$853,454	-	-$175,379	-
	Maximum	$1,193,867	$2,153,076	-	$1,213,284	-
	Prob. of positive CCF/NPV/IRR ≥10%	2%	14.40%	-	32.40%	-
High improved variety yield (42% native; 60% improved)	Minimum	-$713,286	-$837,738	2.13%	$371,623	21.80%
	Mean	$1,085,557	$2,266,291	63.04%	$1,860,802	51.24%
	Maximum	$2,201,810	$4,970,005	173.91%	$4,104,839	108.26%
	Prob. of positive CCF/NPV/IRR ≥10%	99.60%	99.80%	99.90%	100.00%	100.00%

Note: Each scenario isolates the effect of a single variable by holding all other parameters constant at their baseline values. IRR values are omitted in the low kernel yield scenario because nonconventional cash flow patterns made the IRR undefined or unstable.

Figure 2, subplots a and b, show how kernel breakage influences cooperative and member outcomes relative to the baseline. When breakage rises to 20% and more kernels are processed into meal, both cooperative and member distributions shift to the right, with higher mean NPVs and IRRs. This outcome suggests that, despite the additional pecan meal processing cost, meal may provide a reliable outlet that stabilizes returns when priced close to snack-halves (see Tables 4 and 5). It also raises an important managerial question: If meal markets remain strong, should cooperatives consider allocating more product to meal even when kernels are unbroken? A practical implication is that cooperatives could pursue contracts or partnerships with ingredient buyers to ensure consistent meal demand, thereby reducing reliance on premium snack-halve markets alone. At the other extreme, Figure 2c and 2d show that when breakage falls to 7%, distributions compress around zero or become negative. Either way, it shifts to the left, signaling greater downside risk when relying heavily on snack-halves.

Figure 2, subplots e-h, show how reallocating snack-halves between wholesale and retail changes performance relative to the baseline. When the cooperative adopts a retail-heavy strategy (60% retail, 40% wholesale), both distributions move strongly to the right. The cooperative's mean NPV rises to $3.2 million and members to $2.6 million, with substantially higher IRR's. These gains show the higher unit margins available in retail markets, which more than offset the additional marketing and distribution costs. On the other hand, the balanced strategy (50% retail, 50% wholesale) delivers more modest improvements relative to baseline, with a cooperative mean NPV of $2 million and member NPV of $1.6 million. Even though retail sales clearly drive stronger returns, they also expose the cooperative to greater variability in demand and higher marketing risks. The results highlight that channel strategy is a decisive factor in financial performance, with retail expansion offering higher payoffs but requiring stronger market access and risk management.

The next section of results highlights how patronage allocation decisions shape cooperative and member outcomes. Under the cash-heavy allocation (70% cash patronage, 25% nonqualified stock, 5% unallocated reserve), the cooperative posts a 10.2% higher mean NPV ($831,081) than baseline, with an 84.90% probability of positive returns. Members also benefit, with mean NPV rising to $881,339 and IRR above 35%. Nonetheless, a heavy nonqualified stock allocation (25% cash patronage, 70% nonqualified stock, 5% unallocated reserve) weakens outcomes. We observe that cooperative mean NPV declines to $660,622 and member NPV to $652,926. These results suggest that higher immediate cash refunds improve perceived member welfare and maintain cooperative viability. However, solvency tells a different story. Under the cash-heavy policy, year-10 cumulative cash averages -$73,920 and is positive in only 48.2% of runs. This finding signals a frequent end-of-horizon shortfall. By contrast, the heavy nonqualified stock policy averages $347,107 of year-10 cash, with 95% of runs ending positive, indicating a much stronger liquidity position. In short, higher immediate cash refunds lift NPV and member IRR but strain cash balances, whereas heavier use of nonqualified stock keeps returns moderate yet preserves solvency. A balanced rule is to set the cash-patronage rate to the lowest level that meets a solvency target while keeping member IRR attractive, rather than maximizing cash refunds every year.

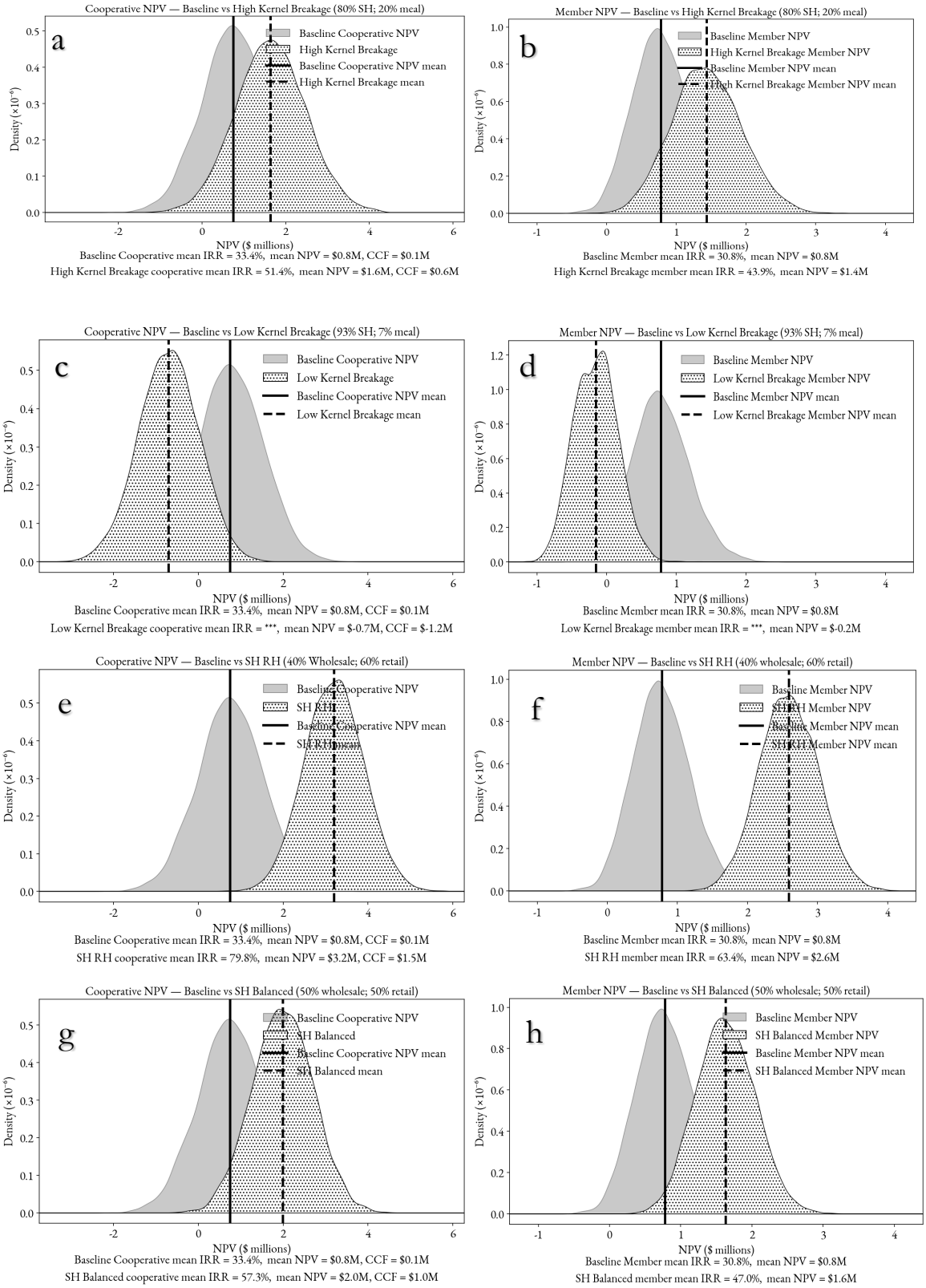


Figure 2. Sensitivity Analysis for Kernel Allocation and Snack-Halves Sales

Note: SH Implies Snack-Halves; RH Implies Retail-Heavy, CCF Implies Cumulative Cash Flow (Year 10).

Table 8: Sensitivity Analysis on Patronage Allocation and Energy Requirement Assumptions

Scenarios		Co-operative			Member	
		Cum. Cashflow /CCF (Year 10)	NPV	IRR (%)	NPV	IRR (%)
Cash heavy (5% UR; 70% CP; 25% NQS)	Minimum	-$2,494,837	-$2,352,114	-43.46%	-$706,304	-35.10%
	Mean	-$73,920	$831,081	35.37%	$881,339	36.02%
	Maximum	$1,174,811	$3,555,141	142.00%	$2,566,644	100.94%
	Probability of positive CCF/NPV or IRR ≥10%	48.20%	84.90%	88.30%	98.50%	98.90%
Heavy nonqualified stock (5% UR; 25% CP; 70% NQS)	Minimum	-$1,963,167	-$1,992,432	-44.17%	-$612,871	-27.57%
	Mean	$347,107	$660,622	30.75%	$652,926	25.41%
	Maximum	$3,444,505	$4,243,191	126.22%	$2,160,134	54.96%
	Probability of positive CCF/NPV or IRR ≥10%	95.00%	81.00%	85.00%	97.10%	97.00%
50% below assumed energy requirement (0.5 HP per lb/h)	Minimum	-$2,101,274	-$1,997,539	-37.42%	-$784,364	-23.71%
	Mean	$275,535	$963,470	37.51%	$917,905	33.65%
	Maximum	$1,745,144	$3,878,889	135.12%	$2,643,800	77.34%
	Probability of positive CCF/NPV or IRR ≥10%	71.8%	89.20%	90.90%	99.20%	99.40%
25% above assumed energy requirement (1.25 HP per lb/h)	Minimum	-$2,479,454	-$2,108,263	-51.41%	-$619,018	-34.87%
	Mean	$22,019	$650,311	31.15%	$713,906	29.31%
	Maximum	$1,619,251	$3,342,736	123.95%	$2,175,762	66.38%
	Probability of positive CCF/NPV or IRR ≥10%	54.90%	80.01%	83..80%	97.10%	97.30%

Note: Each scenario isolates the effect of a single variable by holding all other parameters constant at their baseline values.

The final set of results examines the effects of varying aggregate energy requirements from 0.5 to 1.25 HP per pound per hour around the baseline assumption of 1 HP per pound per hour. These variations did not alter the study's overall feasibility conclusions. Mean cooperative NPV remained positive across all scenarios, ranging from $650,311 to $963,470, whereas cooperative IRR remained well above the 10% benchmark (see Table 8). Although the cooperative remains financially viable across this plausible range of energy requirements, electricity demand represents an important cost component that can influence profitability. This suggests that careful management of energy use and equipment efficiency could further improve financial performance and enhance returns to cooperative members.

Conclusion

This study evaluated the feasibility of a producer-owned pecan shelling cooperative under stochastic prices, production volumes, kernel yields, and patronage allocation policies. It is important to note that any shelling decision should be based on quantified demand potential for the end products prior to planning investment in a facility. Only with recognized market potential can the financial viability of a proposed shelling venture be accurately determined.

The baseline analysis indicates that such a cooperative can be financially viable, with positive NPVs in most simulations and IRRs well above the assumed discount rate of 10%. Members consistently realize higher and more stable returns than the cooperative itself, indicating how collective ownership shifts fixed-cost risk to the organization while distributing value-added benefits to individual growers. Sensitivity analyses show that kernel recovery is the most critical determinant of financial performance, with higher yields driving markedly stronger outcomes. Variety composition, breakage rates, and the balance between wholesale and retail channels further shape profitability. Patronage allocations also directly determine how benefits are distributed between members and the cooperative.

The analysis is not without limitations. Publicly available information and previous research related to pecan shelling economics are virtually nonexistent. Thus, it is difficult to compare these findings with historical returns to shelling operations. To combat this uncertainty, the authors visited pecan shelling operations and received equipment lists and quotes from reliable suppliers. Reliable long-run data exist for in-shell pecan prices, but not for retail snack-halve prices. To address this issue, the study applied a derived shelled-equivalent and markup procedure. While practical, this method may not fully capture actual retail pricing behavior. In addition, the model assumes uniform member participation and does not account for behavioral responses, such as delivery choices or bargaining strategies.

Despite the limitations of this study, the resulting model will be made publicly available to interested pecan growers. These growers will be allowed to modify many parts of the model to fit their specific business scenarios. As they assess situations specific to their pecan production parameters and market opportunities, their feedback will be used to make future modifications and address previously untested risk parameters.

Future research could extend the framework by incorporating member behavioral dynamics, examining alternative marketing strategies such as export contracts, and quantifying the stabilizing role of risk management tools, including forward contracts or insurance. For practitioners, three implications emerge. First, improving kernel yields and maintaining quality are central to cooperative viability. Second, developing stable outlets for both snack-halves and pecan meal can reduce downside risk and at the same time capture retail margins where feasible. Third, boards should design patronage policies that balance organizational liquidity with members' need for timely cash returns. Overall, the results indicate that a pecan shelling cooperative offers a promising pathway for producers to capture more value, but long-run success will depend on disciplined kernel yield management through production, market diversification, and financial policies that align cooperative resilience with member welfare.

Declaration of Interest Statement/Competing Interest

The authors declare no conflict of interest.

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Data Availability

The various data used to parameterize the model are documented in the paper. They were primarily sourced from the U.S. Department of Agriculture–Economic Research Service (USDA-ERS), the U.S. Energy Information Administration (EIA), U.S. Bureau of Labor Statistics (BLS, 2025), retail shops, and the U.S. Environmental Protection Agency (EPA).

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How Much, How Big, and Where? Determining an Optimal Supply Chain Network for Locally Grown Blueberries Using a Facility Location Model

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Abstract

Strategic siting of production areas, aggregation hubs, and distribution routes at the regional level is essential to coordinate supply and demand for local food and establish an efficient food supply chain. This study examines the least-cost supply chain network for distributing locally grown fresh blueberries in Georgia using a geospatial optimization model. Three demand scenarios were evaluated, incorporating production sites, food hub capacities, distribution center locations, road infrastructure, and transportation modes. Results show that smaller food hubs located near production fields minimize costs under the travel distance constraints. More miles are traveled from food hubs to retail centers than from production sites to food hubs. Producers near retail markets hold a comparative advantage. To develop a least-cost local blueberry distribution system in Georgia, public support may prioritize locating food hubs closer to farms and reducing food hubs' outbound transportation costs.

Keywords: facility location, food hubs, investment, local food, supply chain

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Introduction

Over the past few decades, interest in local food systems has been growing among consumers, policy makers, and the fresh produce industry. This trend reflects a broader movement toward sustainable sourcing, regional economic development, and environmental and healthy food conscious consumption (Ethoven and Van den Broeck, 2021). In the United States, sales of local food reached $17.5 billion, a 33.2% increase from 2017 (USDA-NASS, 2022a). Sales of local food are expected to increase as U.S. consumers increasingly prefer fresh fruits and vegetables sourced from local farming systems (Center for Food Demand Analysis and Sustainability, 2025).

Strategic coordination across production, aggregation, and distribution is essential, particularly for enabling small and medium-sized farms to participate in local and regional food systems (Berti and Mulligan, 2016). Compared to long and complex industrialized food supply chains, local food supply chains are typically shorter, involve fewer intermediaries, and depend more heavily on regional infrastructure and logistics efficiency of individual participants (Marsden, Banks, and Bristow, 2000). Local food supply chains can also cooperate or coexist with conventional food supply chains, such as by selling local products in supermarkets (Thomé et al., 2021).

The U.S. federal and state governments have made significant and sustained investments in programs supporting local and regional food system development. For instance, in 2024, the U.S. Department of Agriculture (USDA)'s Local Agricultural Market Program (LAMP) awarded more than $43 million to 113 projects across the United States. However, these projects emphasize training, technical assistance, and community development. Relatively less funding is allocated to strategic supply chain planning or network configurations, although the need for economic feasibility, location, and capacity research on food hub investment and financial support for scaled-up local food distribution system development is widely recognized in many states (Hellwinckel and Velandia, 2016; Furman et al., 2018; Murphy, 2025).

Insufficient infrastructure and supply chain configurations may discourage many small and mid-sized farmers from participating in local food systems (Kinnunen et al., 2020). Research shows that distribution and transportation could account for more than 30% of total expenses for U.S. producers participating in local food systems (Martinez and Park, 2021), and small and mid-sized producers generally prefer not to travel long distances to access local markets (Kremer and DeLiberty, 2011; Bobronnikov, Prenovitz, and Yadav, 2019). Food hubs have emerged as a critical intermediary in this landscape to improve market access for small and medium producers (Low et al., 2015). Food hubs are also important for efficiently handling perishable fruits and vegetables, where cold storage and timely movement through the supply chain are required. According to the 2021 National Food Hub Survey, more than 80% of surveyed hubs engaged in "buy local" promotion efforts, and more than half of their sales revenue derived from direct marketing channels (Bielaczyc et al., 2023). Nonetheless, transportation costs remain a significant constraint, especially for small-scale hubs operating with limited capacity and geographic flexibility.

From a business perspective, the capacity and location of food hubs are critical factors for achieving optimal operations and long-term financial sustainability (Matson and Thayer, 2013).

Many food hubs initially rely on government or institutional funding and grants, with the expectation of becoming economically self-sufficient within three to five years. Once established, a food hub operates much like a new business venture. Without sufficient participation from local farmers or other suppliers, the facility and its services may not be economically viable. Although the "if you build it, they will come" model may succeed in some areas, it can fail in others, as demonstrated by unsuccessful grocery store interventions in some underserved neighborhoods, where low profit margins and high overhead costs undermined efforts to improve access to healthy food (Engler-Stringer et al., 2019). Many food hubs also failed due to not having enough producers (supply) or buyers (demand) to reach profitability (George, 2016; Feldstein and Barham, 2017).

Regional level strategic siting of production areas, aggregation hubs, and distribution routes is essential to ensure the coordination of supply and demand for local food and establish efficient supply chains (Dimitri and Gardner, 2019; Paciarotti and Torregiani, 2021). Logistics is the first key step (Maciejczak, 2014; Rucabado-Palomar and Cuéllar-Padilla, 2020). Optimized logistics ensure sales can happen at a specific location and consistently meet customer expectations regarding food item selection, quantity, quality, and packaging. Food producers learn about consumer demand (preferences and prices) through direct and indirect communication, such as orders, invoices, and customer complaints. Transportation and distribution infrastructure support logistics and communications of the supply chain, including i) connectivity of local and regional road networks between food production sites and the consumption; ii) producers' accessibility to intermediaries that are equipped to handle and have the storage capacity for perishable food items; and iii) appropriate transportation modes, such as truck size and type, for different travel distances and volumes. Simulation and/or optimization methods can be used to investigate the best local food supply chain network design that serves multiple local food producers and intermediaries and saves costs within specific communities or local regions (Tundys and Wiśniewski, 2020; Paciarotti et al., 2022; Bayir, Charles, and Ouzrout, 2024).

This study examines a least-cost supply chain network for locally grown fresh blueberries in Georgia using a geospatial optimization model. The model incorporates production locations, infrastructure constraints, food hub capacities, and multiple demand scenarios to identify cost-minimizing network configurations among farms, food hubs, and retail distribution centers. A sensitivity analysis on yield is conducted to capture the effects of output variability on the network.

Study Region

The study region is the state of Georgia. Georgia has 159 counties and a diverse agricultural economy. More than 75% of its counties are considered rural. Most of these rural counties are in the southern half of the state. Blueberry production in Georgia was initially adopted as a profitable alternative crop following the phase-out of tobacco production. Driven by growing consumer demand for blueberries and a decline in peach demand, blueberries are now the top fruit commodity produced in Georgia (Powers, 2023; Chu and Williams, 2025). In 2021, Georgia's blueberry industry contributed more than $348 million to Georgia's economy compared to $85 million from the peach industry (Powers, 2023; University of Georgia, 2023). The majority of Georgia's bearing acreage is planted in rabbiteye blueberries (*Vaccinium Ashei*), with increasing

acreage in southern highbush cultivars (*Vaccinium corymbosum* hybrids) in the past decade (Chu and Williams, 2025). These varieties are well-suited to the state's climate and support Georgia's early-season market window. Growers coordinate their efforts through marketing cooperatives and industry associations, including the Georgia Blueberry Grower Association and MBG Marketing. Public research institutions, such as the University of Georgia Cooperative Extension, contribute to industry advancement through cultivar development and the dissemination of science-based production practices. The Georgia Blueberry Commodity Commission supports research and promotional initiatives and helps align growers with markets.

In 2023, Georgia ranked as the third largest blueberry producing state in the United States, contributing about 15% of the total utilized production (USDA-NASS, 2022b). Georgia's total blueberry acreage reached 17,800 acres in 2020, 19,300 acres in 2021, 16,800 acres in 2022, and 21,400 acres in 2023 (USDA-NASS, 2022b). Most of Georgia's blueberries are produced in the southern region. Around 90% of its blueberry acreage is located in Appling, Bacon, Clinch, Pierce, Wayne, and Ware counties, where sandy soil is ideal for blueberry production. There are also small producers primarily growing for local markets or pick-your-own operations throughout the state. Many of these small producers are located in the northern region, where there is a higher population density.

Although Georgia blueberry growers are actively seeking to expand their export markets to reach international consumers (Eastfruit, 2023; Yeh et al., 2023), there is untapped potential to further develop the local markets as well. With increasing consumer interest in locally sourced fresh produce, growers have an opportunity to meet the demand for blueberries within Georgia. Approximately 2 million Georgia residents currently reside in areas classified as low-income and low-access to food within 10 miles (USDA-ERS, 2025). Tariffs imposed under the 2025 Trump administration will not affect fresh produce from Canada and Mexico under the United States-Mexico-Canada Agreement. However, future uncertainty in tariff changes may be disruptive to imported blueberries from other countries. This tariff uncertainty could present an opportunity for Georgia blueberry producers to expand their supply to local markets. In addition to farmers' markets and pick-your-own farms, integrating the state's blueberry supply chain with the existing supermarkets can balance efforts to grow both export and local markets and help to create a more resilient and diversified demand for Georgia's blueberry industry.

Facility Location Model and Data

This study models the distribution of fresh blueberries in Georgia as a facility location problem. Blueberries move from production fields to food hubs, where they are aggregated and temporarily stored, and then to retail distribution centers (see Figure 2). Distribution efficiency depends mainly on transportation costs along these routes.

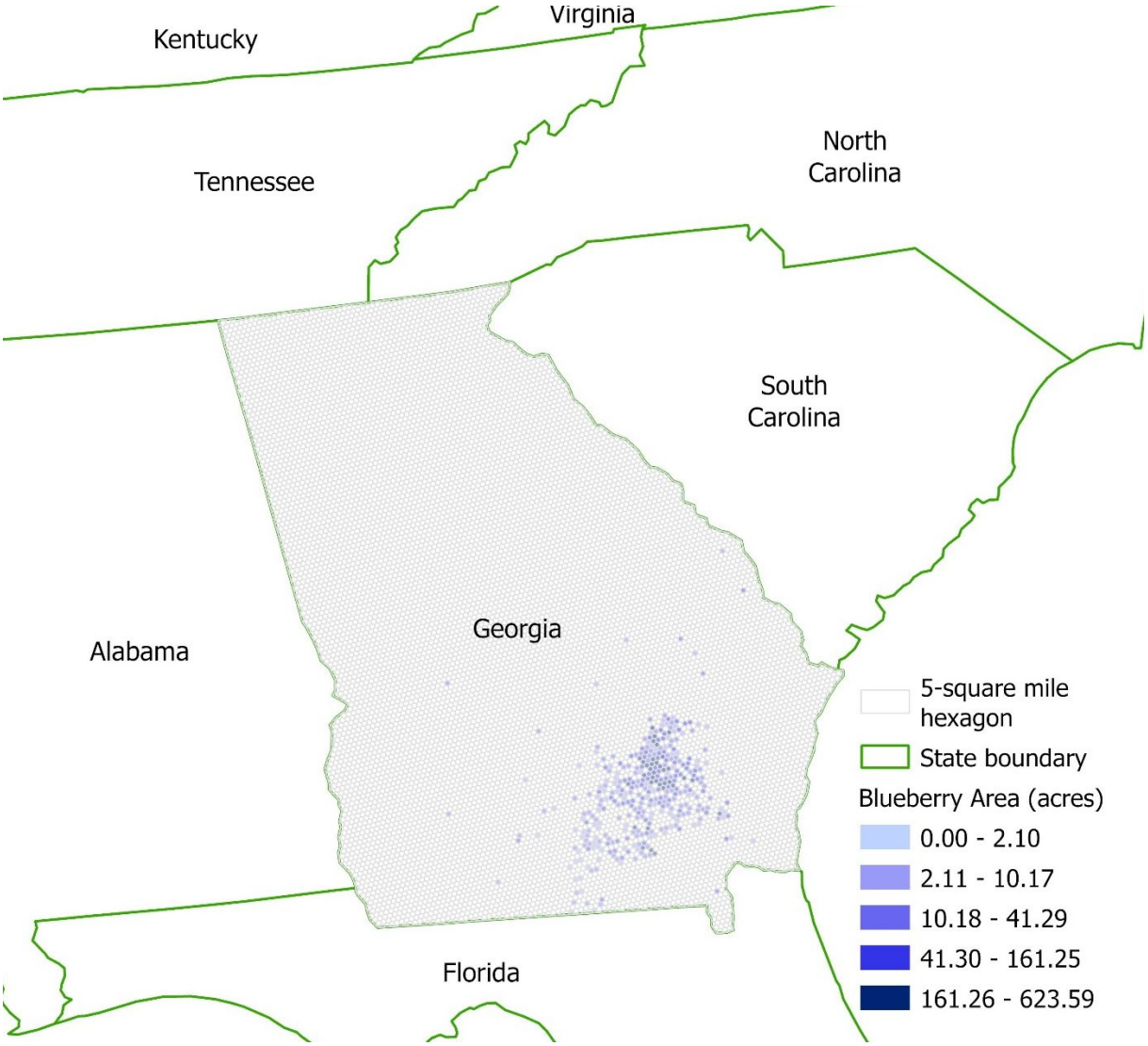


Figure 2. Georgia Blueberry Production Location and Acreage

We use network design theory to identify a cost-minimizing distribution system that meets consumer demand. The model minimizes total system costs by selecting the number, location, and capacity of food hubs, given the existing locations and production levels of blueberry fields, distance limits, and transportation infrastructure. Because food hub decisions directly affect farmers' transportation costs and the amount of production needed to supply local markets, this problem fits the classic facility location framework. The model addresses three main questions: (i) how many food hubs are needed, (ii) where they should be located and at what capacity, and (iii) how blueberry flows should be allocated among fields, food hubs, and retail distribution centers.

There are various types of facility location problems with different measurements of effectiveness of a facility location (Drezner and Hamacher, 2001; Melo et al., 2009). One way to measure a facility's effectiveness is the average distance or time that products or services must travel from a facility to the end users. In 1964, Hakimi (1964) introduced the *p*-median problem. He called a set of p points (facilities) as "medians of the network" if the set of points (facilities) results in a minimum total weighted distance between facilities and product demand nodes. The objective of a *p*-median problem is to minimize the sum of the weighted distances between facility and demand points, subject to a fixed number of facility locations given a distance matrix and candidate locations. The number of facilities is predetermined, but the location of facilities is endogenous. The *p*-median problem can be expanded to include more realistic constraints, such as the maximum travel distance from the facility to customers (Khumawala, 1973) and consideration of transportation and facility setup costs (Baumol and Wolfe, 1958; Balinski, 1965). The Capacitated Facility Location Model (CFLM) is an extension of the *p*-median problem and has been considered one of the most important location models used extensively by public organizations and private industries (Farahani and Hekmatfar, 2009). The CFLM aims to determine an optimal set of capacitated facilities such that the sum of facility construction and transportation costs is minimized. The mathematical formulation of the CFLM is a mixed integer linear programming (MILP) problem with facility locations entering the solution as binary variables.

Mixed Integer Linear Programming (MILP) Model

A Mixed Integer Linear Programming (MILP) model was developed to identify optimal blueberry supply chain network configuration that minimizes the total of food hub establishment costs and transportation costs (see equation 1), subject to a set of constraints on supply, demand, shipping routes, and candidate food hub site locations. Table 1 provides the nomenclature of the model.

Table 1. Nomenclature of the Indices, Variables, and Parameters of the Optimization Model

Index	
i	the location of production field, $i = 1, \dots, 361$
j	the candidate location for food hubs, $j = 1, \dots, 206$
k	the location of retail distribution center, $k = 1, \dots, 36$
m	food hub capacity options, $m = 1, \dots, 3$
Variables	
x_i	area harvested in i to meet the local blueberry demand
z_{jm}	is a binary variable 0 when the food hub candidate location is not selected; 1 selected
v_{ij}	volume of blueberries shipped from production site i to food hub j (tons)
u_{jk}	volume of blueberries shipped from food hub j to demand location k (tons)
Parameters	
Y_i	yield of blueberry in i (ton per acre)
A_i	total blueberry cultivation areas in field i (acres)
G_m	volume can be stored and processed in food hub with capacity m (tons)
D_k	demand of blueberry in location k (tons)
r	percentage of total demand for blueberries fulfilled by local supply (%)

Table 1 (cont.)

Parameters	
H_m	Unit cost for food hub at capacity m (\$ per unit)
c_{ij}	unit costs of transportation from i to j (\$ per ton-mile)
c_{jk}	unit costs of transportation from j to k (\$ per ton-mile)

The objective function is:

$$Minimize\ \ CF + CT \tag{1}$$

where

CF: total food hub establishment costs (\$)

CT: total transportation costs (\$)

Total food hub establishment costs, CF, is the sum-product of a binary variable, z_{jm} and H_m, the establishment cost of food hub facility with capacity m (see equation 2). The binary variable, z_{jm}, denotes the selection of storage location j and its associated capacity type m.

$$CF = \sum_m \sum_j z_{jm} \cdot H_m \tag{2}$$

The transportation cost, CT, includes transportation from production field i to food hub location j and then from food hub j to distribution center k (see equation 3). The unit cost of delivering blueberries from production field i to food hub j is c_{ij}, and the shipment volume between i and j is v_{ij}. The total cost of transporting blueberries from production field to food hub is the sum-product of unit shipment costs c_{ij} and the shipment volume v_{ij}. The total cost of transporting blueberries from food hub j to distribution center k is the sum-product of unit cost c_{jk} and the shipment volume from j to k (u_{jk}).

$$CT = \sum_i \sum_j v_{ij} \cdot c_{ij} + \sum_j \sum_k u_{jk} \cdot c_{jk} \tag{3}$$

Given the limitation of information availability on site-specific fields and post-harvest operational costs, we have assumed homogenous blueberry production, packaging, and marketing costs across each location i. Therefore, they are not considered in the objective function.

Equations 4–8 are model constraints. The blueberry areas harvested to meet the local food demand in field i, x_i, should not exceed the total available blueberry area in i, A_i (see equation 4). The total shipment volume of blueberries from field i to food hub, $\sum_j v_{ij}$ is determined by harvesting area x_i and yield Y_i (see equation 5). The receiving shipment from all i to specific j should not exceed j's capacity (see equation 6). Equation (7) shows that the amount of blueberries shipped from food hub j to retail distribution center k should not exceed the amount shipped into j from production fields.

$$x_i \leq A_i \quad (4)$$

$$\sum_j v_{ij} = x_i \cdot Y_i \quad (5)$$

$$\sum_i v_{ij} \leq \sum_m G_m \cdot z_{jm} \quad (6)$$

$$\sum_k u_{jk} \leq \sum_i v_{ij} \quad (7)$$

Not all demand for fresh blueberries will be met by local production. We assume that only a certain percentage (r) of the total demand in location k, D_k, will be supplied by local production. The amount of shipment from food hub j to retail distribution center k should at least be $D_k \cdot r$. (see equation 8).

$$\sum_j u_{jk} \geq D_k \cdot r \quad (8)$$

Data

Unit of Analysis and Production Areas and Yields

The state of Georgia was digitized into 5-square-mile hexagons using ArcGIS (see Figure 1). These polygons are the functional "decision making units," determining the nodes along optimal transportation pathways. Potential blueberry areas that can be harvested to meet local demand, food hub candidates that distribute locally grown blueberries, and retail distribution centers are identified at the hexagon level.

The blueberry production area and location data are from DTN, a U.S.-based data analytics and information services company that specializes in agriculture, weather, energy, and transportation sectors (https://www.dtn.com/). In this research, DTN data were aggregated and superimposed on 5-square-mile hexagons to identify blueberry production areas in each hexagon (see Figure 1).

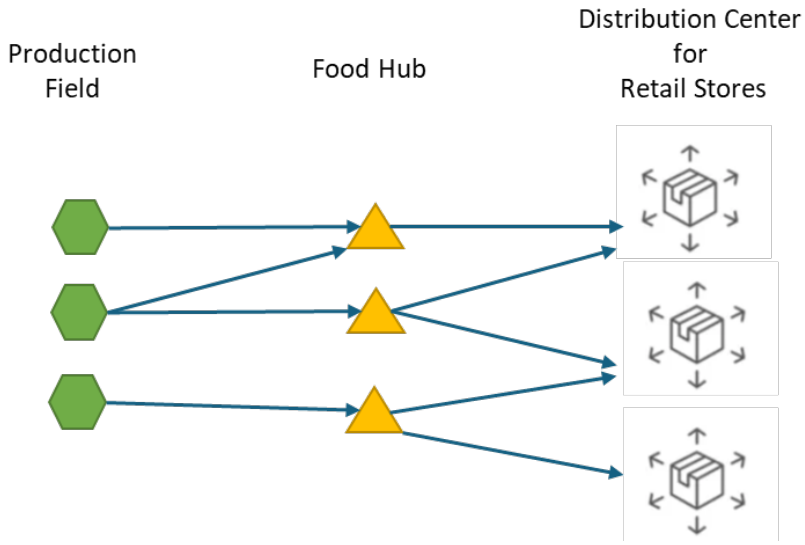


Figure 1. Structure of Modeled Supply Chain

Blueberry yield is assumed to be 4,200 lbs per acre in the baseline. This is the average yield of Georgia blueberries in 2021 (USDA-NASS, 2022b). Blueberry annual yields are affected by various factors, such as weather conditions and plant age (Retamales et al., 2015). To account for the yield uncertainty, we conducted a sensitivity analysis by reducing yields from the baseline level to 70% of the baseline in 5% increments (see Table 2).

Table 2. Yield Scenarios

Yield Scenarios	Description	Value (lbs per acre)
Y100	baseline yield	4,200
Y95	95% of baseline yield	3,990
Y90	90% of baseline yield	3,780
Y85	85% of baseline yield	3,570
Y80	80% of baseline yield	3,360
Y75	75% of baseline yield	3,150
Y70	70% of baseline yield	2,940

Food Hub Candidate Locations and Costs

We used 260 geographic locations of existing warehouses for vegetables and fruits in Georgia as the candidate food hub locations that can be used to serve, gather, and store locally grown fresh blueberries before transporting them to retail distribution centers (see Figure 3[a]).[1]

Three capacities were considered for food hubs, including 50 tons per year (small), 100 tons (medium), and 500 tons (large). Accurately determining the food hub establishment costs for different capacities is challenging. Establishment costs vary by location, construction or renovation requirements, specialized storage and handling equipment, labor and permitting requirements, and necessary utilities or site upgrades. The uncertainty of these factors makes standardized cost estimates difficult. To differentiate costs by hub capacity for modeling purposes, we assume a small 50-ton food hub requires an initial investment of $250,000. This number is based on the total fixed costs reported for a representative food hub case study in the USDA-RDS (2018) report "*Running A Food Hub: Assessing Financial Viability*." The establishment costs for a medium-sized 100-ton food hub and a large 500-ton food hub are assumed to be $500,000 and $2.5 million, respectively, based on proportional scaling of capital requirements.

Proxy of Retail Distribution Center Locations

We used the centroids of metropolitan and micropolitan statistical regions located in Georgia as the proxy of retail distribution center locations (see Figure 3[a]). The U.S. Office of Management and Budget defines metropolitan and micropolitan statistical regions. A metropolitan statistical area has at least one urban area with a population of 50,000 or more. A micropolitan statistical

[1] Data from Mergent Online: https://www.mergentonline.com/basicsearch.php [Accessed January 9, 2023].

region is a smaller region with at least one urban area of 10,000 to 49,999 people. Figure 3(b) presents the population density in 35 metropolitan and micropolitan regions overlaying the state.

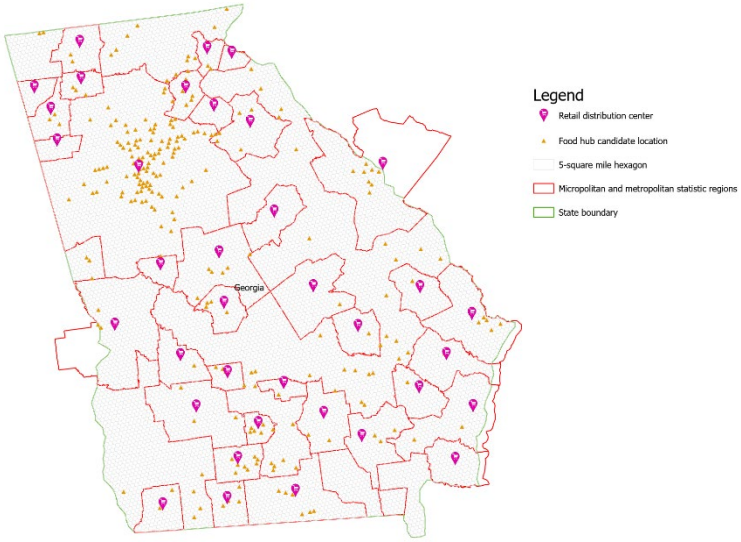


Figure 3a. Candidate Locations of Food Hubs, Centroid of Metropolitan and Micropolitan Statistic Areas in Geogia

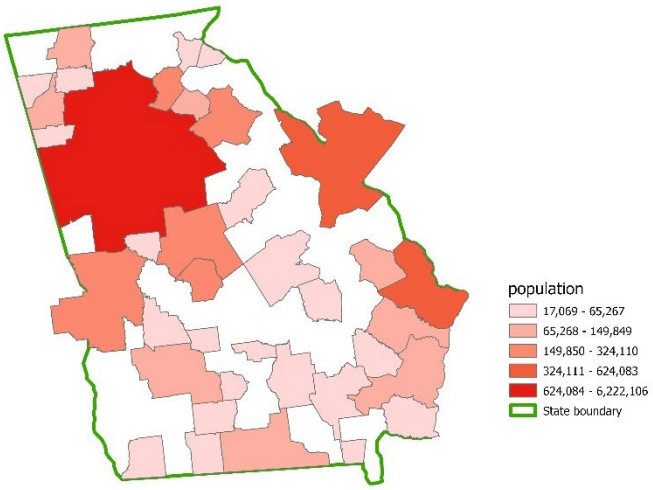


Figure 3b. Population Density in Metropolitan and Micropolitan Statistic Areas

Transportation and Costs

A distance matrix was generated between hexagons using ArcGIS based on the existing road network. The maximum allowable travel distance between production field hexagons to food hub hexagons was 50 miles. The distance assumption is based on the 2013 USDA-FNS Farm to School Census (USDA-FNS, 2015), which reported that 20% of respondents defined local food as produced within a 50-mile radius (Bobronnikov, Prenovitz, and Yadav, 2019). Kremer and

DeLiberty (2011) also found that the median travel distance for small- and medium-sized farmers to farmers' markets was 57 miles. The maximum allowable travel distance between a food hub and a retail distribution center was 400 miles. This distance assumption follows the 2008 Farm Bill that defines the "locally or regionally produced agricultural food product" as the product is transported less than 400 miles from the origin of the product or the State in which the product is produced (Food, Conservation, and Energy Act of 2008, Pub. L., 110-246, 122 Stat. 1929).

We include two truck types with capacities of 4 and 8 tons to represent transportation modes. The 4-ton truck reflects smaller vehicles used for farm to hub and short distance deliveries, while the 8-ton truck represents larger medium-duty trucks used for aggregated shipments from food hubs to retail centers. According to the USDA's Agricultural Refrigerated Truck Quarterly, transportation costs for southeast local routes (under 500 miles) averaged $6 per mile in the second quarter of 2022 (AgRTQ Datasets, n.d.). This translates to $1.50 per ton-mile for a 4-ton truck and $0.75 per ton-mile for an 8-ton truck. For each mile traveled, the cost of transporting an additional ton is lower with the 8-ton truck than with the 4-ton truck.

Demand Scenarios

The USDA-ERS (2016) estimates U.S. per capita consumption of fresh blueberries at 1.76 pounds. This measure includes both domestically produced and imported berries. Regional demand is calculated by applying this per capita consumption value to the metropolitan and micropolitan populations. Although more recent non-USDA sources suggest higher per capita consumption levels in the 2020s, ranging from approximately 2.3 to 2.7 pounds per capita according to trade publications and industry analyses (e.g., USDA-NASS, 2020; Hammami et al., 2024; Karst, 2024), we rely on the USDA estimate for consistency and reliability.

Demand scenarios are based on the percentage of fresh blueberries demand to be fulfilled by local supply in each metropolitan and micropolitan region. Table 3 shows the demand scenarios, including DM-5% (5% of the total demand to be fulfilled by locally grown products), DM-10% (10% of the total demand to be fulfilled by locally grown products), and DM-20% (20% of the total demand to be fulfilled by locally grown products). The total targeted demand volume for the state fulfilled by local supply is 455 tons, 910 tons, and 1820 tons, respectively.

Table 3. Demand Scenarios

Demand Scenarios	Description	Total Targeted Demand Volume from Local Supply (Tons)
DM-5%	5% of the demand for fresh blueberries fulfilled by local supply	455
DM-10%	10% of the demand for fresh blueberries fulfilled by local supply	910
DM-20%	20% of the demand for fresh blueberries fulfilled by local supply	1,820

Software and Solver Routine

The model was programmed in the GAMS (General Algebraic Modeling System) optimization package. The models were solved using the commercial solver CPLEX 10 on the GAMS platform. The relative gap was set to be less than or equal to 0.5%.

Results

Optimal Solution on the Network Configuration

The optimal network configuration includes the location and area harvested, the location of the food hubs, and the retail distribution centers that are served. Figure 4 shows the location and area harvested to fulfill demand for locally grown fresh blueberries under the baseline yield level (4,200 lbs per acre) and different demand scenarios. When the demand is small (i.e., DM-5%), 14 hexagons are identified to supply blueberries to meet the demand at each retail distribution center. The total area harvested to meet the demand is about 213 acres, with a minimum of 5 acres and a maximum of 23 acres per hexagon. Under the DM-10% scenario, 17 hexagons are identified, with a minimum of 0.5 acres and a maximum of 234 acres. The total area harvested is 426 acres, which is linear to the demand because of the homogenous yield assumption in the model. In reality, the yield could be different among these hexagons. The identified number of hexagons reached 20 as the total demand increased to 1,820.43 tons (total acres harvested were 468) under the scenario DM-20%. Most of the harvested areas are located in the southern Georgia major blueberry production region.

Given that demand equals supply, the model always serves all the retail distribution centers. The model identifies food hubs that are within a 50-mile radius of the supply hexagons and a 400-mile radius of the retail distribution centers. The maps of the supply network, from harvesting hexagons to food hubs and from food hubs to retail distribution centers, are presented in Figure 4 for alternative demand scenarios. Most of the food hubs are proximate to the blueberry fields located in the southern part of the state, although most of the candidate food hub locations are located in the northern part of the state, closer to the centroid of the metropolitan and micropolitan regions (see Figure 3[a]). Between production fields and food hubs, smaller trucks require more frequent trips to move the same volume. Locating food hubs near production fields can reduce the total travel distance between fields and food hubs, thereby reducing transportation costs. This result is similar to Ge et al. (2025)'s research in Georgia for identifying the optimal solution for fresh produce food hubs in the United States.

In the DM-5% scenario, 10 food hub locations are selected, each with a capacity of 50 tons (see Figure 5, at Y100). Smaller hubs located close to harvest fields minimize short-haul transportation costs from fields to hubs. When the demand increased to DM-10%, the total number of food hubs remained 10, but with one hub having a capacity of 100 tons. Compared to DM-5%, the model expands capacity at one location from 50 to 100 tons. Under the higher demand scenario DM-20%, the number of food hubs increased to 14, with 9 locations having 50 tons capacity, two locations having 100 tons capacity, and three locations having 500 tons capacity. At this demand level,

increasing hub size is no longer enough. Shipping blueberries over long distances from only a few hubs becomes costly. The model chooses to open more hubs and to build some hubs with a much larger capacity (500 tons). Most of these selected food hubs tend to be placed close to, or at, harvest field locations (hexagons) to keep transportation costs low.

Transportation Miles

Table 4 presents the miles traveled under different demand scenarios. In general, the miles traveled from field locations to food hub locations are much shorter than those from food hub locations to retail distribution centers, due to the shorter travel distances between fields and food hubs. When demand is low, DM-5%, the total miles traveled from field to food hub is about 2,166 miles, whereas the miles traveled from food hubs to retail distribution centers are 14,982 miles. In the demand scenario DM-20%, the miles traveled between food hubs and retail distribution centers could reach 69,384. Higher demand may not necessarily result in much higher travel miles from field to food hub, but it could double or triple the miles traveled from food hubs to retail distribution centers due to a much larger travel radius allowed by the model. The results show that outbound transportation costs for food hubs could become dominant as demand grows, potentially reducing food hub profitability.

Table 4. Miles Traveled under Different Demand Scenarios and Baseline Yield

Scenarios	Field to Food Hub (Miles)	Food Hub to Retail Distribution Center (Miles)
DM-5%	2,166	14,982
DM-10%	3,339	32,322
DM-20%	3,796	69,384

Note: DM-5%, DM-10%, and DM-20% represent cases where 5%, 10%, and 20% of total demand is met with locally grown blueberries, respectively.

Sensitivity Analysis on Yield

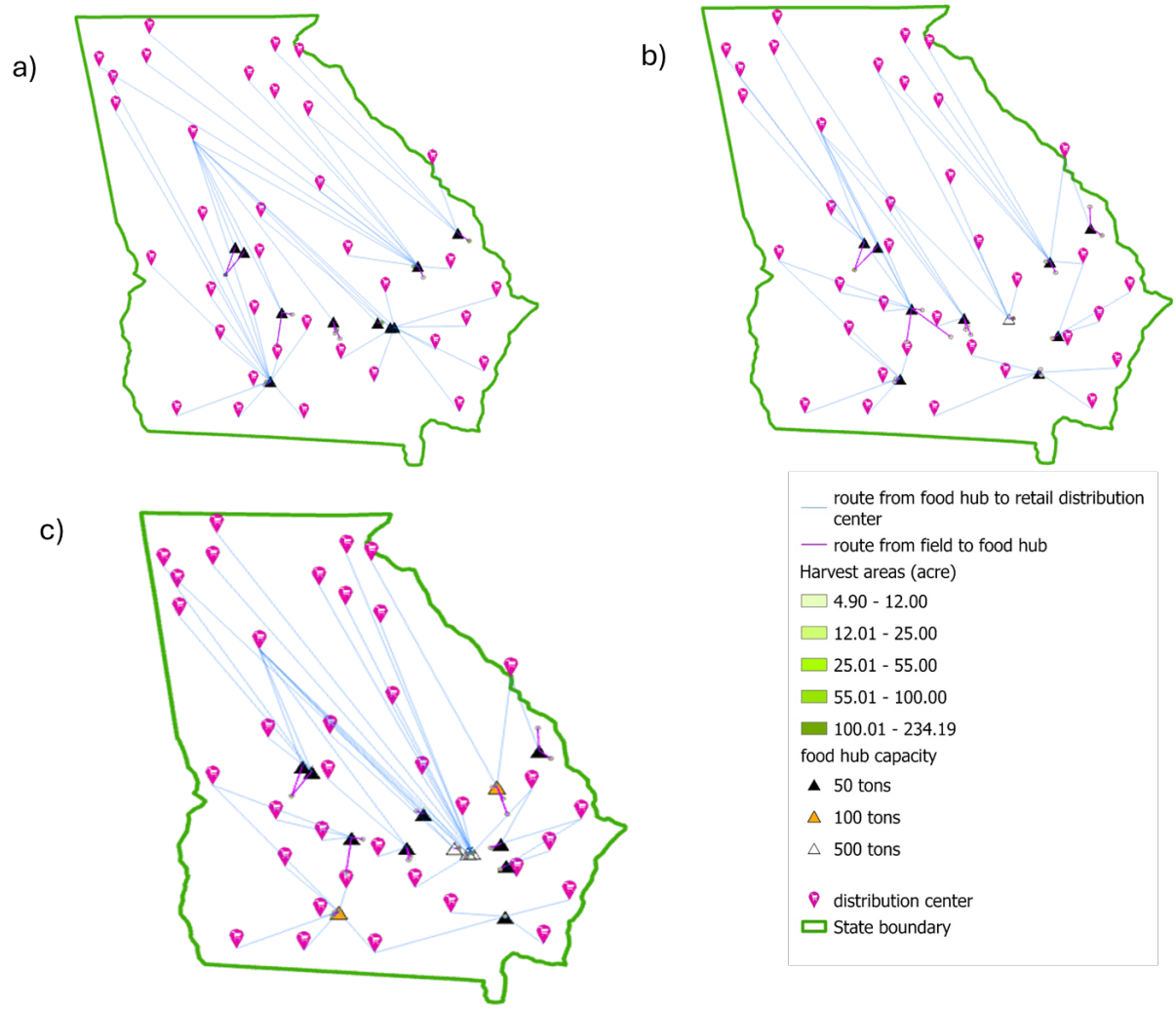


Figure 4. Solutions under Different Demand Scenarios and Baseline Yield (Y100)

Notes: a) DM-5% where 5% of the total demand to be fulfilled by locally grown products; b): DM-10% where 10% of the total demand to be fulfilled by locally grown products; c): DM-20% where 20% of the total demand to be fulfilled by locally grown products. Harvest area refers to area harvested to meet fresh blueberry demand in Georgia.

Decreasing blueberry yields affect the optimal solution for the number and capacity of food hubs. As shown in Figure 5, the number of food hubs increased when the yield is low, with the lower capacity hubs (50 tons) dominating in the network. Whereas the number of 500-ton hubs remained relatively stable, the smaller hubs are needed to aggregate dispersed supply under reduced yield scenarios. Lower yields reduce the amount of blueberries produced in each hexagon with existing fields. To meet the same level of total demand, blueberries must be collected from more hexagons (i.e., more producers) that are spread over a wider area. This practice expands the supply network and increases the need to coordinate across many locations. As a result, lower blueberry

productivity may put more pressure on decentralized infrastructure and may require additional investment in small-scale food hubs to aggregate production.

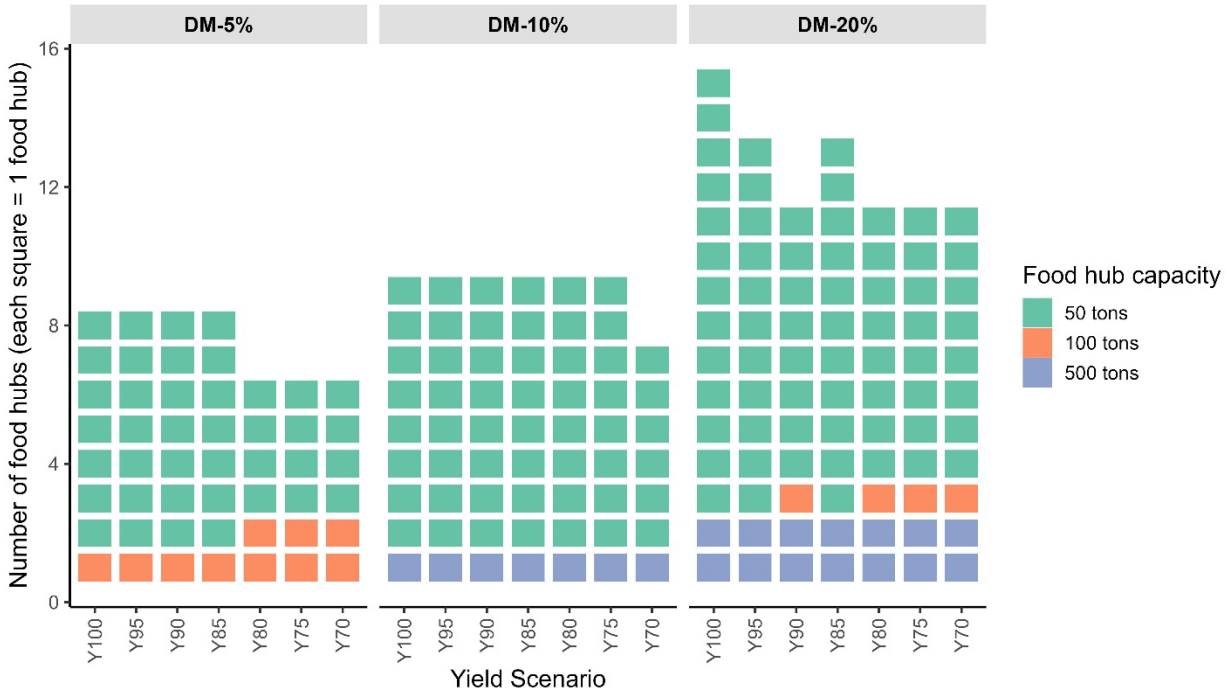


Figure 5. Food Hub Number and Capacity under Different Levels of Yield and Demand Scenarios

Notes: DM-5%, DM-10%, and DM-20% represent cases where 5%, 10%, and 20% of total demand is met with locally grown blueberries, respectively. Y100 denotes the baseline yield level, while Y95 through Y70 represent 95% to 70% of the baseline yield.

Figure 6 shows the total distance traveled under each yield and demand scenario, plotted on a log-transformed scale. As yields decrease, both short-haul (field to hub) and long-haul (hub to retail) transportation distances increase, especially under the DM-10% and DM-20%. The growing share of short-haul distances at lower yields is due to the spatial dispersion of supply sources.

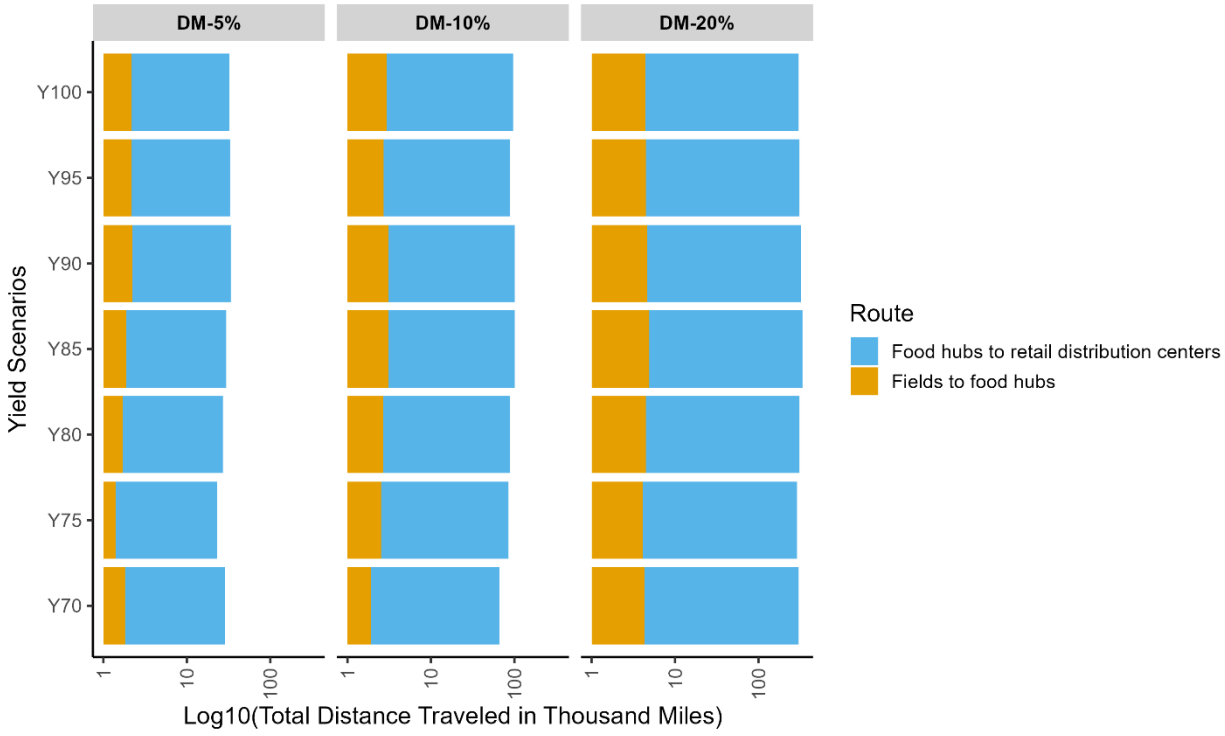


Figure 6. Logarithms of Total Travel Distance under Different Demand and Yield Scenarios

Notes: DM-5%, DM-10%, and DM-20% represent cases where 5%, 10%, and 20% of total demand is met with locally grown blueberries, respectively. Y100 denotes the baseline yield level, while Y95 through Y70 represent 95% to 70% of the baseline yield.

Conclusions

The local food movement has gained widespread support, but questions remain about how to effectively scale it up for small and medium-sized farms interested in supplying local consumers through food hubs. Given that the local food supply chain is still emerging and lacks an established operational structure, *ex post* empirical analysis is not an ideal approach. Instead, *ex ante* research or design work has comparative advantages for specifying and optimizing the system's potential configuration (King, 2012; Zilberman, Kozler, and Yan, 2025).

This research presents a case study of Georgia blueberries to demonstrate how location theory can inform strategic planning for regional local food system development. Although only food hub investment and transportation costs were considered, the findings provide insights into Georgia's supply, demand, and infrastructure for local blueberry distribution. When demand is limited and yields are high, only a small number of producers and smaller food hubs near production areas are needed. Given that small and medium producers prefer to travel no more than 50 miles to a food hub, transportation costs from the hub to retail distribution centers can become high if the demand for local blueberries increases. Planning on investment in food hub numbers and capacity should also take into consideration blueberry productivity fluctuations.

Extension programs in every state are involved in local food systems assessment and development, as evidenced by their prominent placement in the state resources directory of the National Agricultural Marketing Resource Center (AgMRC.org). Extension efforts related to local food hub assessment may be funded by USDA-AMS grants, such as the Specialty Crop Block Grant Program (SCBGP), as partnerships with state agricultural departments, or in multi-entity/agency partnerships with programs such as the MarketMaker United States (https://foodmarketmaker.com/). Ex ante studies such as this one could support extension programs by providing analytical tools that help communities and stakeholders evaluate alternative distribution models, infrastructure needs, or cost structures before investments are made. In addition, research on supply chain network design provides extension educators with adaptable, evidence-based insights that can be translated into guidance for producers, cooperatives, and local government in planning.

There are several limitations to this research. First, we assumed homogeneous productivity across all blueberry fields and standardized transportation modes using 4-ton and 8-ton trucks. These assumptions could be refined in future studies by incorporating field-level data on the age of blueberry bushes and associated yields, as well as operational data on the economic efficiency of transportation modes for distributing fresh blueberries within the state. Second, supply and demand seasonality, uncertainty, and risk management were not addressed in this study. Future research should focus on understanding seasonal and spatial demand patterns to better inform producers' decisions about when and whether to harvest fresh blueberries for local markets. Third, this study used the centroids of each metropolitan and micropolitan area as proxies for retail distribution centers. This approach could be improved by including information on which major retailers would participate in distributing locally grown, fresh blueberries in Georgia. Despite these limitations, the research provides valuable insights into methods and information that can support strategic planning for stakeholders and regional planners interested in developing large-scale local food distribution systems.

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Fragility in the U.S. Egg Sector: Lessons from the HPAI Outbreaks

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Abstract

Recent outbreaks of Highly Pathogenic Avian Influenza (HPAI) revealed fragility in the U.S. egg sector. Outbreaks that began in 2014 and 2022 have impacts beyond the immediate biological shock, as unintended consequences expose how an industry built for maximum efficiency can amplify risk when crisis strikes. This paper argues that it is not the disease alone but the organization of production that can transform outbreaks into systemwide disruptions. A suite of policy measures, both preemptive and reactive, may offer a path forward to reducing fragility without compromising economic efficiency or market stability.

Keywords: economic efficiency, highly pathogenic avian influenza (HPAI), supply chain, systemic fragility

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Introduction

Animal disease outbreaks are a growing concern for food security and agricultural markets. They are no longer rare disturbances but recurring stress tests for how food systems respond under pressure. Animal pathogens impose costs well beyond immediate production losses, often triggering trade disruptions, shifts in consumer behavior, and policy actions that reshape entire supply chains (McElwain and Thumbi, 2017). Highly Pathogenic Avian Influenza (HPAI) is particularly disruptive, not only because of the biological severity, but also because of its frequency and capacity to disrupt markets (Myles, Hood, and Allen, 2009). Supply chain design, market structure, and the availability of coordinated policy tools ultimately affect whether an outbreak is swiftly contained or cascades into a nationwide emergency (Craighead, Ketchen Jr., and Darby, 2020; Choudhury et al., 2023).

In the United States, the 2014–2015 and 2022–2025 HPAI outbreaks have been among the most economically significant animal health events in recent history. The 2014–2015 epidemic resulted in the culling of approximately 50 million commercial birds, primarily in layer and turkey operations, and imposed an estimated $3.3 billion in direct and indirect economic losses across the production, trade, and consumer sectors (USDA-APHIS, 2016; Ramos, MacLachlan, and Melton, 2017; Zhao, Lee, and Saghaian, 2019).

Although surveillance systems and response protocols were strengthened following that episode, the outbreak that began in 2022 was even more disruptive, with cumulative detections surpassing 150 million birds by early 2025, affecting layers, broilers, and turkeys, and becoming the most geographically widespread HPAI outbreak on record (Schnirring, 2025; USDA-APHIS, 2025). Again, these production shocks were accompanied by significant market disruptions. The national average retail price of Grade A large eggs rose from $1.93 per dozen in January 2022, before the onset of the outbreak, to $4.82 per dozen in January 2023, reflecting the sharp contraction in supply caused by widespread flock losses and the biological production lags that delay recovery after depopulation (USDA-ERS, 2023; Mitchell, Thompson, and Malone, 2024). Although prices eased slightly in the months that followed, they remained elevated at around $4.15 per dozen by December 2024, suggesting that supply conditions had yet to fully normalize (USDA-ERS, 2024). Similar pressure was observed upstream: Midwest wholesale quotations for large, white, shell eggs delivered to warehouses in the major Midwest production region increased to $7.81 per dozen in the week of February 14, 2025, compared with $3.21 per dozen in the week of February 16, 2024, indicating continued tightness in monitored terminal markets (USDA-AMS, 2024, 2025).

Media reporting often focused on the escalating prices and offered a view of how price volatility manifested at the consumer level. For example, Reuters noted that average retail prices reached $4.95 per dozen in January 2025, with some urban markets, such as Chicago, seeing spikes as high as $8–$10 per dozen, while wholesale prices were simultaneously setting new records (Polansek and Douglas, 2025). CBS reported instances of retailers limiting customer purchases in response to tightening availability (CBS News, 2025).

We argue that the disruptions caused by HPAI are not simply the result of the biological nature of the virus but are amplified by structural and institutional features embedded within the supply chain itself. Decades of consolidation and efficiency-oriented investment have produced a system that is exceptionally good at supplying large volumes of affordable eggs. Yet that same efficiency has come at the cost of flexibility, allowing localized outbreaks to cascade into a broader market crisis when major disease outbreaks occur.

To understand why some systems bend while others break, we draw on systems theory, supply chain resilience literature, and lessons from both the 2014–2015 and 2022–2025 HPAI outbreaks. The goal is not to evaluate or critique the industry's efficiency, but to explore factors that unintentionally magnify risk and to suggest policy options that may increase system resilience while still preserving economic efficiencies.

Structural Fragility

Vulnerability to disease outbreaks in the food sector is often framed narrowly as a technical or epidemiological issue. Yet, vulnerability lies not only in the biology of the disease, but also in the interconnections that bind the system together. Supply chain fragility arises when a system cannot absorb or adapt to disruption while maintaining its essential functions (Christopher and Peck, 2004), a view echoed by resilience theory (Walker et al., 2004; Tendall et al., 2015). The question, then, is not simply whether the system can prevent a shock but whether it can endure one without unraveling. Cascade risk is a central concept in evaluating fragility; it refers to the phenomenon in which a failure in one part of a tightly coupled system triggers a chain of failures elsewhere, amplifying the original disruption (Pescaroli, Suppasri, and Galbusera, 2024; Zhu et al., 2025). Tightly coupled systems are inherently prone to cascade risk, as sequential and interdependent tasks leave minimal room for local adaptation or autonomous decision making.

Yet, maximizing economic efficiency often leads to highly integrated supply chains and geographic clustering (Shambaugh et al., 2018). While full-capacity production, minimal surplus inventory, and reliance on a narrow set of suppliers reduce costs, they also leave little room to recover from an interruption. A disruption in one node, such as a disease outbreak or transportation halt, can spread rapidly across the network. Systems engineered for maximum efficiency tend to become brittle under crisis or unexpected conditions (Holling, 2001). In systems theory, high-density geographic clustering reduces the "modularity" of the network, or the ability to isolate and contain shocks before they spread. When all the pieces of a network are tightly bound together, a local outbreak ceases to be local.

Organizational structures and policies that once offered a comparative advantage can unintentionally introduce fragility (Rotz and Fraser, 2015; Li et al., 2025). For example, contracts that standardize pricing and delivery under stable conditions can limit adaptive capacity in crises when supply chains need to adjust operations quickly (Leibler, Otte, and Silbergeld, 2008). A single bottleneck, whether a temporary labor shortage, equipment malfunction, or localized disease outbreak, can ripple outward, affecting production schedules, transportation logistics, and ultimately retail availability. These structural characteristics make disruptions disproportionately

impactful, highlighting that operational efficiency alone cannot safeguard against systemic risk. Likewise, while improved digital tools enhance coordination within a supply chain, technology alone does not make a system resilient. Digitalization strengthens performance only when combined with adaptive capacity and recovery mechanisms (Zhao, Hong, and Lau, 2023). Tools such as dashboards and automated alerts are useful only if decision makers can respond and act flexibly.

Fallback options and diversified sourcing strategies are critical for supply chain and market recovery during a crisis (Mishra and Jha, 2024). Trade-offs between efficiency and fragility illustrate a fundamental tension in supply chain design (Lucker, Timonina-Farkas, and Seifert, 2025). Ultimately, resilience is not just about eliminating risk but also about organizing interconnections so that failure in one part of the system does not collapse the whole. Building redundancy and taking preemptive actions in a supply chain, once dismissed as inefficient, can function as insurance for resilience in an era of disruption.

This dynamic has been widely examined in supply chain and systems research. A growing body of literature shows that efficiency-oriented designs often trade long-term robustness for short-term cost savings (Hohenstein et al., 2015; van Staveren, 2023). Investments in resilience, such as inventory buffers or supplier diversification, frequently reduce measurable efficiency (Berendes et al., 2025), even as lean optimization strategies tend to limit adaptive capacity under stress (Markolf et al., 2022). Resilience-enhancing strategies, including fallback systems and modular logistics, can improve disruption response but often come at the cost of short-run performance in tightly synchronized systems (Ivanov and Dolgui, 2020).

Supply Chain Organization in the U.S. Egg Sector

The U.S. egg industry offers a clear illustration of the trade-off between efficiency and resilience: a sector engineered for speed, scale, and cost minimization that is increasingly exposed to systemic disease risk. Tight vertical integration and geographic concentration have long characterized the industry (Martinez, 2002). A small number of vertically integrated firms manage nearly every stage of production. In 2023, Cal-Maine Foods and Rose Acre Farms alone accounted for 13.8% and 7.9% of U.S. table-egg layers, with approximately 44.5 million and 25.5 million hens, respectively (USDA-NASS, 2023; Dawson, 2024). Their operations extend from pullet rearing and feed manufacturing to egg processing, packaging, and nationwide distribution. This structure delivers substantial efficiency gains through economies of scale, tight coordination, and standardized biosecurity, keeping unit costs low under normal operating conditions.

However, the same features that enhance efficiency also limit flexibility when disruptions occur. Highly integrated operations reduce modularity, making it difficult to isolate risks without affecting the entire network. HPAI outbreaks have exposed this fragility (Mitchell, Thompson, and Malone, 2024). Entire vertically integrated supply chains were idled not because all facilities were infected but because biosecurity protocols required shutting down interconnected components across the system. Even the largest integrators were unable to fully insulate their operations despite extensive in-house veterinary, compliance, and logistics capacity. In tightly coupled systems,

shocks propagate rapidly through shared infrastructure and contractual linkages, transforming localized disease events into systemwide disruptions.

Contractual arrangements within the U.S. egg supply chain designed to maximize economic efficiency can exacerbate fragility. Fixed-volume, fixed-price contracts between the wholesale and retail stages provide stability under predictable conditions but restrict adaptive responses during crises. When flock losses occur, producers may be unable to meet contractual volumes, triggering financial penalties, strained buyer relationships, and logistical breakdowns. Independent producers, even when geographically distant from outbreaks, often lack the scale, certifications, or contractual access needed to replace lost supply. Similarly, just-in-time logistics systems minimize inventory holding costs and improve efficiency in stable periods, but they leave little room for rerouting or scaling when disruptions arise. Thin buffers, limited transportation alternatives, and tightly synchronized schedules erode shock-absorbing capacity, increasing the likelihood of cascading failures (Gereffi, 2020; Mu, van Asselt, and van der Fels-Klerx, 2021).

Automation and digital systems are used within vertically integrated supply chains but leave little room for industry-wide coordination and are not designed for adaptive response. Large integrators have invested heavily in proprietary automation, inventory tracking, and centralized control systems to enhance efficiency and coordination (Martinez, 2002). Yet these technologies introduce new dependencies on specialized labor, software, and technical infrastructure. Equipment malfunctions or personnel shortages can halt entire production lines, particularly in facilities without redundancy or manual fallback systems. Automation is less prevalent among midsized producers, where cost and technical complexity limit access to integrated platforms (Caputo et al., 2023). While some smaller firms may adjust operations more nimbly at the farm level, their adaptive capacity rarely extends across the broader supply chain.

Spatial organization further amplifies systemic risk. U.S. poultry production is heavily concentrated in the Midwest. In 2024, three states—Iowa, Ohio, and Indiana—accounted for roughly 32% of the national flock (USDA-NASS, 2025). This clustering emerged for sound economic reasons, including proximity to corn and soybean feed supplies, established transportation corridors, and dense producer networks (MacDonald, Dong, and Fuglie, 2023). Yet this spatial efficiency has proven fragile under disease pressure. During the 2014–2015 HPAI outbreak, Iowa alone lost more than 30 million birds, nearly 70% of national losses (USDA-APHIS, 2016). What began as a regional shock quickly rippled through national markets, ultimately affecting over 48 million birds (Greene, 2015). Subsequent analyses confirmed that geographic concentration magnified these impacts, as localized depopulation cascaded into national supply shortages and price spikes (Ramos, MacLachlan, and Melton, 2017). Similar patterns re-emerged during the 2022–2025 outbreak, with the densest production regions again experiencing the earliest and most severe losses (Biondo, 2025).

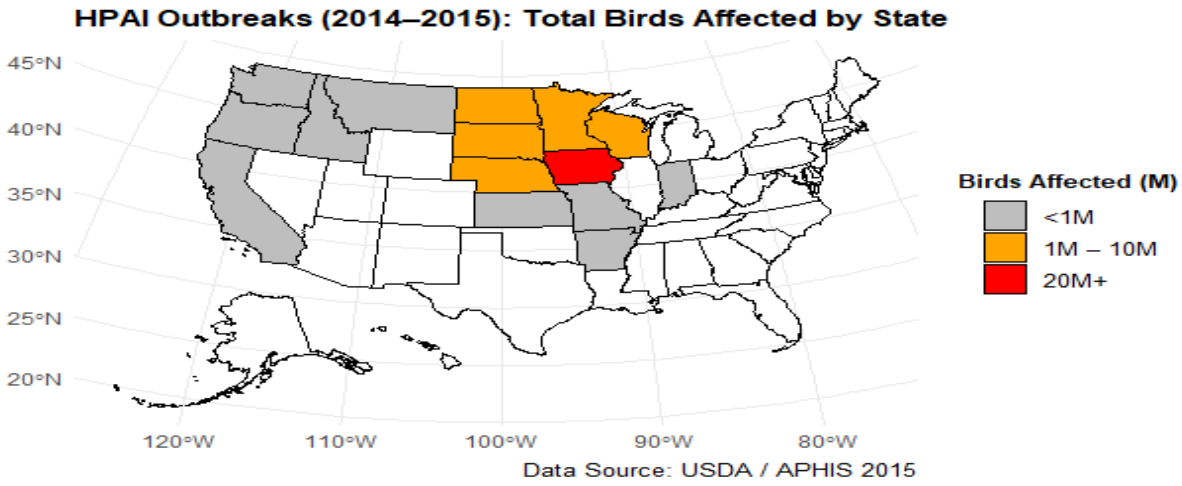


Figure 1. Geographic Distribution of Bird Losses during the 2014–2015 HPAI Outbreak in the United States

Clustering across poultry species heightens cascade risk. In states such as Iowa and Minnesota, layer farms are often located near turkey and broiler operations, increasing opportunities for cross-species transmission. Mixed-species proximity can sustain viral circulation and prolong outbreaks (Torremorell et al., 2016). Shared service providers, including feed mills, manure haulers, equipment suppliers, and contract labor crews, create additional organizational linkages that function as hidden transmission pathways. Reviews of the 2014–2015 outbreak found that shared equipment, vehicle movement, and personnel contacts materially contributed to farm-to-farm spread (USDA-APHIS, 2016). Although wild birds were identified as primary carriers during the 2022–2025 outbreak, lapses in biosecurity and equipment handling played a role in amplification (Patyk et al., 2023).

High-density production can constrain response logistics once outbreaks occur. In heavily affected regions, depopulation crews, composting capacity, and carcass disposal sites are often limited. During the 2014–2015 outbreak, these constraints delayed culling and disposal in several counties, prolonging viral circulation and compounding economic losses (USDA-APHIS, 2016). The result is a recurring feedback loop: the same density that improves efficiency during normal operations generates congestion and bottlenecks during crisis response.

Finally, demand-side conditions magnify the consequences of supply-side fragility. Eggs are a household staple with relatively stable demand, meaning supply disruptions translate quickly into price volatility. Panic buying and retailer adjustments can amplify price volatility further (Bakhtavoryan et al., 2021; Zamani, Bittmann, and Ortega, 2024). USDA and BLS data show sharp increases in national average egg prices during both the 2014–2015 and 2022–2025 HPAI outbreaks, closely tracking periods of large-scale depopulation and production loss (see Figure 2).

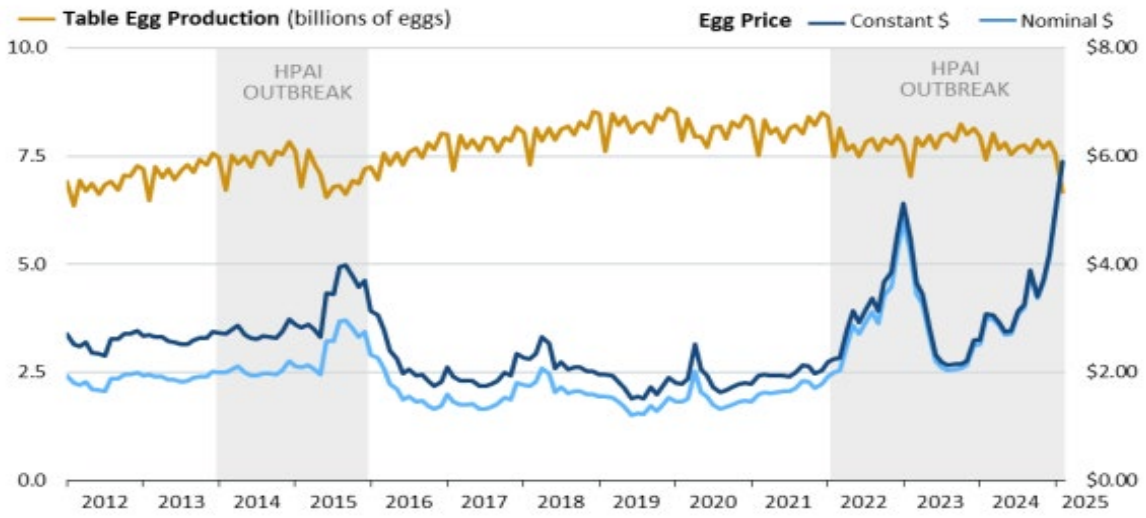


Figure 2. U.S. Table Egg Production and Retail Prices, 2012–2025
Source: Biondo (2025)

Poultry Health Governance in the United States

Poultry health governance in the United States is organized around a policy framework that combines preventive measures, such as biosecurity standards, disease surveillance, and certification programs, with reactive outbreak response tools, including depopulation, movement controls, and indemnity payments (USDA-APHIS, 2015). Federal oversight is led by USDA-APHIS in coordination with state animal health authorities and industry actors. This framework has evolved through repeated disease shocks and reflects both the biological realities of poultry production and the institutional structure of U.S. animal health governance. While the system has been effective at limiting catastrophic collapse during major HPAI events, it remains heavily oriented toward managing outbreaks after detection rather than preventing localized shocks from escalating into systemwide disruptions.

The National Poultry Improvement Plan (NPIP) is central to existing **preemptive measures**, providing standardized testing, monitoring, and biosecurity certification that underpins interstate and international poultry trade (USDA-APHIS, n.d.; USDA-APHIS, 2016). These efforts are complemented by federal and state surveillance programs that monitor commercial flocks, backyard poultry, and wildlife reservoirs, reflecting long-standing recognition of migratory pathways as persistent sources of HPAI risk.

Despite this foundation, preventive capacity is unevenly distributed across the production landscape. Participation in NPIP and compliance with enhanced biosecurity and reporting requirements are closely tied to firm size, vertical integration, and access to veterinary and administrative resources. Large, vertically integrated operations typically possess the infrastructure needed to comply continuously with surveillance and documentation standards,

whereas small and mid-scale producers, including independent growers and regional suppliers, often face financial, informational, and administrative barriers (Leibler, Otte, and Silbergeld, 2008; GAO, 2017). These disparities create gaps in surveillance coverage and preparedness, limiting the ability of preventive instruments to operate uniformly across a highly concentrated and tightly coordinated industry.

Once disease is detected, governance shifts decisively toward a **reactive response**. USDA-APHIS and state partners implement movement restrictions, depopulation orders, disposal protocols, and emergency biosecurity measures to contain spread and stabilize markets (USDA-APHIS, 2016). Indemnity and compensation mechanisms are intended to support compliance with these measures, but access is conditioned on extensive documentation, verified flock inventories, and proof of biosecurity compliance under VS Guidance 8603.2 (USDA-APHIS, 2023). In December 2024, APHIS further strengthened these requirements by conditioning indemnity payments and restocking approvals on verified biosecurity audits under the Secure Poultry Supply Plan (USDA-APHIS, 2024). While large operations routinely manage these requirements with dedicated compliance staff, smaller producers often experience delays that complicate recovery and, in some cases, force permanent exit from production.

Reviews of past outbreaks have also documented coordination challenges between federal and state agencies and weaknesses in emergency logistics, including deficiencies in the National Veterinary Stockpile (GAO, 2017; USDA-OIG, 2020). These governance frictions are not merely administrative; they directly affect the speed, consistency, and effectiveness of outbreak response in highly integrated supply chains, where delays or uncertainty can amplify both economic and epidemiological impacts (Kalaitzandonakes and Ridley, 2025).

Preemptive Policy Options

As recent outbreaks demonstrate, existing baseline prevention and response measures have not prevented localized shocks from cascading through tightly coupled supply chains. Resilience increasingly depends on policies that act before exposure or at the point of exposure (i.e., preemptive), rather than after outbreak detection (i.e., reactive). Preemptive policy approaches differ from baseline prevention in that they are designed to anticipate failure and reduce the likelihood that localized disease events escalate into systemwide disruption. These measures seek to preserve production continuity while maintaining disease control. Such approaches have been implemented in varying forms in other poultry-producing countries and are now under active consideration in the United States (Swayne, 2024). The following sections examine four preemptive policy options and assess their relevance within the structural constraints of the U.S. poultry sector.

Vaccination As a Risk Mitigation Strategy

Vaccination is a core disease-control tool in animal health, designed to reduce susceptibility, viral shedding, and onward transmission within and between hosts. In the context of HPAI, vaccination does not eliminate the risk of viral introduction from wildlife reservoirs, but it can lower outbreak

intensity, shorten transmission chains, and reduce the scale of depopulation required once exposure occurs. Despite its widespread use in many livestock systems globally, vaccination against HPAI has historically been approached with caution in the United States (Cohen, 2023), largely based on operational and governance concerns.

Large-scale vaccination programs require coordinated deployment, repeated administration, and continuous monitoring, all of which increase labor demand and program complexity. In addition, vaccine performance can vary across poultry species and production systems, and effectiveness depends on the match between vaccine strains and circulating viruses. Recent advances in vaccine technology have substantially improved performance against contemporary HPAI strains. However, protection duration and immune response vary by species, production stage, and vaccine platform, making adaptive program design essential. These challenges underscore the need for vaccination strategies that are tightly integrated with surveillance and biosecurity rather than implemented as standalone interventions. Rising economic losses from repeated outbreaks, improvements in vaccine design, and growing awareness of zoonotic spillovers have renewed policy interest in vaccination as part of a broader risk-management portfolio (Ison and Marrazzo, 2024).

These biological realities reinforce a key lesson from prior experience: vaccines are only as effective as the institutional systems that deploy, monitor, and calibrate them. Early national vaccination efforts in Egypt reduced clinical disease but struggled with antigenic mismatch and limited monitoring capacity, allowing the virus to persist in backyard and rural production systems (Peyre et al., 2009). By contrast, Vietnam achieved more durable control by pairing vaccination with routine surveillance and systematic program adjustment in response to outbreak feedback (Tran et al., 2016). Vaccination outcomes can depend less on the act of immunization itself than on how it is embedded within governance, surveillance, and response frameworks.

More recent evidence comes from the 2023–2024 HPAI vaccination campaign targeting domestic ducks in France. A nationwide program was implemented to combine mass vaccination with enhanced epidemiological surveillance. As shown in Figure 3, poultry outbreaks declined sharply immediately after the campaign's launch in October 2023 (Panel A), even as detections of HPAI in wild birds remained high throughout the same period (Panel B). Observed poultry outbreaks fell far below levels predicted by models calibrated on historical wild-bird and poultry data (Panel C), suggesting that vaccination effectively disrupted transmission within domestic flocks. France experienced substantially fewer outbreaks than neighboring non-vaccinating countries facing similar ecological conditions during the same season (Panel D) (Guinat et al., 2025). These patterns indicate that vaccination can decouple exposure from outbreak escalation when deployed at scale and supported by surveillance.

The French experience does not imply that vaccination eliminates HPAI risk, but it demonstrates how immunological barriers can limit repeated introductions from cascading into widespread production losses. For U.S. policy makers, the relevance lies not in replicating any single national model, but in recognizing vaccination as a preemptive tool that can limit the magnitude and

persistence of outbreaks. Vaccination complements existing biosecurity and response measures by reducing systemic vulnerability rather than replacing established controls.

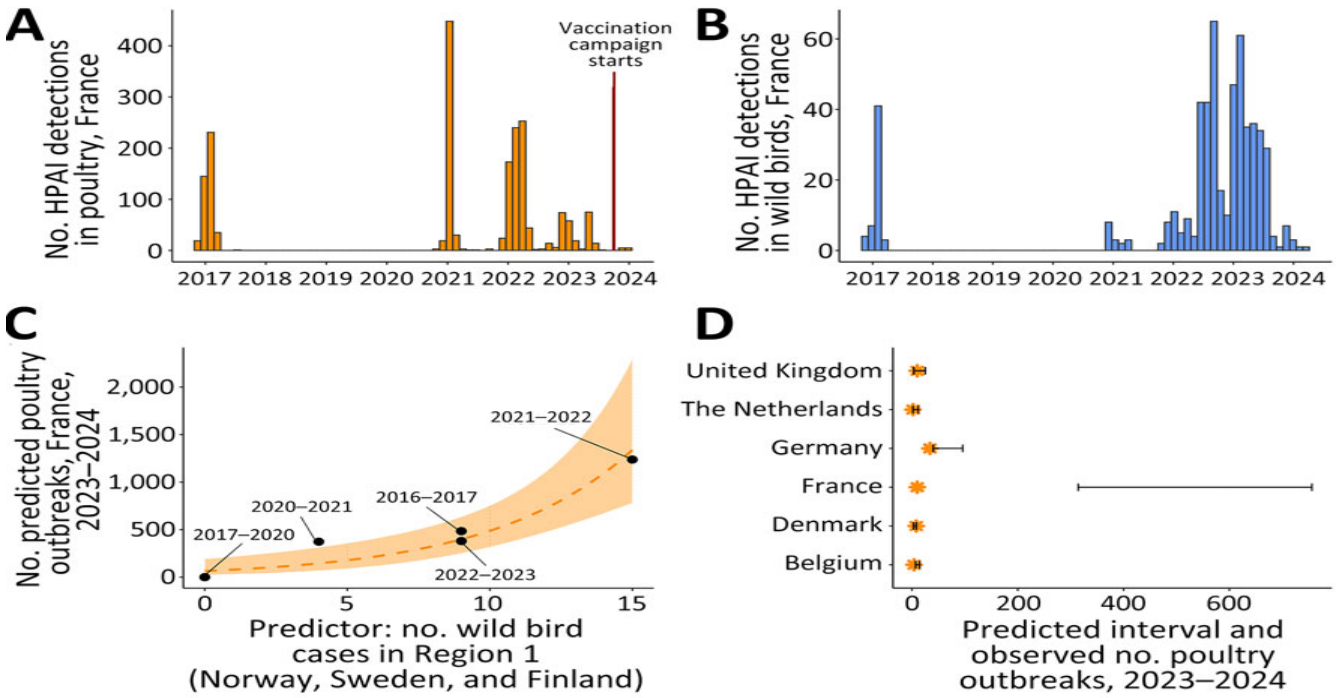


Figure 3. Outcomes of France's 2023–2024 HPAI Vaccination Campaign
Source: Guinat et al. (2025)

(A) Sharp decline in poultry outbreaks after vaccination.
(B) Wild bird cases remained high, indicating ongoing exposure.
(C) France's outbreak count fell well below model predictions based on regional wild bird data.
(D) France outperformed five non-vaccinating countries in outbreak reduction.

Compartmentalization and Supply Chain Continuity

Compartmentalization refers to animal health governance that defines disease-free status not by geography, but by how production systems are organized and managed. Recognized by the World Organization for Animal Health, a compartment is an epidemiologically distinct production unit that operates under a common set of biosecurity, surveillance, and traceability standards, allowing it to maintain continuity even when outbreaks occur elsewhere (WOAH, 2024). If disease risk is generated through management practices and network connections, then control measures should reflect those realities rather than rely solely on spatial boundaries (WOAH, 2000).

In theory, compartmentalization offers a way out of the all-or-nothing response that characterized early HPAI control efforts. Instead of shutting down entire regions or supply chains when infection is detected, certified compartments can continue operating under heightened monitoring, limiting

unnecessary disruption. This practice is particularly appealing in highly integrated food systems, where blanket movement restrictions can trigger cascading failures far beyond the original outbreak site.

European experience highlights both the promise and the limits of this approach. During recent HPAI outbreaks, France paired vaccination with compartment-based trade arrangements within the EU, allowing certified units to maintain market access despite widespread infection pressure (Guinat et al., 2025). These outcomes were not the product of compartmentalization alone, but of sustained investment in surveillance, regulatory coordination, and trust between public authorities and industry. Replicating such arrangements in the United States would require confronting long-standing fragmentation across federal and state jurisdictions, as well as uneven capacity among producers.

In early 2024, United Egg Producers endorsed the creation of pilot vaccination zones in high-risk states, implicitly raising questions about whether compartment-like structures could reduce reliance on mass depopulation in a consolidated but geographically dispersed system (United Egg Producers, 2024). These proposals do not yet amount to a coherent compartmentalization framework, but they reflect growing interest in alternatives to geographically indiscriminate shutdowns as outbreaks become more frequent.

Rather than a standalone policy, compartmentalization should be understood as a selective tool for managing spillovers in tightly coupled systems. Its value lies not in preventing exposure outright, but in limiting how far disruption spreads once exposure occurs. Whether it ultimately strengthens resilience in the U.S. poultry sector will depend less on formal recognition than on how deliberately it is designed to work within and across existing supply chains.

Surveillance Systems

Early detection and sustained monitoring are central to preemptive disease governance because they determine whether outbreaks remain localized or cascade through tightly coupled production systems. Surveillance platforms enhance resilience not by eliminating risk, but by enabling timely coordination, targeted containment, and informed fallback decisions. When embedded within governance frameworks that link diagnostics to compartmentalization, compensation, and movement controls, surveillance becomes a preemptive instrument rather than a purely reactive one. Surveillance systems can also underpin reactive policies once outbreaks occur, enabling movement controls and depopulation measures to function as coordinated interventions rather than isolated responses. In vaccinated populations, surveillance capacity becomes especially critical, as diagnostic systems must distinguish vaccine-induced immunity from active infection to preserve epidemiological visibility (DVFA, 2022).

A recent global expert review emphasized that vaccination against HPAI is only effective when paired with robust, science-based surveillance systems capable of detecting virus circulation in vaccinated flocks (Sajjadi et al., 2025). Surveillance system performance depends on coordinated reporting across producers, laboratories, and regulatory authorities (Hoinville et al., 2013). In

practice, surveillance data are often distributed across multiple organizational and regulatory actors, and their usefulness depends on whether reporting systems allow diagnostic findings to be rapidly translated into operational awareness and intervention (Meidenbauer, 2017).

In the United States, surveillance capacity remains unevenly distributed across firms and jurisdictions. Access to diagnostic tools, reporting platforms, and real-time data sharing varies widely, and proprietary systems often operate in silos, delaying detection and complicating a coordinated response (Meidenbauer, 2017). These gaps limit the ability of surveillance to function as a systemwide early warning mechanism, particularly in a highly consolidated industry where delays in one segment can rapidly propagate through national supply chains.

Comparative experience demonstrates that surveillance effectiveness depends less on the volume of data collected than on institutional integration. European animal health governance emphasizes interoperable databases, standardized alert thresholds, and clear reporting hierarchies, reducing coordination delays during transboundary livestock emergencies (EC, 2021; EC, 2025). In the Netherlands, surveillance operates under One Health principles that integrate veterinary, environmental, and public health actors within a unified national framework (Royal GD, n.d.; WOAH, 2000). As a result, an estimated 98% of poultry outbreaks are detected through active surveillance rather than passive reporting, substantially improving response speed and containment effectiveness (Vredenberg et al., 2025).

Surveillance platforms also enable differentiated and less disruptive response strategies. Tools such as digital animal identification, movement tracking, and geofencing support risk-based interventions that prioritize high-transmission nodes rather than relying on blanket depopulation (te Beest et al., 2011). In this way, surveillance creates functional redundancy by preserving operational flexibility and allowing production continuity in lower-risk segments, even during periods of elevated disease pressure.

Recent U.S. policy developments indicate growing recognition of these principles. Updated USDA-APHIS surveillance guidance for poultry shipments, effective August 2025, strengthens premovement testing requirements by introducing short isolation periods and tighter testing timelines prior to slaughter. These measures aim to reduce the risk of moving infected but asymptomatic birds, particularly from states outside designated control zones, and to align indemnity eligibility with verified surveillance compliance (Fairman, 2025). While these updates do not constitute a fully integrated national surveillance platform, they signal a shift toward more proactive, risk-based monitoring consistent with international best practices.

Small and Mid-Scale Producer Support

Strengthening poultry biosecurity requires active participation from producers of every size. In practice, policy options are inseparable from questions of who can realistically participate. While the U.S. egg sector is concentrated among larger operations, thousands of small and mid-scale farms remain essential to rural livelihoods and local food networks. Enhancing long-term system resilience will depend on the ability of all producers to meet the new standards. Smaller operations

often exist at the edges of official surveillance systems, creating epidemiological "blind spots" where HPAI can circulate undetected (Otte et al., 2007). Effective national preparedness must therefore ensure that no segment of the production chain is left out of early warning and response systems.

In the United States, flocks with more than 30,000 birds account for approximately 80% of all laying hens nationwide (USDA-NASS, 2025). While the majority of production is concentrated in these large operations, almost 20% remain in smaller flocks. Simplified indemnity claim forms, mobile-friendly reporting systems, and smallholder response funds could make participation easier for these producers. Cooperative models could further strengthen resilience by allowing farms to share diagnostic costs, coordinate vaccination efforts, and access veterinary extension services that would otherwise be unaffordable individually.

Several states have pioneered outreach initiatives aimed specifically at small and noncommercial poultry keepers. The University of Minnesota Extension, for example, provides bilingual biosecurity workshops and easy-to-use resources for small flock owners (University of Minnesota Extension, 2023). In California, the Department of Food and Agriculture (CDFA) and the California Animal Health and Food Safety Laboratory (CAHFS) jointly operate programs such as Backyard Biosecurity for Poultry and Necropsy Services for Backyard Poultry Owners. These programs provide free or low-cost diagnostic testing, educational materials, and practical tools to improve on-farm biosecurity (CDFA, n.d.; CAHFS, 2024). Such initiatives demonstrate that accessibility and trust, not merely enforcement, are key to achieving broad compliance.

International experience reinforces this lesson. Denmark maintains one of Europe's most comprehensive surveillance systems, requiring all holdings with more than 100 birds to participate in risk-based testing. This mandate is coupled with support for compliance, including mobile veterinary training units and public funding for essential biosecurity improvements (DVFA, 2022). France and the Netherlands also extend targeted support and training for smallholders, while the European Food Safety Authority continues to promote cooperative models that combine technical and financial assistance for backyard producers (EFSA, 2023). These programs recognize that risk mitigation succeeds only when the smallest producers are equipped to meet standards that are practical and proportional to their capacity.

Conclusions

The extent of HPAI impact on U.S. egg markets cannot be explained by biology alone. The way an industry is organized plays a defining role in how far and fast economic and physical disruptions spread. Recurrent HPAI outbreaks have exposed systemic fragility in the U.S. egg sector and have shown that the system is calibrated for maximal efficiency under normal conditions but becomes acutely fragile in the face of shock. Tight supply chains, geographically concentrated production, and limited inclusion of smaller flocks have created a system that is highly efficient but brittle in times of crisis. The consequences of failure extend far beyond the farm, affecting prices, supply chains, and public confidence.

Ultimately, resilience is not only about eliminating risk but also about how interconnections are organized. Systems designed for speed and tight coordination perform well under stable conditions, but when shocks occur, those same linkages allow disruptions to spread rapidly. As shown earlier, digital tools and automation can improve visibility and coordination, yet they do not, on their own, prevent cascading failure. In this sense, redundancy and optionality are not signs of inefficiency, but structural features that determine whether disruptions remain localized or escalate into systemwide crises.

The revealed weaknesses, however, are not inevitable and may be, at least partially, mitigated through a broader national policy approach that shifts from a predominantly reactive stance to one that expands preventive capacity. The scale and persistence of HPAI outbreaks indicate a need to expand preemptive policies along with reactive containment strategies to manage and respond to disease risk. Regulatory adjustments have signaled a shift toward stronger preventive accountability. Comparative lessons from global markets offer examples of how coordinated, inclusive, and evidence-based strategies might help mitigate epidemic risks. Maintaining economic efficiency that supports low pricing in the egg sector is critical for consumers. But unintended consequences of system fragility suggest a balance is needed. Building on world-class scientific expertise, technological capacity, and institutional reach, policy adjustments could blend preemptive and reactive policies to make disease control less destructive, while still preserving efficiencies and market access.

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Profitability of On-Farm Cold Storage in the New Mexico Pecan Industry

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Abstract

Pecan producers face limited pricing power in traditional markets and must explore tools to reduce costs or capture added revenue. This study evaluates the feasibility of on-farm cold storage as a capital investment strategy in New Mexico. A 30-year financial model was developed, considering construction, equipment and operating expenses, with revenues estimated from seasonal price differentials and quarantine cost avoidance to assess key return measures. Findings highlight net present values ranging from -$2.5 million to $1.2 million, depending on selling strategy. While on-farm cold storage offers potential for greater control and profitability, outcomes are highly sensitive to price volatility, introducing vulnerability to year-to-year cash flows.

Keywords: cold storage, farm profitability, marketing strategies, New Mexico agriculture, on-farm investment, pecans, value-added agriculture

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Introduction

Pecans are an important specialty crop grown in many southern states. Leading pecan-producing states include Georgia, New Mexico, Arizona, Texas, and Oklahoma. New Mexico's 2021 pecan production of 78.7 million pounds accounted for approximately one-third (30.8%) of the total U.S. production, behind Georgia's 88.6 million. Pecans represented 25% of the state's total crop revenue, with $190 million in cash receipts in 2021.

Traditionally, southwestern producers have sold in-shell pecans in late fall or early winter. They rely on other supply chain participants to process the nuts and market them. Some producers, often larger operations, have expanded into downstream activities such as cleaning and shelling. One hesitation for producers in exploring options to expand downstream in the supply chain may be related to the fact that pecans require cold storage to maintain quality.

Pecans contain high levels of unsaturated oils that can easily go rancid. As such, pecans require cold storage to maintain quality. Without cold storage, in-shell pecan storage life is only several months (e.g., four months if stored at 70 °F). When stored at colder temperatures, the storage life increased dramatically. For example, in-shell storage life is estimated to be between 2 and 5 years when stored at 0 °F (Byford, 2005). Traditionally, pecan storage has been the responsibility of downstream supply chain participants (e.g., processors).

Purpose

This report explores the financial feasibility of cold storage capacity deployed at the farm level to support extended pecan marketing strategies in New Mexico. The analysis is framed around a representative cold storage facility that could be owned and operated by a single large producer or jointly utilized by multiple producers through coordinated arrangements. In either case, the economic drivers of feasibility are storage capacity utilization, marketing timing, and exposure to seasonal price volatility, rather than the ownership structure alone.

Potential benefits of on-farm or coordinated cold storage include greater marketing flexibility, the ability to target sales opportunities outside the traditional harvest window, and, in quarantine areas, avoidance of third-party cold storage costs required for regulatory compliance. At the same time, the investment introduces substantial fixed capital requirements and increases exposure to inter-year price variability, making capital constraints and risk-sharing central considerations in assessing the practicality of such investments.

Background

Pecan Cold Storage

As indicated earlier, pecans are high in unsaturated fats, a trait responsible for their distinct flavor and health benefits. While pecans' high oil content offers benefits and contributes to their desirability, it also makes them vulnerable to deterioration from heat and oxidation. The storage

life of pecans before shelling, or "in-shell," can be extended from approximately 4 months when stored at 70 °F to 5 years if frozen at 0 °F (Byford, 2005). Some estimates suggest that the extension could even be greater (e.g., up to 8 years) (Picha, 2015). Regardless of the maximum storage life, the seasonal nature of pecan yields requires stabilization via cold storage to ensure a profitable and steady supply of pecans year-round.

Current Pecan Cold Storage Practices

Pecans are typically harvested and transported from the producers to centralized buyers while still in the shell. The nuts are then stored and shelled throughout the remainder of the year. Distributors, manufacturers, and exporters buy pecans throughout the year, either shelled or in-shell, for further distribution, processing, and sale to end users. Some growers may use forward contracting with their respective supply chain partners, thus locking in a price before harvest (Florkowski and Hubbard, 1994; Lillywhite, 2003).

The seasonal inventory cycle generally peaks during late winter or early spring, after which withdrawals pull the inventory down to a low in the fall. The pattern observed is consistent over time, with the same pattern observed over many years.

Pecan Marketing Structure and Price Reporting Limitations

The U.S. pecan industry is characterized by a relatively large number of producers and a comparatively small number of downstream shellers, processors, and exporters. While no comprehensive national dataset exists documenting exact counts, available evidence suggests that pecan production is distributed across several thousand farms nationwide (USDA-NASS, 2020). Industry directories and secondary sources indicate that approximately 35 to 45 pecan shelling operations are active nationally, depending on classification and data source (American Pecan Council, 2024).

This asymmetry between widespread production and more concentrated downstream handling shapes price discovery in the pecan market. Prices are commonly determined through private negotiation, including forward contracting and inventory-based purchasing by downstream firms, rather than through transparent spot markets. Shellers and large buyers typically acquire substantial volumes during the harvest period and manage inventories throughout the year to supply domestic and export demand as it arises.

This market structure contributes to the limited availability of publicly reported domestic monthly pecan prices, particularly outside primary harvest and holiday marketing windows. In contrast, export quantities and values are consistently reported through USDA's Foreign Agricultural Service (USDA-FAS), making export prices one of the few sources of monthly pecan price information. Given that exports account for a substantial share of U.S. pecan production and that domestic and export prices exhibit moderate correlation on an annual basis, export value seasonality is used in this analysis as a proxy for potential domestic seasonal price movements. This approach is applied with caution, recognizing that monthly domestic price behavior may

differ in magnitude and timing from export markets. Additional discussion of how these market dynamics relate to observed pricing behavior is provided below.

Potential Benefits of On-Farm Cold Storage

The analysis described in this report accounted for two potential benefits or revenue streams associated with on-farm cold storage—potential seasonal price differentials and reducing or eliminating quarantine costs.

Seasonal Price Differentials

Many agricultural commodities exhibit seasonal price variation as the market responds to supply and demand factors. Pecans in the Southwest are harvested in late fall and early winter. During and shortly after this period, many pecans enter the supply chain. On the demand side, domestic consumers tend to buy more pecans and pecan-containing products during the winter holiday (Capps, Goodwin, and Burns, 2022). These supply and demand forces result in natural seasonal price fluctuations. Unfortunately, little seasonal pecan price data are publicly available for domestic markets.

While monthly prices for domestic pecans are limited, monthly prices for pecan exports are available through the USDA Foreign Agricultural Service (FAS) Global Agricultural Trade System (GATS) database. Using export value and quantity, prices for exported pecans can be approximated. A seasonal price index for pecan exports, based on data from January 1989 through November 2023, indicates that average monthly export prices have historically risen by more than 19% between a typical low point in March and a high point in September over the 35-year period. In more recent years, export prices have generally been lower during mid-to-late winter and have tended to peak in December.

Export and Domestic Pecan Markets

While monthly prices for domestic pecan markets are unavailable, monthly export values may serve as a potential proxy, as exports make up a large portion of U.S. production, and annual prices in domestic and export markets are both available and correlated.

Table 1 presents U.S. pecan production and export quantities over the last 15 years and associated exports. In the previous 15 years, almost one-half of pecans produced in the United States have been exported, ranging from a low of 30% in 2022 to a high of 59% in 2018. As exports make up a large percentage of domestic production, it is reasonable to assume that the export market significantly impacts the domestic market and domestic prices.

Table 1. U.S. Domestic Pecan Production and Exports

Year	Pecans Produced (lbs.)	Quantity Exported (lbs.)	Percent Exported
2008	202,080,000	115,488,578	57%
2009	302,020,000	107,683,782	36%
2010	293,740,000	101,721,387	35%
2011	269,700,000	104,640,304	39%
2012	302,300,000	151,731,649	50%
2013	266,330,000	121,344,489	46%
2014	264,150,000	151,939,544	58%
2015	254,290,000	148,002,314	58%
2016	268,770,000	138,167,063	51%
2017	304,850,000	170,948,660	56%
2018	240,930,000	141,103,617	59%
2019	255,600,000	138,379,588	54%
2020	304,050,000	143,364,014	47%
2021	256,450,000	142,843,723	56%
2022	277,700,000	82,871,886	30%
Average	270,864,000	130,682,040	49%

Source: USDA-NASS, USDA-FAS

Export-Domestic Annual Price Correlation

A close relationship between annual pecan export and domestic prices per pound can be observed using data drawn from the USDA National Agricultural Statistics Service (USDA-NASS) and USDA FAS databases (USDA-FAS, 2024; USDA-NASS, 2024). Between2008 and 2022, the two price series exhibited a correlation coefficient of approximately 0.6, indicating a moderate relationship between domestic prices and export values over the past 10 to 15 years. However, this relationship appears to have weakened in more recent years (see Table 2).

Table 2. Correlation Coefficients Between Domestic and Export Prices, Various Periods

Period	Correlation Coefficient
2008–2022 (last 15 years)	0.61
2013–2022 (last 10 years)	0.57
2018–2022 (last 5 years)	-0.12

Source: USDA-NASS, USDA-FAS 2023

Analysis of price data from commodities with characteristics like pecans can help validate whether the correlation between annual and monthly domestic import and export prices is reasonable. For example, apples share several features with pecans. Both crops are seasonally harvested, both utilize cold storage, and the U.S. is a major exporter of both—approximately one-third of the U.S. apple crop is exported (Agricultural Marketing Resource Center, 2024). Importantly, monthly domestic and export prices for apples are available from 2013 to 2024.

A correlation coefficient of 0.57 is observed between these domestic and export prices for apples. When simple seasonal indexes for domestic and export prices are created, it can be observed that seasonal price fluctuations of domestic and export prices show patterns like each other, as well as seasonal fluctuations in pecan export prices. This similarity is discussed more in Appendix II Apple Price Seasonality.

Reducing Quarantine Costs

Some pecan growers in New Mexico have suffered pecan weevil infestations (*Curculio caryae*). Endemic to North America, the adults of this species emerge from the soil in late summer. After mating, the females lay their eggs in walnuts and pecans. While the shells are still soft, the insect can bore into the kernel and deposit eggs. The resulting larvae consume the nut flesh before exiting, falling to the ground, and entering a dormant state until the following monsoon restarts the cycle. An air blast sprayer is used to apply insecticides directly to the trees, targeting the weevil in the adult stage (Mulder and Grantham, 2017).

Current New Mexico Department of Agriculture protocols center on the mandatory quarantine and treatment of in-shell pecans transported from Chaves, Eddy, Lea, and Otero counties. Nuts must be frozen for seven days if below 0 °F, or 14 days at 12.2 °F, or immersed in 140 °F water for 5 minutes before shipping (21 NMAC 21.17.36). For a pecan producer, these requirements entail additional costs before the crop can be marketed. For example, the producer may need to pay for a cold storage facility to hold the crop at the required temperature and time before marketing it. Avoiding this third-party cost, a potential benefit of on-farm cold storage is included in the analysis described below.

Methodology and Assumptions

The potential financial returns associated with on-farm cold storage are estimated using a capital investment model. The model uses the assumptions described below to forecast cash flows. Cash outflows include construction and operating costs for the cold storage facility. Cash inflows include potential seasonal price differentials and quarantine-related cold storage cost savings. Projected cash flows from the model can be used to calculate the standard investment return measures, including net present value, internal rate of return, and discounted payback period.

Methodology

The capital investment model used to explore the potential benefits of on-farm pecan cold storage was developed in Microsoft Excel. As previously indicated, cash flows include benefits of potential seasonal price premiums and savings from eliminating third-party quarantine costs. Costs included various fixed and variable expenditures associated with constructing and operating the facility. All revenues and costs are assumed to remain constant over the life of the model, and prices are measured in "real" terms. Net cash flows are assumed to occur over a 30-year investment period.

Discount Rate

As the project's cash flows are projected to occur over a long period, it is important to identify an appropriate discount rate to convert future cash flows into current dollars. The discount rate is used to calculate the present value of future cash flows while accounting for the time value of money. As a rule, the discount rate should reflect the owner's cost of capital, either equity or debt, or a combination of the two. From an equity standpoint, one measure that could be used is the returns available via investment in the stock market. The average real rate of return for the S&P 500 over the last 30 years, when dividends are included, has been 6.81%.[1] Interest rates for New Mexico agriculture returns range from 7% to 9% on similar investments, depending on the precise characterization of the farm business, land type, and operational details. New Mexico State Cooperative Extension Enterprise budgets and this analysis assume 8.75%.

Measures of Return

Three measures of return are used to characterize the-investment: net present value (NPV), internal rate of return (IRR), and discounted payback period (DPP). The measures provide general insights into an investment's viability. The definition of each measure of value and its general purpose for supporting conclusions follows.

Net Present Value

The net present value, or NPV, is the sum of an investment's annual discounted net cash flows over its lifetime, in this case, 30 years. By discounting future net flows, NPV accounts for the potential returns that an investor could have earned if the same capital were invested in an alternative asset for the same period. Typically, higher values of NPV signal a favorable investment, but a positive value must be at least observed to indicate that discounted cash inflows (benefits) exceed discounted cash outflows (costs).

Internal Rate of Return

The internal rate of return, or IRR, provides a similar measure of investment return as the NPV, except that the return is measured in a percentage term. Mathematically, it uses the same formula as the NPV calculation but solves the equation for the discount rate associated with an NPV of zero. Estimated internal rates of return are compared to an individual business's cost of capital. An IRR greater than the cost of capital indicates that the investment should be undertaken.

Discounted Payback Period

The discounted payback period, or DPP, is the number of years that it will take for discounted cash flows to pay for the initial investment. Typically, lower values for DPP signal a favorable investment because the investor is expected to "make their money back" in a shorter period.

[1] Calculated using a geometric mean.

Key Assumptions

Data used to inform model assumptions were obtained from various sources, including interviews with industry members familiar with on-farm cold storage and secondary sources (e.g., published tariff rates from local utilities, equipment specifications and costs from distributors, and historical prices from public agencies). The data and corresponding model assumptions are outlined in the sections below.

Infrastructure

Infrastructure for the project includes land and the cold storage facility.

Land

The analysis assumes the cold storage facility requires 1 acre of land. The land is assumed to be in immediate proximity to commercial pecan orchards in New Mexico and near necessary utilities. The land is valued at $30,000 per acre.

Building

The assumed cold storage facility is a purpose-built, subfreezing warehouse designed to store approximately 1.15 million pounds of in-shell pecans using reusable wooden containers stacked to maximize vertical space. Facility size, container configuration, insulation, and cooling system specifications are selected to reflect commercially feasible on-farm cold storage design. Detailed engineering considerations and design assumptions are provided in Appendix I. The cold storage facility is assumed to be 2,860 square feet (52’ x 55’) with a 30’ ceiling. The building is a steel frame with 6-inch insulated walls. The insulation is composed of glass fiber sandwiched by non-porous plastic surfacing. The building is built on a 1’ concrete slab floor supported by 2’of gravel. Construction costs are estimated to equal $500,000 with a salvage value of $55,000. The model assumes that the building has a useful life of 30 years. More information about facility engineering and design considerations can be found in Appendix I.

The facility described above has an interior volume of 85,800 cubic feet, sufficient to hold 600 wooden storage containers measuring 4’ x 4’ x 4’ stacked five high in 10 rows with 12 stacks per row. Each container can hold 1,920 pounds of in-shell pecans for a maximum facility capacity of 1,152,000 pounds. The analysis assumes the building operates at full capacity continuously for 30 years. Assuming an annual average yield of 1,680 pounds per acre (USDA-NASS, 2023), the facility would support one or several farms consisting of approximately 685 acres.

Estimated Costs

Additional costs beyond land and buildings for an on-farm cold storage facility include equipment and other operating expenses, such as utility and labor costs. The key assumptions related to these costs are described below.

Equipment

A redundant, one-stage heating and air conditioning system controls the facility's climate. Two compressors are installed in parallel, each able to maintain a temperature under 0 °F by supplying two pairs of condenser and evaporator units. Using a digital controller, load cycling can be managed such that optimal cooling can be maintained while remaining below peak energy demand of 50 kW, a threshold that, if exceeded, would result in considerable energy cost increases. The total cost of the system, including installation, is assumed to be $50,000 with a salvage value of $5,000. The system's usable life is assumed to be 20 years, after which a new system will be purchased and the old system sold for the salvage value the following year.

Other equipment needed for the on-farm cold storage operation includes a forklift and wooden storage containers. A single forklift is used to stack, unstack, and load the containers. It is estimated to cost $40,000 and have a 20-year useful life with a salvage value of $4,000. The containers are assumed to cost $286 each and have a useful life of 20 years with a salvage value of $5 each. Pecans are assumed to be stored in reusable wooden storage containers for the duration of the storage period. These containers remain on-site and are used solely for internal stacking and handling within the cold storage facility. When pecans are shipped off-farm, including shipments subject to quarantine requirements, they are assumed to be transferred into industry-standard flexible intermediate bulk containers ("superbags"), consistent with prevailing commercial and regulatory practices. Costs associated with superbags used for quarantine compliance are included in the avoided third-party quarantine cost estimates described below.

Electricity

The analysis assumes that the facility can maintain subfreezing temperatures while limiting peak monthly electrical demand to 48.69 kW, slightly below the 50kW cap for small commercial customers. Going above the 50kW peak demand level would result in significantly increased costs. Annual electricity use is estimated to be 50 kWh per square foot, representing the midpoint of the industry average range of 40–60 kWh per square foot (Faramarzi, Coburn, and Sarhadian, 2002). The total annual electricity use of 143,000 kWh is averaged across calendar months, with weights assigned based on each month's average temperature. Electricity use and cost estimates are provided in Table 3.

A 7% Gross Receipts Tax (GRT) is applied to baseline monthly electricity expenditure. The GRT varies between 4.8750% and 8.9375% within New Mexico, but an expected value of 7% is used for this analysis (New Mexico Taxation and Revenue Department, 2024). A monthly service fee of $83 is also included in the calculation of monthly electricity costs. The model assumes that electricity costs cease at the time of sale (e.g., if pecans are sold in June, all electricity costs for the following months are zero).

Table 3. Assumed Monthly Electricity Use and Corresponding Cost

Month	Cost / kW	Use (kWh)	Cost / kWh	Baseline Monthly Cost	Total Monthly Cost	Cumulative Cost
January	$13.93	8,966	$0.01152	$780	$918	$918
February	$13.93	9,877	$0.01152	$791	$929	$1,847
March	$13.93	10,942	$0.01152	$803	$942	$2,790
April	$13.93	12,157	$0.01152	$817	$957	$3,747
May	$13.93	13,373	$0.01152	$831	$972	$4,719
June	$18.63	14,588	$0.03963	$1,483	$1,670	$6,390
July	$18.63	14,588	$0.03963	$1,483	$1,670	$8,060
August	$18.63	14,132	$0.03963	$1,465	$1,651	$9,712
September	$18.63	13,373	$0.03963	$1,435	$1,619	$11,331
October	$13.93	12,005	$0.01152	$815	$955	$12,286
November	$13.93	10,181	$0.01152	$794	$933	$13,219
December	$13.93	8,814	$0.01152	$778	$916	$14,135

Labor

Though a significant amount of labor is associated with pecan production and storage, a majority might be considered a sunk cost from the point of view of cold storage. That is, most related labor would be required whether an on-farm cold storage facility existed or not. Additional labor is, however, required for loading and unloading pecans and facility maintenance (e.g., monitoring cooling systems). An estimated 60 hours of labor at a rate of $15 per hour for a total of $900 annually is included to account for this cost, based on the median wage data for farm workers in New Mexico from the Bureau of Labor Statistics (BLS, 2023).

Operating Loan Interest Expenses

The owner is assumed to secure an operating loan at the end of January each year, equal to the expected income from the sale of the pecans, to cover expenses until selling later in the year. Under a 10-year average price of $2.24 per pound, the anticipated revenue from selling 1,152,000 pounds of pecans is $2,580,480. Farm operating loans typically carry interest rates ranging from 5% to 10%, and it is assumed a loan is taken out at a 7% annual interest rate, with no significant transaction or additional fees. The total annual interest cost is calculated on the assumption that the loan is repaid at the end of the month in which the sale occurs. Consequently, if the sale is delayed beyond January, the interest costs increase by $15,053 for each month of delay, summarized in Table 4. This operating loan functions analogously to a seasonal operating credit line secured against stored inventory, with financing costs increasing as the marketing window is extended.

Table 4. Estimated Operating Loan Interest Expense by Month Pecans Are Sold

Sale Month	Total Interest Expense
February	$15,053
March	$30,106
April	$45,158
May	$60,211
June	$75,264
July	$90,317
August	$105,370
September	$120,422
October	$135,475
November	$150,528
December	$165,581

Insurance

The model assumes that stored pecans can be insured at an annual rate of 0.45% of their value. Following a similar approach as used in the calculation of interest for operating loans, the insurance cost is based on pecan values using the 10-year average price of $2.24. If the pecans are stored for the entire year and sold in December, the total cost amounts to $10,644. However, it is assumed that insurance premiums cease at the point of sale, meaning the total premium depends on the month of sale. Table 5 summarizes the total insurance expenses based on the sale month.

Table 5. Total Estimated Insurance Expenses by Sale Month

Sale Month	Total Insurance Expense
February	$968
March	$1,935
April	$2,903
May	$3,871
June	$4,838
July	$5,806
August	$6,774
September	$7,741
October	$8,709
November	$9,677
December	$10,644

Miscellaneous Overhead

The model includes a $5,000 per year miscellaneous cost to account for remaining incidental or administrative expenditures that derive from the cold storage operation. These costs may include normal maintenance and repairs, cleaning, waste management, or other fringe expenses not captured by the preceding cost estimates.

Shrink and Storage Loss

The analysis assumes that pecans entering cold storage have been adequately dried prior to storage consistent with standard post-harvest practices, resulting in minimal additional weight loss during storage. Under these conditions, incremental shrink attributed to cold storage is assumed to be negligible relative to other modeled costs and is therefore not explicitly deducted from salable volume.

This assumption is consistent with industry guidance indicating that properly dried in-shell pecans stored at subfreezing temperature experience limited additional moisture loss over time. Any unanticipated quality or quantity loss would reduce realized returns and represents an additional source of downside risk not explicitly modeled.

Estimated Cash Inflows

As indicated earlier, the model accounts for two potential revenue streams: the capture of possible seasonal price differentials and the elimination of third-party quarantine costs when quarantine is required.

Cash Inflows Associated with Seasonal Price Differentials

The revenues associated with earning differential prices are the additional revenue for the farm associated with selling pecans after January, the traditional month in which sales are made. Table 6 shows average differentials between export prices in January and other months for the last ten years (2013 through 2022).

Table 6. Monthly 2022 Export Prices, Price Differentials, and 10-Year Average Differentials

Month	Price/lb. (2022)	Differential (2022)	Average Differential (2013–2022)
January	$1.95		
February	$1.78	-$0.17	+$0.00
March	$2.07	+$0.12	-$0.01
April	$1.31	-$0.64	-$0.11
May	$2.12	+$0.17	-$0.02
June	$2.37	+$0.41	+$0.06

Table 6 (cont.)

Month	Price/lb. (2022)	Differential (2022)	Average Differential (2013–2022)
July	$2.38	+$0.43	+$0.07
August	$3.19	+$1.24	+$0.15
September	$3.82	+$1.87	+$0.22
October	$2.91	+$0.96	+$0.29
November	$2.00	-$0.04	+$0.23
December	$3.32	+$1.37	+$0.29

Also shown in Table 6, average price differentials from February through May are negative, indicating that stored pecans during these periods would be expected to result in a loss. In contrast, price differentials from June through December are positive, suggesting expected positive revenue flow.

It should be noted that while the average price differential is positive, the differential in any given year may be positive or negative. Over the last 10 years (10 years used in the averages shown above), the number of months with positive differentials ranged from zero (2020) to 11 (in 2017). Specific months ranged from 30% positive differentials over the last 10 years (April) to 90% (October and November). Figure 6 shows the price differential for four of the last 10 years. Careful observation of Figure 6 shows that marketing later in the year, while offering potentially higher prices, results in greater price variability.

It should also be noted that whereas positive price differentials are often observed later in the marketing year, the differential must be large enough to cover the additional costs associated with storing the pecans (i.e., the "cost of carry" or the total cost of holding the pecans).

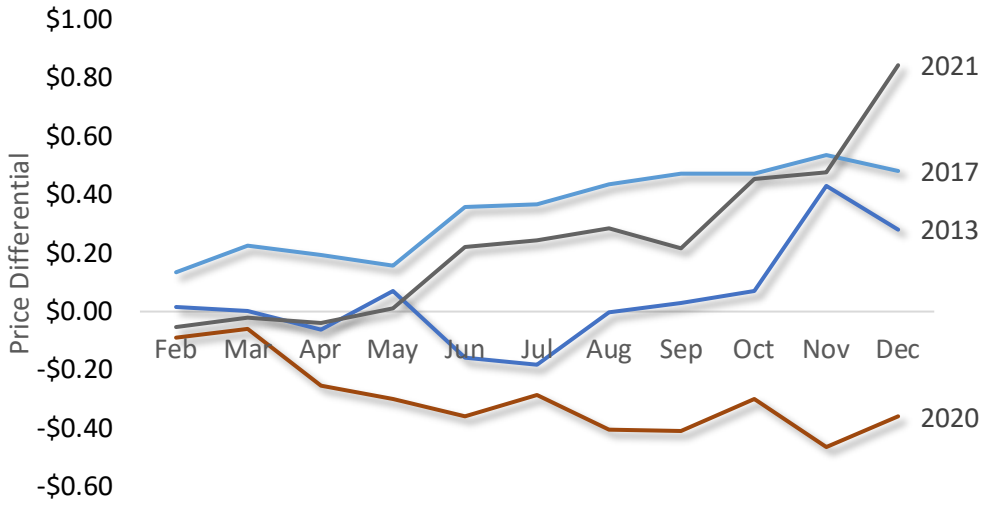


Figure 6. Price Differentials of Four Randomly Selected Years in the Last 10 Years

Cash Inflows Associated with Avoided Quarantine Costs

The analysis assumes that producers in quarantined areas of New Mexico and Texas must pay $30 per pallet (about 2,000 pounds of pecans) to store the nuts for 10 days at 0 °F. The $30 fee translates to an average cost of $0.015 per pound. The required 7-day countdown can only commence once the center of a pecan mass—typically stored in a 36" x 36" x 48" duffle or "superbag"—has reached the designated temperature. Additionally, there is a cost of $30 each for the super bag itself, which averages $0.01 per pound. Due to the latent heat within the mass, an extra three days of cooling is necessary before the countdown begins. For a facility with this capacity (i.e., 1,152,000 pounds), the total cost for a 10-day quarantine would be approximately $28,800 annually. By investing in on-farm cold storage, producers could avoid this expense.

Assumed Selling Behavior

It is assumed that the facility consistently operates at full capacity. Inventory is sold every year within a specific month for 30 consecutive years.

Results

Summarized in Table 7 are the net present value (NPV), internal rate of return (IRR), and discounted payback period (DPP) for the investment. For example, the first line shows returns associated with storing pecans for one month and selling the entire inventory in February. In this case, the 10-year average price differential is $0.00 per pound, resulting in an NPV of nearly -$800,000, and a DPP exceeding the investment's lifespan.

If the entire inventory were sold in any month before September, a negative NPV is predicted. September through December show positive returns to the cold storage investment. Based on the 10-year price differentials described above in Table 7, investment returns are maximized with sales in October, where the investment's present value is over $1 million, and the internal rate of return is nearly 25%. The returns are calculated using the 10-year average price differential. As previously discussed, price differentials for any given month or year can vary significantly, hence returns in any given year may be positive or negative.

Table 7. Measures of Return by Sell Month, Average Price Differential at Maximum Capacity

Month	NPV	IRR	DPP
February	-$781,611	ND	>30
March	-$785,036	ND	>30
April	-$2,477,892	ND	>30
May	-$1,514,180	ND	>30
June	-$793,199	ND	>30
July	-$797,238	ND	>30

Table 7 (cont.)

Month	NPV	IRR	DPP
August	-$13,911	8.5%	>30
September	$639,263	17.4%	8
October	$1,236,827	24.9%	5
November	$386,288	14.2%	10
December	$868,597	20.3%	6

Note: ND = Not Determinable

Figure 7 illustrates the minimum price differential needed to have a net present value of 0 (the point at which the investment becomes successful). This "hurdle" price increases over the year, from $0.065 to $0.214 per pound, as electricity, tax, operating loan, and insurance costs increase the longer the pecans are held in storage. Figure 7 shows the 10-year average monthly price differential obtained from UDSA Foreign Agricultural Service monthly export values. If the differentials shown for exports held in the domestic market, then pecans sold out of storage before August would fail to meet the hurdle price and would result in a negative NPV.

The average monthly differential from January, depicted by the columns in Figure 7, shows a notable increase in the later months, as previously discussed. However, price differentials have varied significantly from year to year over the past decade. The range of differentials, illustrated by the vertical lines, also tends to increase in the later months. For instance, in September, the difference between the lowest and highest observed differentials was $2.28, over four times greater than the range for February. Additionally, the differential ranges for the fall and winter months—from August to December—consistently exceeded $1.00.

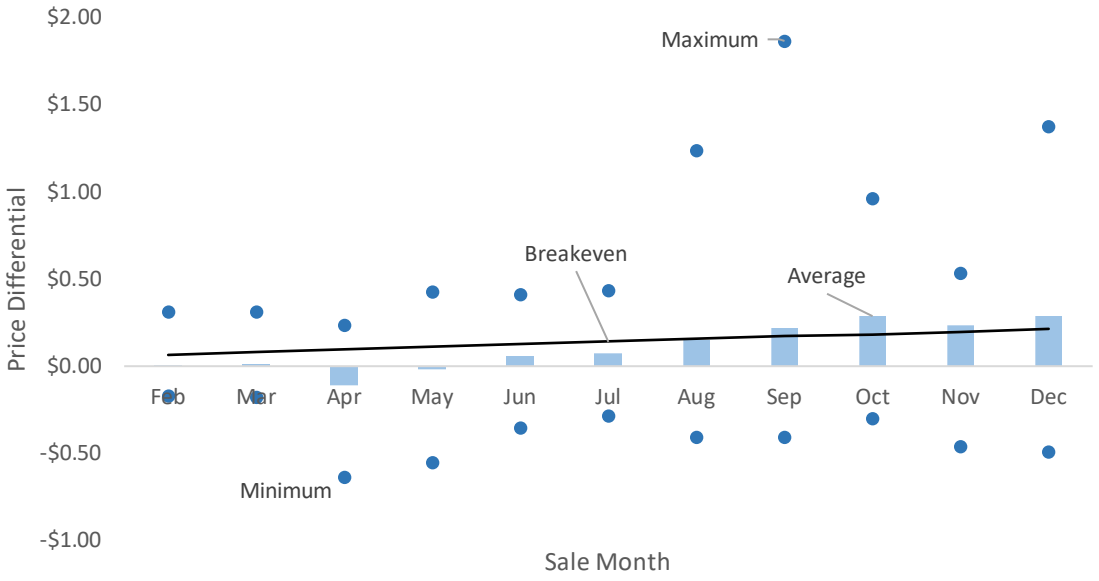


Figure 7. Minimum Price Differential Needed for Positive Investment Return and Average Differential, 2013–2022

One way of exploring the effect of variability in monthly price differentials on the investment returns is to look at a cumulative frequency distribution. For example, Figure 8 illustrates the cumulative frequency distribution for price differentials observed each October from 2013 to 2024. A differential of $0.18 or less, the hurdle price for October sales, was observed only 30% of the time, or three out of the last 10 years. This finding suggests a 70% likelihood of achieving a sufficiently high seasonal differential to justify the investment based on the last decade of pecan sales and assumptions outlined above. Notably, three of the differentials even exceeded $0.40, more than twice the hurdle price.

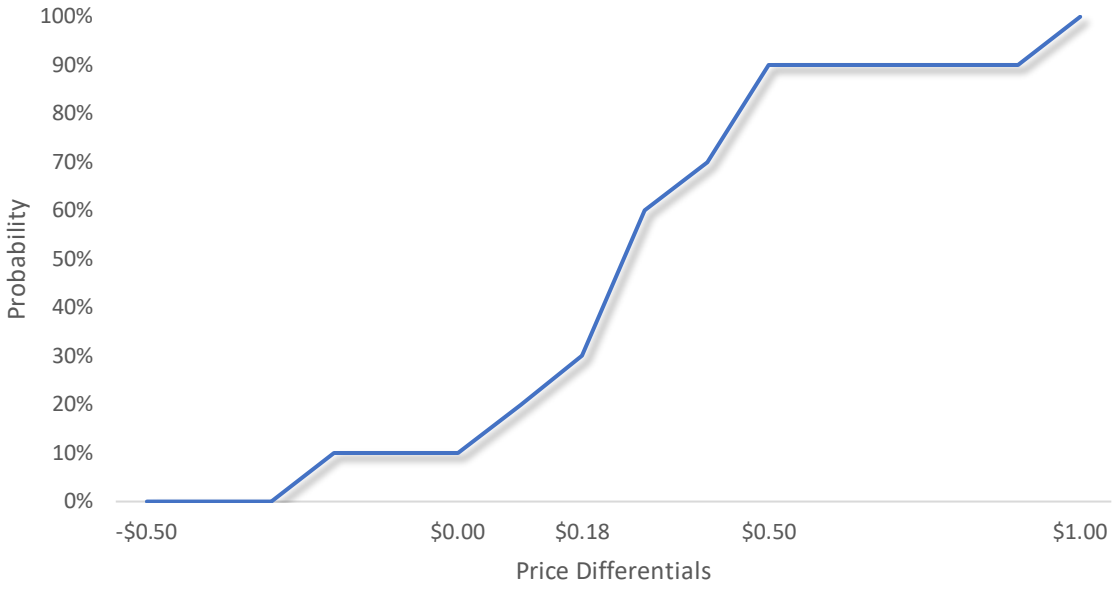


Figure 8. Cumulative Frequency Distribution, USDA Foreign Agricultural Service October Export Value Differentials, 2013–2022

Source: USDA-FAS

Using average differentials, a marketing strategy that held pecans until after August would result in positive investment returns measured by NPV or IRR. While evidence suggests that on-farm cold storage could produce positive investment returns, the year-to-year variability observed in Figures 6 and 7 suggests the strategy could suffer significant negative differentials in any particular year, increasing the importance of cash flow management. These dynamics imply that while extended marketing windows may increase expected returns, the associated cash flow volatility and capital intensity may limit feasibility for smaller producers unless capital requirements and price risk are shared across several operations or supported by access to substantial operating credit lines. Even with sufficient credit, however, prolonged exposure to adverse price differentials can increase financing costs and balance-sheet risk.

Many producers do not face quarantine requirements and the corresponding costs associated with quarantine; thus, the current model overstates the returns to cold storage. Removing the benefit of

avoiding third-party quarantine costs in the model reduces the internal rate of return (IRR) by approximately 3.8% for each sales scenario. For example, if a producer marketed their pecans in October, the month with the largest price differential, the IRR would decrease from 24.9% to 21.1%.

Conclusion

Agricultural producers, including pecan producers, are price takers with little control over the price they receive for their products. One way in which pecan producers may gain more control over their prices is by adding market flexibility made available through storage. Due to their high oil content, pecan storage requires the use of cold storage facilities. This analysis has explored potential investment returns associated with building and operating an on-farm pecan cold storage facility. Key findings suggest that, while investment shows financial potential, significant downside risk is also present.

Using the assumptions described in the body of the paper, including average pecan export value differentials, an investment in on-farm cold storage could produce positive returns. However, returns are directly related to the season in which the pecans are sold. The ability to extend marketing windows beyond the traditional early winter window will likely increase price volatility and corresponding volatility in revenue and profits. The increased volatility would likely increase cash flow requirements and expose investors to significant risk.

While the analysis reported in this paper suggests that on-farm cold storage may have promise as a potential marketing tool and a means of providing more control over prices received for their pecans, producers should conduct their due diligence to ensure that model assumptions are consistent with their unique circumstances. Additionally, producers should be prepared for potential increases in price variability impacting cash flows and the need for additional capital should persistent negative price differentials be encountered over the investment lifespan.

Limitations and Future Research

Limitations

Several limitations to the research described in the body of the report should be acknowledged. A significant limitation is the availability of monthly price data for pecans. Some monthly data are available for portions of the year, but a government-validated dataset for domestic monthly prices is not available. The use of monthly USDA-FAS export values may not accurately reflect domestic price differentials.

Even if domestic and export differentials are identical, the analysis described above relied primarily on export value (price) differentials observed over the last 10 years. Agricultural markets and policy remain dynamic and future market behavior may not remotely resemble past data, voiding the results provided in this research.

Given the industry's reliance on production contracts, it is unclear whether pecans can be marketed effectively outside traditional market windows. Producers using on-farm cold storage may have difficulties in marketing their pecans on a month-to-month basis.

The results of this study are based on a relatively simple model. They are intended to provide general insights into the potential feasible investment opportunity under basic assumptions. Like all investments, many factors cannot be readily quantified and predicted. Investors should consider any analysis as guidance rather than conclusive facts. Interested stakeholders should conduct their due diligence, including obtaining and validating investment and operating costs and expected revenues.

Future Research

Future research regarding the economic and financial viability of on-farm cold storage may include updates to the analysis that use newly available domestic prices and resulting seasonal price differentials in domestic prices. Given the potential increased price volatility, the analysis could benefit from a more in-depth analysis, including Monte Carlo simulation to explore tradeoffs between risk from price differential volatility and potential benefits.

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Appendices

Appendix I. Cold Storage

The potential for better marketing control and the increasing need for local biological control have made on-farm cold storage an attractive investment for some producers. However, the complexity and costs of such a project can pose challenges.

Cold storage facilities maintain an internal temperature below freezing using heavy insulation and specialized air conditioning systems. The structure is often a steel frame, either self-supporting or supported using an internal storage rack system. Pecan warehouses typically require a standalone building, given the use of heavy wooden storage crates. Ceiling heights of 20’ or greater are considered desirable for five-high stacks of the 4’ x 4’ containers standard in nut storage, a strategy that limits the facility's footprint.

With internal temperatures persistently under 32 °F, increased floor thickness or insulation is essential to prevent structural stress from ground freezing, a principle known as “frost heave.” Considering the requirement of expensive floor solutions, conserving square footage is a high priority in facility design.

Various wall and ceiling insulation materials are suitable for cold storage facilities. Fiberglass, mineral wool, polystyrene, polyurethane, and natural fibers have all been successfully implemented and possess unique strengths and weaknesses. Due in part to the low cost, ease of installation, and availability, a combination of fiberglass cloth and polystyrene boards over 6 inches thick is a standard solution.

Arguably, the most critical design feature is the choice of cooling system. One- or two-stage anhydrous ammonia systems are the most common in commercial-grade cooling, and they are desired for their cost and engineering efficiency. Unfortunately, even trace amounts of ammonia inside a storage space can permanently discolor in-shell pecans, ruining their market value. Though single-stage hydrofluorocarbon-based systems (HFC) are increasingly rare in the commercial sector due to regulatory pressure, they remain a good candidate for small installations where the required system size is limited and food products are present. New commercial cold storage systems increasingly rely on cascade designs with an internal CO_2-based system that poses less inventory or personnel risk and is more environmentally sensitive. Aside from the increased complexity and cost, CO_2 coolants are incompatible with older systems designed for HFCs, unlike ammonia, which is interchangeable with only slight system modifications. Thus, retrofitting older systems, while possible, is often unpreferable for food storage, often necessitating investment in an entirely new system.

Removing latent moisture content from the nut is necessary to prevent mold formation during shipping, processing, and storing. It is especially vital, however, before cold storage to avoid condensation in the facility and the formation of large ice crystals inside the nuts or on the exhaust fans. Traditionally, nuts were placed in hot and dry areas for two weeks or more to be dried.

Modern production has sped this process using forced air-drying machinery, commonly installed into harvest wagons for time efficiency. When used for pecan processing, these systems typically force 95 °F air through the mass of pecans as they sit inside the harvest equipment, quickly reducing the moisture content to approximately 4% to 4.5% from between 8% and 30% before storage or transport. Ambient humidity and the stage of nut maturity, early or late in the season, can alter the time required for drying and should be considered carefully before storing.

Appendix II. Apple Price Seasonality

Apples display similar seasonal price fluctuations to that of pecans. Both import and export market prices for apples follow comparable seasonal patterns. When comparing the seasonal price indices for both markets, it is observed that from January to July, prices are below average, before rising sharply toward the end of the year (see Figure 8). This seasonal price trend is based on the average apple prices from 2015 to 2023, with a slight gap in the data from 2013 and 2014 due to the absence of domestic price information.

The primary difference between them lies in the timing of the price spikes. Domestic apple prices typically peak in September, averaging more than 7% above the annual average for that month. In contrast, export apple prices experienced a spike in December, reaching a maximum of 4.9% above the average for that period.

Despite these timing differences, the seasonal price patterns for both markets show strong similarities in month-to-month seasonal fluctuations and price differentials. Given that apples and pecans share many characteristics, it is reasonable to assume that the price seasonality in both domestic and export pecan markets follows a similar pattern.

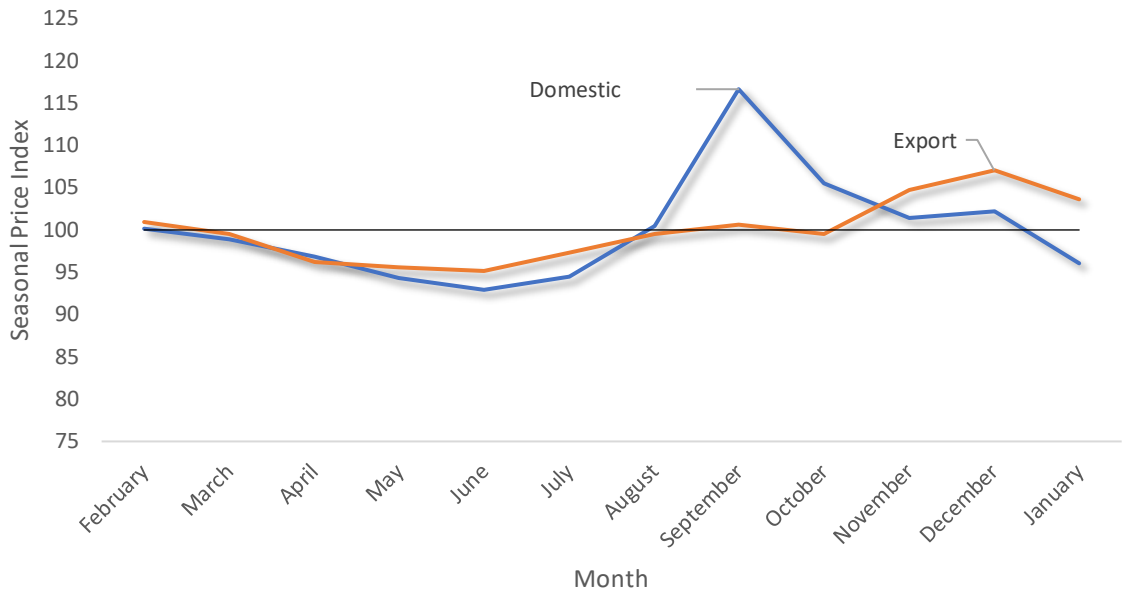


Figure 8. Price Seasonality, U.S. Domestic and Export Markets, 2015–2023

Source: USDA-NASS, USDA-FAS 2024