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Theme Overview: Why Is Mechanization in Specialty Crops So Hard?

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JEL Classifications: Q16, O33, D81
Keywords: Innovation, Risk, Specialty crops

The competitiveness of U.S. agriculture, including regional and specialty crop sectors, is impacted by multiple factors, including shifting global climate trade, and policy (see CRS, 2022; Gustafsson et al., 2022; Hammami, Guan, and Cui, 2024). During the recent COVID-19 pandemic, production and supply-chain disruptions highlighted vulnerabilities for U.S. industries and consumers (Hobbs, 2020; Peterson et al., 2023).

The call for game-changing innovation has reemerged among science and research agencies as one way to address competitiveness issues across agriculture (FFAR, 2023; USDA, 2023). Artificial intelligence, digital technologies, precision farming, and automation are foundational technologies that have the potential to transform food supply chains. Recent breakthroughs could be leveraged to affect agricultural systems positively, but realizing the benefits depends on developing feasible applications and increasing the uptake of emerging technologies (Kanioura and Andrew, 2024; IFPA Future Trends, 2023).

Since fruit, vegetable, and tree nut production is highly dependent on manual labor, Worker availability and affordability are often highlighted as one of the leading challenges for competitiveness of U.S. specialty crops (U.S. House Committee on Agriculture, 2023). Mechanized alternatives are one potential solution to labor challenges faced by specialty crop industries but progress from development to deployment to widespread use remains limited (NAS, 2019; Martin, 2024).

Decisions are not made in isolation, and one size does not fit all (Charania and Xi, 2020; Calvin, Martin, and Simnitt, 2022). While there are common interests to improve the U.S. specialty crop sector's competitiveness via research and development (R&D), unique needs among the myriad commodities, markets, and supply chains that comprise specialty crops can make finding common solutions challenging, even within seasonal markets. Funders and developers emphasize the need to de-risk new technologies to attract potential users and entice change by testing and eliminating options that are not viable in the development (or precompetitive) phase. Numerous research efforts have focused on developing technologies; however, there is a pressing need to extend the focus to the production systems and supply chains within which technologies are applied.

Articles in this Theme:

- **Balancing the Scales: Finding Relative Advantage Incentives for Mechanization of Specialty Crops**
  Mary T. Serviss and Suzanne Thornsbury
- **Extension's Role in Reducing Uncertainty for New Technology Adoption**
  Andres Bejarano Loor and Fritz M. Roka
- **Balancing Challenges of Scale and Scope Economies in the Development of Labor-Saving Technology for Specialty Crop Production**
  Clinton L. Neill
- ***Skill Economies Address the Supply Chain Squeeze***
  Kimberly L. Morgan

What Can Economists Contribute?

Over 30 years ago, a seminal article by John Holt in the *American Journal of Agricultural Economics* emphasized that managing change involved much more than explaining new research findings or advertising new technology. It required active engagement with people within the context of production and marketing systems. Long before the terminology was trending, Holt recognized that "participatory management places a prime responsibility to 'focus on the future, rather than on undoing the past, on the opportunities, rather than on the problems'"" (Holt, 1989, p. 872). The lessons Holt delivered and the approach he used are extremely relevant to the challenges of today. Funds have been invested and brilliant minds are developing exciting new labor-saving technologies for specialty crops. However, implementing system-wide change is difficult and mechanization for specialty crops is no exception. There are no quick fixes when building new attitudes, skills, and systems.

Holt was recognized with the Lifetime Achievement award from the Southern Agriculture Economics Association in 2000 for cutting edge contributions to professional thought about risk management in agriculture, about entrepreneurship and comparative advantage as tools for constructively managing change in agriculture, and about profitability as an integral part of sustainable agricultural systems. His even-handed analysis of, and education about, regulatory impacts in agriculture has helped decision-makers at all levels understand these enduringly important issues. (Holt, 2000, p. v)

The papers in this *Choices* theme issue utilize the foundational systems-based risk-management approach espoused by Holt to consider “why mechanization in the specialty crop sector is so hard.” The papers highlight what is missing from the existing literature on this subject and explore how economists can help to de-risk labor-saving technologies for specialty crops and overcome bottlenecks in their implementation.

- In the first paper, Serviss and Thornsbury examine innovation through an investment lens and asks fundamental questions framed as relative advantage incentives that exist at both the industry and operator levels. What does it mean for a technology to be cost saving? How can economists frame the system-wide impacts from new technologies?
- In the second paper, Loor and Roka explore the dissemination of knowledge about new technologies and applications through the channels of producer and industry awareness. What information of this type is already known and what is still needed? How can agricultural extension help?
- In the third paper, Neill gauges the potential benefits of “right-sizing” technology across the many diverse farms and commodities that make up the U.S. specialty crop sectors. To what extent will new technologies fit within existing production systems? How can we encourage the development of labor-saving technologies that will address the challenges of scope and scale?
- In the fourth paper, Morgan highlights an approach that starts with human beings and asks how an economies of skill approach could be applied. What is the optimal place for new technologies and tech-savvy workers? Where are the biggest constraints? Are we asking the right questions?

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Balancing the Scales: Finding Relative Advantage Incentives for Mechanization of Specialty Crops

Mary T. Serviss and Suzanne Thornsbury

JEL Classifications: J43, O13, O33, Q16, Q55
Keywords: Technological innovation, Agricultural technology, Agricultural labor markets

There is widespread recognition that the cost and availability of labor form one of the leading challenges for U.S. specialty crop growers (e.g., Calvin, Martin, and Simnitt, 2022; IFPA, 2023; USDA-ERS, 2023; Martin, 2024). On average, labor expenses account for 12% of total gross cash farm income across all U.S. farms (USDA-ERS, 2023). While this average share has changed very little over time, even as total costs have increased, the labor landscape looks very different for most specialty crops. From 2003 to 2020, nursery and greenhouse industries spent the largest portion of their total gross cash farm income on labor, averaging 34% (Figure 1). The fruit and tree nut industries followed closely behind at about 30% of gross income. Differences among individual specialty crops are even more notable. For example, labor expenses expressed as a percentage of gross income are estimated to be as high as 50% for almonds and 60% for table olives (Niederholzer, Ott, and Jarvis-Shean, 2024; Cicek, 2011).

Mechanized solutions such as precision agriculture, remote sensing, mechanical harvesters, and labor-aids offer potential benefits as labor-saving technologies. Yet the adoption of such technologies has been uneven, over time and across commodities (Gallardo and Sauer, 2018). Rogers' (1962) classical depiction of innovation adoption includes five stages:

1. awareness of the need,
2. persuasion by using information to reduce uncertainty,
3. decision to adopt (or reject) the innovation,
4. initial use of the innovation to test it, and
5. continued use of innovation.

In the end, Rogers concluded that just five factors drive (or oppose) adoption:

1. relative advantage,
2. compatibility,
3. apparent simplicity,
4. trialability, and
5. observability.

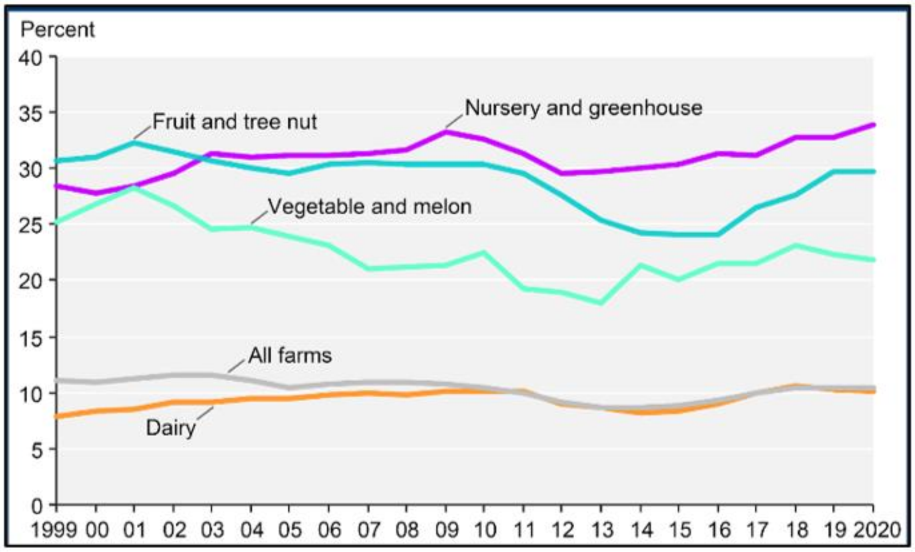
This article examines why growers might adopt mechanization through an investment, or relative advantage, perspective.

Technology Availability

An obvious first step (not mentioned by Rogers) in substituting mechanization for labor in specialty crops is that the technologies must exist and be available for commercialization. Concerns over labor availability and affordability are not new, and neither are attempts to develop mechanization. For example, the seed drill, threshing machine, handheld seed tube, and cotton gin predate the 1800s, and the first factory for internal combustion tractors was established in 1902 (Figure 2). Technology solutions designed for specialty crops did not emerge as early, but several crops (typically serving processed product markets) transitioned to mechanical harvesting solutions. Harvesting for processing tomatoes was largely mechanized by 1970 (Schmitz and Seckler, 1970) and mechanical harvesting for tart cherries was pervasive by the early 1970s (Wright, Martinez, and Thornsbury, 2006; Ricks, Hamm, and Chase-Lansdale, 1982). In the 1970s, mechanical harvesting also emerged for processing olives, juice grapes, some wine grapes, carrots, almonds, and pistachios (Hendrickson and Oberholster, 2017; Sarig, 2012).

The specialty crop sector comprises hundreds of unique crops and growing situations, with the emergence of new or differentiated crops ongoing. While this creates opportunities for market development and response to consumers, it can create challenges for the commercialization of innovative technologies. Agricultural research and manufacturing interests are more likely to focus on the needs of the almost 300,000 U.S. farms (80.6 million acres) growing corn for grain in 2022 than the needs of the less than 8,500 U.S. farms (73,500 acres) growing strawberries or even the 27,500 farms (411,000 acres) growing apples. Technology development for specialty crops must either target a relatively small number of potential users or be adaptable over differentiated use cases. As they mature,

Figure 1. Total Gross Farm Income Spent on Labor in Various Farm Specializations, 2000-2020



Source: USDA-ERS (2023).

additive manufacturing technologies could eventually expand solutions for small-volume agricultural needs as they have in manufacturing sectors of the economy (Lu et al., 2024).

Even accounting for small volumes, the high value of most specialty crops may provide opportunities for investment in mechanization. In Florida alone, the nursery and greenhouse industries generated $3.98 billion in total sales in 2022 with labor expenses totaling 34% of farm income (Khachatryan et al., 2023); fruit industries generated $1.29 billion in revenue and vegetable and melon industries added an additional $1.31 billion in revenue in 2020 (FDACS, 2024).

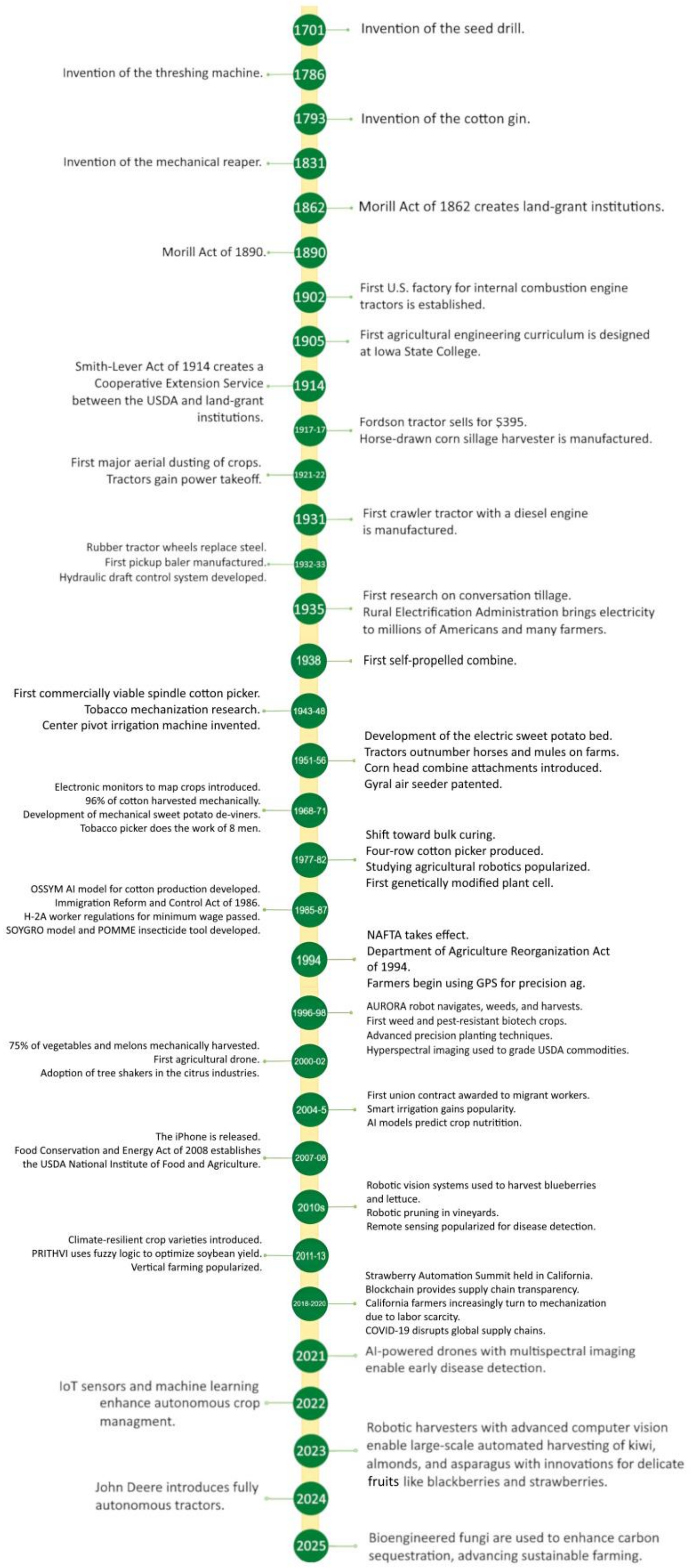
Investment in Innovation

Understanding the potential benefits and need for modern agricultural tools, the U.S. Department of Agriculture (USDA) has invested in the development of mechanized and automated solutions for specialty crop industries. Astill, Perez, and Thornsbury (2020) identified six programs across four USDA agencies that had made investments totaling $287.7 million (nominal) in 213 projects with a focus on automation or mechanization for specialty crops between 2008 and 2018. Each of these programs was designed differently to achieve unique objectives, with specialty crop automation or mechanization projects as a subcomponent. While substantial in value, these investments accounted for only 3% or less of the total funds allocated by the programs. An additional three programs in USDA Rural Development (RD) were identified that funded $3.4 billion from 2010 to 2018 to support the digital infrastructure needed for adoption of automation or mechanization. More recent policies may impact incentives for mechanization or technology development including policies proposed to improve working conditions, expand legal pathways for migrant workers, and disaster relief programs (USDA-FSA, 2022). In 2024, the USDA announced a $2 billion investment to help specialty crop growers overcome market barriers and expand crop storage (USDA, 2024).

Industry associations are also investing in technological solutions. For example, the California Strawberry Commission funds an initiative to develop and test mechanical harvesters, particularly in fields with varying terrain and foliage density (Yeh et al., 2023). Their investments in innovating robotic technologies and automated harvesting systems demonstrate how pivotal some believe these technologies will be in assuring the strawberry sector’s long-term future.

More recently, there has been growing interest from sectors that have not traditionally focused on agriculture. Investment from both private equity and venture capital firms has grown over time (Brady, 2023). Total agricultural investments from venture capital markets did decline in 2022 (largely driven by market shakeouts in eGrocery and alternative protein spaces), but continued to increase in ag biotech, bioenergy and biomaterials, farm management software and internet of things (IoT), and novel farming systems (AgFunder, 2023).

Figure 2. How Technology Has Shaped Agriculture in the United States over the Past 3 Centuries, 1701—2025.



1701
Invention of the seed drill.

1786
Invention of the threshing machine.

1793
Invention of the cotton gin.

1831
Invention of the mechanical reaper.

1862
Morill Act of 1862 creates land-grant institutions.

1890
Morill Act of 1890.

1902
First U.S. factory for internal combustion engine tractors is established.

1905
First agricultural engineering curriculum is designed at Iowa State College.

1914
Smith-Lever Act of 1914 creates a Cooperative Extension Service between the USDA and land-grant institutions.

1917-17
Fordson tractor sells for $395.
Horse-drawn corn sillage harvester is manufactured.

1921-22
First major aerial dusting of crops.
Tractors gain power takeoff.

1931
First crawler tractor with a diesel engine is manufactured.

1932-33
Rubber tractor wheels replace steel.
First pickup baler manufactured.
Hydraulic draft control system developed.

1935
First research on conversation tillage.
Rural Electrification Administration brings electricity to millions of Americans and many farmers.

1938
First self-propelled combine.

1943-48
First commercially viable spindle cotton picker.
Tobacco mechanization research.
Center pivot irrigation machine invented.

1951-56
Development of the electric sweet potato bed.
Tractors outnumber horses and mules on farms.
Corn head combine attachments introduced.
Gyral air seeder patented.

1968-71
Electronic monitors to map crops introduced.
96% of cotton harvested mechanically.
Development of mechanical sweet potato de-viners.
Tobacco picker does the work of 8 men.

1977-82
Shift toward bulk curing.
Four-row cotton picker produced.
Studying agricultural robotics popularized.
First genetically modified plant cell.

1985-87
OSSYM AI model for cotton production developed.
Immigration Reform and Control Act of 1986.
H-2A worker regulations for minimum wage passed.
SOYGRO model and POMME insecticide tool developed.

1994
NAFTA takes effect.
Department of Agriculture Reorganization Act of 1994.
Farmers begin using GPS for precision ag.

1996-98
AURORA robot navigates, weeds, and harvests.
First weed and pest-resistant biotech crops.
Advanced precision planting techniques.
Hyperspectral imaging used to grade USDA commodities.

2000-02
75% of vegetables and melons mechanically harvested.
First agricultural drone.
Adoption of tree shakers in the citrus industries.

2004-5
First union contract awarded to migrant workers.
Smart irrigation gains popularity.
AI models predict crop nutritition.

2007-08
The iPhone is released.
Food Conservation and Energy Act of 2008 establishes the USDA National Institute of Food and Agriculture.

2010s
Robotic vision systems used to harvest blueberries and lettuce.
Robotic pruning in vineyards.
Remote sensing popularized for disease detection.

2011-13
Climate-resilient crop varieties introduced.
PRITHVI uses fuzzy logic to optimize soybean yield.
Vertical farming popularized.

2018-2020
Strawberry Automation Summit held in California.
Blockchain provides supply chain transparency.
California farmers increasingly turn to mechanization due to labor scarcity.
COVID-19 disrupts global supply chains.

2021
AI-powered drones with multispectral imaging enable early disease detection.

2022
IoT sensors and machine learning enhance autonomous crop managment.

2023
Robotic harvesters with advanced computer vision enable large-scale automated harvesting of kiwi, almonds, and asparagus with innovations for delicate fruits like blackberries and strawberries.

2024
John Deere introduces fully autonomous tractors.

2025
Bioengineered fungi are used to enhance carbon sequestration, advancing sustainable farming.

Source: Authors.

Challenges to Commercialization

Moving technologies from development to commercialization has not been easy. It is useful to consider innovation for specialty crops through the lens of technology readiness levels (TRLs), a standardized metric used to assess the maturity level of a particular technology as it moves through development to widespread use (Mankins, 1995; Tomaschek et al., 2016). TRL stages 1–4 correspond to the precompetitive space, where research primarily focuses on basic or foundational science and is often exploratory and driven by a big-picture, long-term need. In TRL stages 5–8, the focus is advancing revolutionary technologies that need further refinement before commercialization; for instance, adjustments to specific end-uses. In the final stages (TRL 8–9), technologies that have been created and fine-tuned undergo a process of technology transfer and deployment.

The innovation “valley of death” occurs when a technology has reached proof of concept (meaning it works in a controlled setting) but still requires significant development to operate in real life (Gbadegesjn et al., 2022). Typically, this demise happens when an innovation fails to progress from TRL 4 to TRL 7. Although the field of agricultural technology continues to expand (Mickolio, 2024), many applications are lingering in the valley of death. Challenges such as data standardization, interoperability, and rural broadband connectivity are often significant barriers to mass adoption.

Heterogeneity, not just between different specialty crops and growing systems but within the individual crops and plants themselves (e.g., apples are not located in exactly the same places on every tree), creates significant challenges to operable solutions, particularly for fresh produce. These logistical challenges can slow the rate of technological development. For example, despite high labor costs and multiple technologies in various stages of development, strawberry harvesting is still mostly performed by hand (Yeh et al., 2023). Strawberries are delicate and highly perishable, so harvesting tools developed for processed products cannot be readily adapted without causing significant damage. During harvest, fruit clustering is a significant challenge for mechanical strawberry harvesters, and solutions to separate clusters of ripe and unripe berries in a consistent fashion have not been perfected (Zhou et al., 2022). Bruised fruit is also more susceptible to pests and pathogens, creating additional quality problems in the supply chain (Hussein, Fawole, and Opara, 2020). Crops that require multiple harvests, either within or across seasons, face additional challenges from damage to the plant (or tree) itself (Charlton et al., 2019). Unique needs among the myriad commodities, markets, and supply chains comprising specialty crops make common solutions challenging.

Relative Advantage: Tipping Point

Mechanization in agriculture represents a critical tipping point where the balance between labor-intensive practices and automated solutions shifts decisively toward (or away from) technology. Just because technology exists does not mean an individual firm will be incentivized to adopt it. There is increasing economic pressure to find solutions, as farm labor is likely to continue to become less available and more expensive in the future (USDA-ERS, 2023).

According to a survey by the California Farm Bureau, over 40% of farmers have faced challenges in securing sufficient labor for their main crops in recent years (Daniels, 2019). Factors identified as exacerbating shortages include stricter immigration policies and an aging immigrant farmworker population. In New Jersey’s nursery crop operations, Gohil, Waller, and Cabrera (2022) found that despite challenges in mechanizing tasks like pruning due to the diversity in plant sizes and shapes, there was growing recognition of the need for greater mechanization to enhance operational efficiency.

Still, individual adoption of new technologies and diffusion of those technologies across communities is complicated, and the pace of change is intense, requiring integration of assets from disparate sources for the successful delivery of solutions. Low margins and agronomic challenges can shift interest and attention toward the short- and medium-term survival of the farm operation, decreasing the operator’s ability and interest to invest in new technologies.

Affordability and scalability of technologies are prime examples of relative advantages, as conceptualized by Rogers (1962), that drive on-farm adoption. Existing mechanized harvesting solutions (e.g., robotic picking and vision systems) are expensive and vary widely in cost. Large-scale operations often find mechanization to be more feasible, as fixed costs can be spread over a larger production volume. For citrus harvesting, the cost of such technology starts at $80,000 for robotic materials and several hundred thousand dollars for a vision system, not counting maintenance expenses (Yeh et al., 2023). Adjusting the technology to specific crops and situations can be challenging; any damage to vulnerable plants and fruit will add to costs (Moran, 2016).

What Economists Can Offer

While labor costs and availability heavily influence the decision to mechanize, comparing manual labor costs and the capital investment required for mechanized equipment is only a first, and insufficient, step in the decision process. The partial budgeting approach often applied to measure the feasibility of a new technology does not provide relevant information in and of itself. Data limitations typically constrain this type of analysis to an aggregated level or a representative farm. Thus, by definition, the results will not reflect the situation for individual decision making. At a minimum, scenario analysis projections could account for a range of potential adopters across farm size and type. Unlike technologies with widespread markets (e.g., iPhones), the cost of technologies with a limited market is not likely to decrease over time. A realistic assessment of market size for a new technology that includes purchase and maintenance costs can provide insights into the likelihood of the technology’s eventual commercialization. Risk analysis for individual firms is critical.

Often, technology adoption is not just a trade-off between the initial investment and annual operating costs. Instead, it also involves significant system redesign, including how labor is integrated into the resulting new system. For example, in a 2015 survey of apple operations in Washington, Gallardo and Brady (2015) found that only 11% of apple operations were using platforms, even though that relatively low-tech labor aid had been available on the market since the 1990s. The primary reason cited for nonadoption was the technology’s incompatibility with the existing orchard design. Adoption continued to lag even as producers transitioned to high-density trellis planting which would physically accommodate platforms. While platforms reduce the number of workers needed, workers are constrained to pick apples at roughly the same pace (i.e., accommodating the speed of the slowest picker).

Additional difficulties arise for perennial crops. Wright et al. (2006) demonstrated that the ability to adopt new mechanical harvesting technologies for tart cherries was not only dependent on the relationship between improved yields and the investment in new technology. Adoption was also critically dependent on the time that the grower needed to recuperate sunk cost investments in required redesign of the orchard. These transition periods and lags were critical factors increasing the reluctance to adopt new systems.

Every farm and location site are unique, and not every technological solution is a fit. For example, slow-moving conveyor belts have been used in Oxnard, California, as a labor aid to assist pickers in the strawberry industry. However, conveyor belts are far less useful in the hillier terrain and smaller fields found in the Salinas-Watsonville area of California (Calvin, Martin, and Simnitt, 2022).

Progress from development to deployment to widespread use of some new technologies emerging in agriculture continues to face obstacles. There are no quick fixes when building new attitudes, skills, and systems. A seminal article by Holt (1989) highlighted the importance of going beyond explaining new research findings and touting new technology to actively engage with people within the context of their production and marketing systems. Economists can help by including information on strategic investments based on potential for adoption, payoffs, or future supply shortages.

Conclusions

Labor shortages have compelled U.S. specialty crop growers to explore mechanization as a potential path to lower costs. On-farm labor-saving technologies are rapidly evolving, with innovations such as precision farming, autonomous tractors, and robotic harvest aids that can create a foundational platform and raise the probability of finding application solutions. Opportunities to integrate artificial intelligence and machine learning in agricultural production and marketing tools promise to further revolutionize farming practices.

Ultimately, transitions will be driven by individual decisions to adopt new technologies. Each operation must evaluate productivity and profitability while fitting the new technology within the context of its production system, overall financial situation, risk profile, and global supply chains. A simple evaluation of relative advantage based on partial, or enterprise, budgets will not serve as a good indicator of adoption feasibility. As technologies continue to advance and regulatory landscapes evolve, the future of agriculture hinges on fostering innovation that not only enhances but also fits into farmers’ daily lives.

By recognizing system-wide implications and asking the hard questions, economists can help stakeholders navigate the hurdles of technological adoption more strategically. Farms must survive within the context of their supply chains and the competition of the global marketplace. Ultimately, relative advantage as measured by partial budgeting does not address firm (or industry) competitiveness. A firm can decrease total costs and still not be competitive. As industry continues to witness rapid advancements in agricultural technologies, understanding these dynamics will be crucial in shaping the future of the global food system.

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Extension's Role in Reducing Uncertainty for New Technology Adoption

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JEL Classifications: Q13, Q16, O33
Keywords: Agricultural innovation, Extension services, Specialty crops, Technology adoption

Risk and uncertainty come with any new technology (Feder and Umali, 1993), and adoption is not a foregone conclusion. Land grant universities are at the forefront of developing new technologies to improve production, sustainability, and efficiency of farming operations. But the very definition of "new" imparts uncertainty in the minds of potential adopters. Are the projected benefits accurate, and will those benefits exceed the adoption costs? To what extent will the estimated costs and benefits change as new technology moves from the experimental to the commercial phase? How steep is the learning curve for incorporating new technology into existing operations? What is the likelihood of costly mistakes and operational inefficiencies? Are decisions reversable? This paper uses a case study approach to examine selected technology transitions in specialty crops, highlighting the critical role extension services play in reducing uncertainty. By analyzing specific instances where new technologies were introduced, the study provides insights into the challenges faced by producers and the strategies employed by extension services to facilitate adoption and mitigate risks.

New Technology and the Economic Impact of Uncertainty

New production technologies in agriculture offer opportunities to increase yield, improve quality, and lower costs. Uncertainty is prevalent with any change, and farmers must prepare for substantial costs. Large upfront expenditures in infrastructure, training, and equipment are often necessary to successfully implement new technologies. This cost can be especially taxing for small-scale farmers with tight budgets (Feder and Umali, 1993), though larger operators must also be cognizant of cost.

Impacts go well beyond a simple comparison of expenditures. For example, substituting mechanical harvesting systems for manual labor in specialty crops fundamentally alters the cost structure. Manual labor typically is paid by the piece, with the duration of employment limited to the harvest period (e.g., in Florida, October–March and December–early May for Florida tomatoes and juice oranges). As such, manual harvest labor can be viewed as a variable cost. When the farm transitions to mechanical systems, harvest becomes heavily weighted to fixed costs. The capital expenditures of the harvest machines will be expensed across several years, independent of whether a crop is harvested (Nobuyuki, Emerson, and Walters, 2008; Roka and Hyman, 2003). High upfront costs for new infrastructure and equipment may not promptly result in sufficient returns. Maintaining positive cash flow, reducing financial risks, and guaranteeing operational stability all depend on quick returns on large upfront investments. Return delays might reduce chances for investing in new initiatives, restrict money, and raise vulnerability to technology or market uncertainty.

Adjustment periods to adapt to new technology, operational inefficiencies, and economic losses from errors further increase uncertainty. These expenses are especially significant for resource-constrained, small-scale producers. Operational mistakes that result in crop damage, lower yields, or higher input costs often occur when new technology is introduced into the farming operation, with profitability directly impacted (Feder and Umali, 1993). The expense of regular maintenance and repairs may increase due to learning curves associated with new technology, adding to short-term inefficiencies. As farm resources are diverted to accommodate new challenges, there may be additional opportunity costs incurred from adjustments necessary across the entire farming operation. For example, spraying a hayfield with Curtail, a combination of 2,4-D and clopyralid herbicides, forces a farmer or rancher to delay hay harvest for at least 30 days so that Curtail's active ingredients will be deactivated by sunlight and soil microbes (Davis, Johnson, and Jennings, 2020).

Most farmers recognize these costs as an investment. Most believe that once the technology is adopted and its promised efficiencies fully exploited, the returns on the investment will surpass the original costs. At the very least, it takes time for a farm manager to fully optimize the efficiencies expected from new technologies. Early adopters are especially vulnerable as they pioneer the use of a new practice or machine. Technology developers do not fully account for costs due to inexperience and design limitations (Rogers, Singhal, and Quinlan, 2014). Successful adoption is greatly facilitated if a farmer has sufficient financial resources to weather risks associated with early prototypes. Farmers without adequate resources gamble on an immediate payoff or risk significant losses from prototype failures. In these scenarios, the new technology may (1) not perform, (2) perform but cannot be sustained, or (3) perform but not at a sufficient level to cover investment and operational costs.

Additional uncertainties arise from the fit of the new technology within a production system. What works under controlled experimental conditions does not always translate to commercial-scale operations. For example, platform harvesters and in-field conveyors were introduced as aids to boost manual labor productivity for tree fruit harvesting. Unfortunately, these designs failed to consider that system productivity was limited to the slowest worker on the platform, as well as the variability of fruit growing on a single tree (USDA-ARS, 1998; Sarig, Thompson, and Brown, 2000). Several growers in Southwest Florida attempted to incorporate a conveyor belt system as a harvest aid for fresh market tomatoes. Conveyors improved harvest labor productivity by eliminating a worker's time spent carrying 30-pound buckets between a field row and crop collection truck or gondola. The productivity gains, however, were not sufficient to pay for the added capital costs of the conveyor.

Technology Transitions

Transition in technologies is not new for specialty crops. After an adaptation, it is easy to gloss over the operational challenges that had to be overcome. We offer several examples to illustrate the pressures that led to the transition, the uncertainties that impacted successful implementation, and the role of extension throughout.

Florida Sugarcane Harvest (1980–1990)

Before the 1970s, Florida's sugarcane harvest was difficult and labor-intensive, relying on a significant number of guest workers from Jamaica and the Bahamas (Nobuyuki, Emerson, and Walters, 2008). The development of mechanized harvesters offered to drastically decrease labor expenses and reliance on immigrant workers. While the transition offered a significant boost in harvest productivity, several obstacles arose. Mechanical harvesters weakened plant root structures, reducing the viable lifespan of a sugarcane stand from around 7 years to 4 years (Roka et al., 2010). While producers in regions with lower yields implemented mechanical harvesting in the mid-to-late 1970s, growers in other regions of the state did not switch over until the early 1990s. To close the gap, extension services provided training courses, held field demonstrations, and disseminated best practices. In addition, sugarcane breeding research shifted to identify varieties that could better withstand the rigor of machine harvesters. In the end, this assistance enabled wider adoption by lowering the perceived and real limitations of mechanical harvesters.

Michigan Tart Cherry Harvest (1960–1980)

Public pressure for workplace reform can amplify economic pressure to adopt new technologies. Michigan tart cherry growers in the early 1960s faced serious concerns in terms of labor availability and affordability to manually harvest their trees (Michigan State Extension, 2019). Farm labor union organizers effected strikes and walk-outs to increase Michigan tart cherry farm workers' earnings. The harvest window for tart cherries is relatively short, between 4 and 6 weeks. Consequently, any disruption in harvest labor services could result in serious economic ramifications for the growers. The labor market challenges motivated cherry growers to find harvesting solutions that were less dependent on migrant manual labor.

University researchers, growers and equipment manufacturers combined efforts to design and develop mechanical harvesting systems. Early prototypes were problematic and significant number of cherry trees were destroyed (Wright, Martinez, and Thornsbury, 2006). However, as research advanced, more sophisticated, less damaging mechanical harvesting systems evolved. In addition to improved equipment design, the tree structure and horticultural practices were reconfigured to better accommodate the new harvesters. Post-harvest fruit handling was fundamentally altered to include water cooling systems both in field and at processing facilities. During this time, extension educators were crucial in fostering dialogue between producers and equipment manufacturers, assisting in the identification and resolution of several technical issues that sprang up during the mechanization process (McManus, 2012).

Florida Citrus Harvest (1960–1970, 1997–2007)

Mechanical harvesting of Florida's juice oranges was explored for the same reasons that motivated Michigan tart cherry and Florida sugarcane growers—availability and cost of manual labor for harvesting. The first iteration of citrus mechanical harvesting (1960-1975) was driven largely by university and USDA-ARS researchers. These efforts did not achieve commercial success. Meanwhile, a series of freezes during the 1960s reduced juice-orange acreage in Florida to where concerns over sufficient harvesting labor were largely abetted.

The second iteration of Florida's citrus mechanical harvesting program (1995-2007) proved more successful. Equipment from the California almond and nut tree industries was utilized, and new canopy-shaking technology was introduced into Florida citrus groves. One fundamental difference from the first program was the greater level of engagement by growers in the second program. The Florida Department of Citrus (FDOC) created a special grower-led harvesting committee to coordinate research and development. The committee allocated more than $2 million each year for research and development projects conducted by manufacturers and university researchers. Extension faculty provided the harvesting council with vital data on machine performance and the development of fruit abscission products. Technological confidence expanded over this period, demonstrating the critical role of extension in promoting mechanical harvesting (Whitney, 2006).

Despite some commercial adoption, mechanical harvesting of juice oranges was never completely embraced. The "high-water" mark of 12,000 mechanically harvested acres in 2005 represented less than 2% of the total state juice orange acreage. Commercial adoption was concentrated in Southwest Florida, where larger, more uniform citrus plantations had been established.

In retrospect, extension faculty failed to fully embrace grower concerns about tree damage and post-mechanical "shiners."[1] A first impression of a freshly mechanically harvested block of oranges could be horrific. Broken tree limbs, leaf litter, and smashed fruit covered the grove floor. Many growers reacted negatively to these visual signs and concluded that tree damage was irrevocable. Most of the damage was superficial and a subsequent study indicated that long-term tree productivity was not adversely affected by mechanical harvesters (Mosley, House, and Roka, 2012). First impressions, however, proved hard to shake. After the initial group of early adopters, the perception of tree damage caused subsequent waves of adopters to wane.

An important condition for mitigating tree damage was that trees were well-nourished and healthy ***before and after*** mechanical harvesting. Ultimately, Florida's second mechanical harvesting program collapsed with the confirmation of citrus greening or Huanglongbing (HLB) in 2005. HLB, a bacterial infection, removed the ongoing assumption that trees were well-nourished and that vigorous trunk or canopy shaking only added stress to the trees, thereby exacerbating HLB impacts. HLB was the final factor in a list of other concerns that contributed to the slow acceptance of mechanical harvesting. In addition to worries about tree damage, growers expressed concerns about fruit quality, million-plus dollar capital investments per harvesting unit, inconsistent machine performance under varying grove conditions, and greater volumes of debris being handled at juice processing plants.

Florida Citrus Oxytetracycline (OTC) Injection (2023–Present)

Just as a catastrophic threat like HLB can discourage the adoption of some new technologies, it can also add significant pressure to find new solutions to address the threat. Millions of dollars have funded the development of numerous strategies to combat citrus greening, but a definitive solution remains elusive, underscoring the complexity of the disease and the ongoing need for dedicated research and innovation (UF/IFAS, 2023). When the OTC injectable bactericide was first proposed in December 2022, there was some doubt about its overall efficacy. Trees had to be individually injected by hand, which raised even greater concerns that this technology would be economically feasible. The bactericide was designed to mitigate the adverse effects of HLB, restore tree health, and enable trees to produce more fruit.

Prior to release, extension faculty worked closely with private companies and individual growers to develop an effective treatment formulation and administration protocol. Several large trials were established on growers' properties. Although these trials were under "crop-destroy" requirements, these growers enjoyed a front-row seat to observe how the proposed OTC bactericide could affect HLB-infected trees, including a noticeable improvement in tree health. Grower observations rapidly spread through the citrus industry. When OTC technology became available in early 2023, adoption was widespread. Growers participating in early trials innovated methods of bactericide injection that were more economical than predicted. Practical assistance for growers to implement technologies remains a priority (McGill, 2023).

Role of Extension Services

New technology adoption is often driven by high-stakes situations where farmers have no choice but to change. Given the time lag between developing and applying a new technology, it is crucial to build risk management strategies into the innovation process. As the pace of change accelerates, multiple perspectives must be integrated to ensure successful outcomes. However, even with decisive action, success is not guaranteed. This raises the question: How can extension services help increase the chances of success?

Holt (1989) emphasizes the need for extension services to evolve alongside technological advancements. A flexible, responsive extension service keeps stakeholders agile and informed about innovations and

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[1] A "shiner" is an orange remaining in a tree after a harvesting crew leaves a grove.

emerging challenges. On the other hand, misunderstandings and knowledge gaps create significant barriers to adoption. Extension agents must proactively address these challenges by staying current with technological developments, understanding farmers' unique needs, and adjusting communication strategies accordingly.

Effective knowledge diffusion has always been key to breaking down adoption barriers. While providing accurate, reliable information remains essential (Rogers, Singhal, and Quinlan, 2014), today's information-saturated environment demands more than just dissemination. Extension services must actively dispel myths and address misconceptions that hinder adoption. By offering clear, practical, and relevant information, extension agents empower growers to make well-informed decisions, ultimately enhancing productivity, efficiency, and satisfaction.

The role of extension services goes beyond communication—it involves building trust, offering technical support, and bridging the gap between researchers and practitioners. This includes broad awareness campaigns that highlight the benefits of new technologies through traditional channels such as print, radio, and television, as well as newer platforms like social media (Vanclay, 2004). Social media can be a valuable tool to reach a wider audience of growers and other stakeholders more effectively. Extension agents must encourage stakeholders to become active participants in development. The importance of the early involvement of growers has been demonstrated by the rapid adoption of OTC injections to combat HLB infection after several commercial growers participated in early trials.

Misinformation and incomplete information among stakeholders are one of the main obstacles to adopting new technologies. In some cases, stakeholders may simply be unaware of new technologies that could potentially help their operations. Extension professionals must learn about farmers' problems and levels of expertise firsthand. Information on the technical characteristics of developing technologies, potential advantages, and related costs is often lacking.

More challenging, however, is when stakeholders are fully aware of new technology but do not trust recommendations. The second citrus mechanical harvesting program in Florida (1997–2007) illustrated this point. Early impressions of damage from trunk and canopy shakers created doubts and made new growers cautious about venturing into mechanical harvesting. If the citrus mechanical harvesting program had continued beyond 2007, equipment refinement and operational adjustments may have reduced overall tree damage. More growers might have adopted mechanical harvesting for the sheer labor savings advantage.

Extension services must constantly adapt to the shifting demands of farmers and the agricultural sector to better support technological adoption. To remove obstacles, extension services must take the initiative to identify and solve them. Extension agents must also engage in ongoing professional development to stay current on the most recent advancements in technology and the most effective communication strategies.

It is essential to use communication techniques customized for the needs of various stakeholder groups (Vanclay, 2004). This entails tailoring messaging to the intended audience and utilizing a range of communication channels. It is necessary to establish monitoring and evaluation methods to gauge how well information distribution tactics work. This requires gathering input from interested parties, assessing the results of extension initiatives, and making ongoing adjustments considering these discoveries.

Conclusion

For new technology to be widely adopted in specialty crop industries, it is crucial to overcome barriers that delay the spread of information. Extension services play a vital role in reducing the risks associated with uncertainty and promoting technical innovation in agriculture. By effectively sharing knowledge through extension services, farmers can be motivated to embrace new methods that enhance productivity and sustainability as trust and confidence grow. Addressing knowledge gaps and grower concerns about unintended consequences from crop damage and higher operational costs can ensure that farmers receive personalized assistance and choose techniques that maximize efficiency and competitiveness.

Extension services bring academics, industry players, and farmers together to ensure that new technologies are useful and easy to use. The efficacy of these extension initiatives is critical to the specialty crop industry's acceptance of new technologies. These case studies demonstrate how important extension services are to fostering agricultural innovation and maintaining the industry's viability long-term.

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Balancing Challenges of Scale and Scope Economies in the Development of Labor-Saving Technology for Specialty Crop Production

Clinton L. Neill

JEL Classifications: Q16, J23, D24
Keywords: Change management, Labor-saving technology, Scale, Scope, Specialty crops

Technology adoption, often considered a fixed cost in the short run, is one of the key reasons why economists often argue for economies of scale in many agricultural operations (Stigler, 1958). Yet to increase the per acre value of an operation, economies of scope are also a common argument when evaluating whole farm enterprises (Fernandez-Cornejo et al., 1992). (See Box 1 for definitions of economies of scale and scope.)

Box 1. Definitions
Economies of Scale – The principle of scale economies is defined by the different types of production costs incurred, and a firm can cover those costs more efficiently by increasing the number of units produced. By reducing the marginal cost (cost per unit) of production, a firm can increase the amount of profit earned per unit (Stigler, 1958).

Economies of Scope – Economies of scope is based on the principle that goods/crops are easily interchanged within the production process (Fernandez-Cornejo et al., 1992). In the case of traditional row crop production, this could mean changing between varieties of the same crop or changing to an entirely different crop.

While economies of scale focus on the quantity side of the revenue equation, economies of scope often address price. Many farms growing row crops have taken advantage of economies of scale, but specialty crop operations must consider the scope, in terms of multiple varieties or crops, to optimize profitability. This is pertinent when considering the trade-off between perennial crops and annual crops, especially when considering varying pest and disease pressures. In other words, managing the risk of technology adoption in specialty crop operations is not as simple as spreading the cost across more acres.

Shifts in consumer preferences for a wider variety of produce that is locally, regionally, and globally produced and available year-round has placed a need for more efficient specialty crop systems. Such systems, though, depend heavily on labor and are the focus of much of the technological innovation within the sector. In general, finding labor locally is often difficult for larger operations and expensive for smaller operations—though it is often difficult and expensive for both, with different options to solve the issue (Castillo, et al., 2021). Larger operations typically look to workers from the H-2A Temporary Agricultural Program to fill their labor needs, which adds to the variable costs incurred, but these costs are somewhat alleviated due to economies of scale. Smaller operations typically lack the ability to hire H-2A workers and often look to family and part-time labor to fill their needs. Smaller operations also tend to be more diversified in crops and variety, leading to a need for more specialized skills and/or knowledge throughout the growing season.

Specialty crop operations must cope with both economies of scale and scope to meet their specific consumer demands while managing their varied and unique risks (Neill and Morgan, 2021). When it comes to the adoption of labor-saving technologies, proposed solutions must tackle the need for specialized skills while appealing to a wide range of operation sizes and geographic constraints. For example, wine grape growers in the northeast United States must contend with a different climate and terrain than their counterparts in California. This observation extends generally to the more than 270 American Viticultural Areas throughout the United States, where each growing region is better suited to certain varieties due to specific climate adaptations (U.S. Alcohol and Tobacco Tax and Trade Bureau, 2024). Between terracing and farming on contours to contending with drier or wetter climates, scaling labor-saving technology within one specialty crop across multiple geographies can be difficult if the technology is not flexible enough to accommodate the vast differences in regional production.

On the other end of the spectrum are small farms that predominately produce specialty crops for local consumption at farmers' markets and small grocery outlets. While most of the sales value throughout the country comes from a small percentage of large farms, small farms make up most of the farms in the United States (USDA-NASS, 2024). These producers take advantage of economies of scope to maximize profit and often switch out the varieties and mix of crops from one year to the next. While more localized production is often smaller than commercial operations,[1] the necessity to scale their operations is paramount if the goal is to maximize profits. Yet adopting labor-saving technology is often lacking unless it applies to multiple crop needs. For many local producers, the adoption of high tunnels, greenhouses, tractors, and tilling, and seeding equipment is common because they are crop-agnostic.

Given these variations in specialty crop production, the lackluster adoption of labor-saving technologies is no real mystery. However, it does beg the question of how we create change and encourage the development of labor-saving technology that can address the challenges of scope and scale. The remainder of this article offers three main ideas on this point and suggestions about where agricultural economists can contribute. First, labor-saving technology must be cost-effective to scale across the variation in farm sizes and diffuse across the market. Second, technology must have a generalized use or be easily adaptable to switch between crop types to address the scope problem on farms. Last, research and extension efforts must tackle the need to provide resources for managing the risks of labor-saving technology and how these risks interact with people throughout the production system.

Cost Effectiveness of Technology—The Scale Perspective

Many labor-saving technologies tend to be crop-specific based on the physical characteristics of one particular crop. For example, a robotic strawberry harvester with color-sensing technology that is delicate enough not to bruise a large portion of the crop would reduce the need to have workers in the field harvesting. Several companies have created such robots and made the following claims: Their robots are the answer to the labor shortage, they are time saving, they are precise (many do not touch the fruit), and they collect better data on quality and yield, among other benefits (Dogtooth Technologies, 2024; Organifarms, 2024).

Let us start with the perspective of large, commercial growers. While a robotic strawberry harvester may be labor-saving, growers understand the need to be reactive to in-season market prices. Thus, the timing of harvesting is just as important of a decision as how much to harvest and take to market. This decision becomes less complicated if robotic harvesters can get into the field quickly and pick strawberries as quickly as their human counterparts. Most sources find that human labor is much faster and harvests a greater amount. The adverse effect wage rate (AEWR) of H-2A workers in major strawberry-growing regions ranged from $14.50 to $19.75 per hour in 2024 (U.S. Department of Labor, 2024). The capital cost of each robotic strawberry picker is above $50,000 by many estimates. Given that an acre of fruit requires an average 720 labor hours for harvesting each year (Klodd, Tepe, and Hoover, 2021), a robotic harvester would need to harvest between 3.5 and 4.8 acres to break even, assuming the robotic harvester works as fast as human laborers (Guillaumot, 2023). At the prevailing AEWRs, the cost of human labor per acre is between $10,440 and $14,220.

Let's now look at scaling this technology across the number of strawberry farms in the United States to better analyze how the potential demand could affect the cost-effectiveness of the technology itself. According to the 2017 Census of Agriculture (USDA-NASS, 2024), 9,000 farms produced approximately 60,000 acres of strawberries, for an average farm size of 6.7 acres. Looking more at the farm size distribution, 90% of strawberry farms in 2017 were 8 acres or less. If we were to examine the harvesting labor cost of an 8-acre strawberry farm at the high end of the AEWR, the total labor cost would be $113,760 (Santiago et al., 2021). This would require at least 2 robotic harvesters for any farm above 3.5 acres for a total robotic harvest cost of at least $100,000. This would be discounted over time with multiple years of use, but it only serves a single use, while human labor can be utilized in other types of farm labor. Moreover, even with rotational planting to allow for one acre to be harvested at a time during a 14-week season, the grower would likely lose money given the timing of price fluctuations under the robotic harvester only situation.

This means that for the vast majority of strawberry farmers, this particular robotic harvester is not cost-effective (Cruse, 2022). This leaves only 10% of farms as the main buyers of this technology, likely not enough to drive the costs of the technology down to be more widely adopted. Becoming cost-effective at replacing a

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[1] The definition of a commercial operation varies and can be subjective based on size of operation in acres, sales, or geographic distribution. For the sake of discussion, commercial operations here are those classified above the Small Business Administration's threshold within the specific industry code found at https://www.sba.gov/sites/default/files/2023-06/Table of Size Standards_Effective March 17, 2023 (2).pdf

large portion of harvest labor requires the demand for the technology extend beyond large operations. The fact that many farms would likely need multiple robotic harvesters to optimize day-to-day price fluctuations increases the per acre cost, even for large growers.

At the same time, it seems extreme for anyone to assume that the harvesting technology would completely replace all labor hours. A better example would be to replace a percentage of the harvest labor. Having one machine for smaller farms to do a first pass, to focus on part of an acre, or to harvest for a more consistent buyer (a weekly distribution to a farmers' market or farmstand, for instance) are potential ways to spread the fixed cost over a small number of acres, although the payback period would be extended.

Another option would be to utilize the technology to optimize/lengthen the harvest timing/day. If the robotic harvester can start earlier in the day or go later into the day than humans, then a larger total area could be harvested per day. There are creative ways to augment the human labor aspect of harvest, but complete replacement is generally cost-prohibitive. Plus, the demand for such harvesters would still be limited to a very small number of farms given the current costs. Moreover, the farm owner/operator would still need to generate enough income to support themselves or have time to earn income off-farm. All of this is to say that labor-saving technology for specialty crops must scale both on farms and across industry to be cost-effective.

General Use Technology on Farm—The Scope Perspective

The pursuit of technology development and eventual adoption of technologies by the specialty crop sector is motivated by a simple fact: technologies need to be beneficial across the scope of the whole farm. This fact is particularly relevant for smaller farms, which make up a majority of specialty crop producers. Many small farms in the specialty crop sector are highly diversified in the type of crops they produce, as they are focused on local sales and consumption. As such, the cost of crop-specific technology is often cost-prohibitive. For these producers, a labor-saving technology needs apply to the scope of the whole farm. Tractors are one of the most prominent labor-saving technologies adopted by small farms. While this example may seem outdated, tractors offer a model for future labor-saving technologies given the extensive amount of research conducted on this topic. As noted in Ankli and Olmstead (1981), the tractor was clearly an advantage on large monoculture-focused and small diversified farms in California. They found that this was due to the high fixed costs associated with horses and also the ability to use tractors across different crops.

While the tractor initially did not reduce harvest labor costs, it did save the time of the owner/operator. The diffusion of tractor technology was initially seen as inefficiently slow, though the reality is that the adoption of this labor-saving technology increased with the utility of the tractor and the development and improvement of implements for the tractor (Martini and Silberberg, 2006). Not only were tractors more cost-effective than horses, they also provided adaptability through the use of various implements, which enabled tractors to address the scope problem of the farm.

Labor-saving technologies for smaller, more diversified specialty crop operations must address economies of scope. At the same time, labor-saving technologies that are versatile across operations of different sizes, even if those operations are monocultural, are likely to have larger markets for adoption. While a specialized technology can solve specific labor issues, it will have a limited market. A technology that addresses the economies of scope within a specialty crop operation and across the entire specialty crop sector will likely see more success within the overall market.

Managing Change Through Research and Extension

While the development of labor-saving technology is important, the key is to build upon our knowledge of all aspects of specialty crop production. Creating technology to replace or augment labor just for the sake of doing so ignores the impacts on profitability across the whole farm and income earning on and off farm. Managing the risks of technology, both from financial and labor-related, is vastly different in specialty crops as compared to traditional row crops. Thus, researchers and extension services must cater to the specific needs of the specialty crop industry.

Research on specialty crop development, frequently funded by the USDA's Specialty Crop Research Initiative grant program, is often initiated by lead investigators who have an idea for a new technology or the development of new varieties. Yet agricultural economists are rarely consulted in the core idea development stage. Instead, they are consulted as a necessary component to determine whether the project will lead to financial and market feasibility. This does a disservice to the field of agricultural economics as a vital component of idea generation and to specialty crop producers, who require *affordable* labor-saving technologies. Agricultural economists need to encourage our interdisciplinary collaborators to include them in the idea generation stage rather than proposal development.

From an extension perspective, many programs have been targeted to assisting small and mid-sized farms with business planning, enterprise analysis, and whole farm budgeting. But, as List (2022) notes, people do not scale. In fact, one thing has not changed since Holt's (1989) article: Extension professionals are often charged with running multiple programs and are asked to do more each year without a change in resources, responsibilities, or training. Extension resources continue to be stretched thin over a decreasing number of people. Change is not simply an inevitability for extension; it is truly the only constant. To manage that change, extension professionals need proper support in terms of finances, time, and people. New programs, often funded by research programs, must be assessed by their opportunity gain (cost) and the potential long-term viability of the program. Agricultural economists can better assess these costs if, again, they are consulted in idea generation rather than proposal development. With proper planning, future labor-saving technology can address the scale and scope issues within specialty crop production.

Conclusions

Several concepts were discussed in this article, but the main focus was the scale and scope issue faced by potential adopters of labor-saving technologies in the specialty crop industry. While I provided two specific examples, and certainly not perfect representations of either, there are a plethora of applications for the economic trade-offs that specialty crop producers must consider when it comes to technology adoption. Scaling production is feasible for only a small percentage of specialty crop growers, which means that driving down the cost of a labor-saving technology through a larger market is a slow, if not impossible, task. For many small producers, crop-specific technology is often less useful than general technological advances due to on-farm economies of scope.

But this does not mean there is no hope. Instead, it is up to agricultural economists to step forward and engage with transdisciplinary teams of researchers and producers earlier in the idea generation phase when labor-saving technologies are developed. As Holt (1989) notes, the human element of change management is key and cannot be substituted by technology. Agricultural economists are the experts when it comes to analyzing and managing risk, and there are a vast number of prospects to find the opportunity gains for specialty crop producers.

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Skill Economies Address the Supply Chain Squeeze

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Some economists (e.g., MacDonald, Hoppe, and Newton, 2018; Hamilton et al., 2021; McFadden, Njuki, and Griffin, 2023; Lee et al., 2024) question why we are witnessing a decades-long disconnect between the adoption of labor-sparing technology and application of precision agriculture (PA), artificial intelligence (AI) tools, and big data analysis. We begin exploring answers where Lloyd Fisher picked up in 1951 and proceed with the necessary conditions to move “the structureless market” into a market that is characterized by the skills of an organized workforce. In this article, we propose avenues of exploration where economists and economic principles may lead research efforts that identify labor-sparing, profitable, solutions that will be maximize benefits (not limited to wages) for the workforce and likewise incentivize adoption by U.S. producers.

In 2015, large and very large specialty crop farms employed 0.72 labor hours per sales dollar full-time-equivalents (FTEs) annually per $100,000 of gross cash farm income, three times higher than the number of FTEs per sales dollar employed on comparably scaled cash grain farms (MacDonald, Hoppe, and Newton, 2018). Much of this difference is due to the seasonal and perishable nature of fresh fruits and vegetables, which limit storability and shelf life. Though operating costs represent just one side of the profit equation, we contend that it is the unpredictable and wide-ranging variations that present growers with greater challenges in planning how to best reduce risk exposure. For example, the Florida adverse effect wage rate (AEWR) for H-2A workers is projected to go up 9.9%, effective immediately upon publication by the U.S. Department of Labor in December 2024 (Ayoub, 2024), directly in the middle of the Florida specialty crop growing season. While costs may be offset by increases in cash receipts, which rose 12% to $8.8 billion in 2022, labor expenditures alone increased 49% to $2.81 billion from 2022 to 2023 in Florida (USDA, 2024a,b). Specifically, access to reliable labor continues to plague Florida produce growers, who sourced 51,987 H-2A positions in 2023 to fill the industry-wide gap (U.S. Department of Labor, 2023). Nationwide concerns around labor access and rising wage rates continue to motivate grower interest in the adoption of labor-reducing technology.

Since the turn of the century, economists have analyzed the trade-off between human work (labor) and automation or mechanization (capital) within the context of existing and available technologies. Hamilton et al. (2021) investigated the slow adoption rate of mechanical harvesting in U.S. agriculture and concluded, “If farmers are less willing to invest in capital that ultimately leads to higher wages, then long-term productivity growth is likely to be lower, and the problem will persist (p. 1456).” Additional research showed that, not surprisingly, adoption rates of digital agriculture (DA) technologies in row crops varied by farm size and that technology adopters are more likely to download public data when making farm decisions (McFadden, Njuki, and Griffin, 2023). The Cooperative Extension System (CES) is tasked with diffusing technical change to agricultural decision makers, yet insights from a survey of 255 CES educators “emphasize the importance of addressing the human and social dimensions of knowledge transfer to overcome the historical challenges of delayed adoption (p. 18)” (Lee et al., 2024).

Following John Holt’s prescription in his 1989 AJAE article “Managing Change in Extension,” we must first assess “forces of change” to set expectations for results based on a long-term perspective. To acquire a sense of emerging niches and the competitive context, economists are uniquely positioned to evaluate the perishable food system to determine (1) how to distribute human resources and (2) how to grow human skillsets to enhance individual and farm-level wellbeing across the food system.

Economies of Skills

We contend that there exist “economies of skills” (see Box 1) with the potential to drive systems-wide solutions that utilize relatively cheap technology with the goal of maximizing human productivity. This approach requires that we view the entirety of fresh fruit and vegetable supply chains, look at where people are, and use these observations to inform the development of technology

Box 1. Economies of Skills

Economies of skills are built in to humans and drive our capacity to co-create technologies and produce long-term competitive enterprise solutions. The fresh produce industry historically attracts students and stewards of the land, air, and water resources, who instinctively and rapidly adapt to the unknown. Learning is a two-way street between the business and the humans. Economic models must incorporate data beyond changes in average and marginal output levels. Now is the time for the agriculture industry, which is traditionally a 365/24/7 business model, to identify human factors beyond pay rates for hours worked. Instead, find where each person's innate abilities and core values exist and can be captured to improve overall business performance. Driving the decision-making process with skill economies at the forefront allows a business to discover how best to select from choice sets of production practices that incorporate labor-sparing technical improvements.

with the goals of improving our most valuable and constrained resources—the people themselves

We propose an examination of the opportunity costs inherent to the human and machine co-learning environment, where humans and technology evolve dynamically to achieve the goals of the farm and the people on whom the farm depends. Or as explained by Extension economist Kenny Burdine (2024), when he calculates profitability specific to understanding how to address unpaid operator labor:

> I tend not to treat labor as an expense but instead make the point that any return must be sufficient to adequately compensate the operator for the time they spend. Sometimes an hour of operator labor is not just an hour of operator labor, especially if there are a lot of other expenses being incurred during that hour.

In his discussion, he noted that these "other expenses incurred" beyond the operator's time may vary in proportion from low-tech fence clearing tasks using pruning shears to baling hay using a tractor and hay baler.

Building on Burdine's observations, we extend our awareness to envision how the opportunity costs of integrating humans and technology are not limited to direct trade-offs, rather, they move codependently and dynamically. To postulate what economic realities are needed to support the fresh produce supply chain going forward, grower interviews provide invaluable insights:

> I recognize the younger generations are tech savvy. That's partly true. The more specific truth is the younger generations are technology *dependent*. So they look for and place a high degree of trust in information sources from technological feeds. They're not like an agronomist who feels the ground with their fingers to determine moisture; They want a sensor to provide that information. So how do we collect the data through technology to allow smart decision makers to utilize that, to drive efficiencies? (Wilson, 2023a).

From this viewpoint, it is no longer a question of X machine solving Y problem for decades to come, all other things held constant; rather, it is using what you have (a tech-trusting workforce) to get what you want most (competitive enterprises).

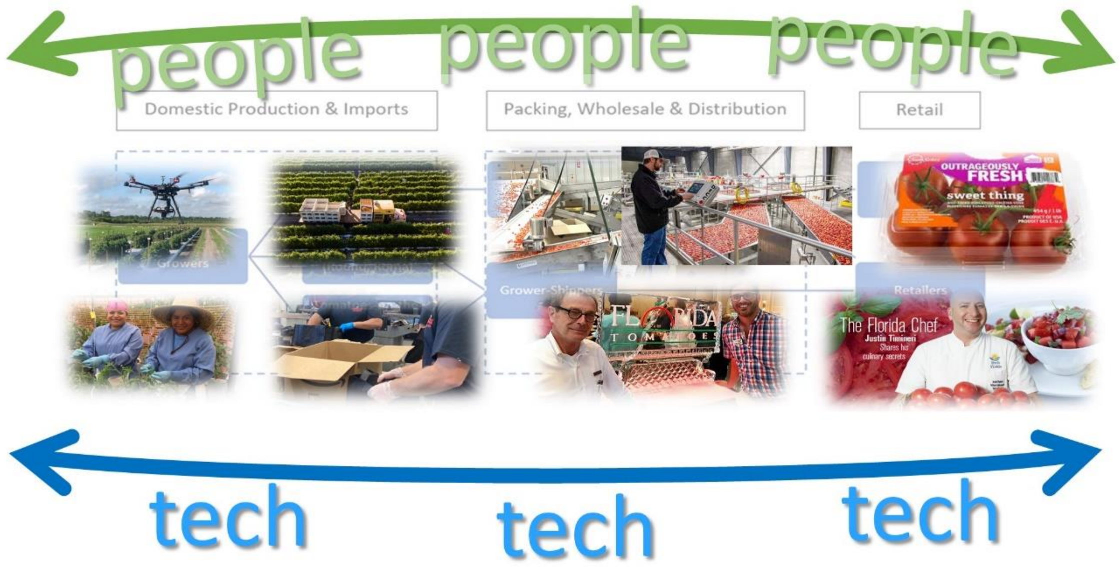
Economists define inputs belonging to a farm business as either land, labor, or capital, which they allocate according to scarcity constraints. Beginning at the long-run production planning stage, growers account for land allocation and usage, the amount and type of (skilled/unskilled) work, and the existing technological investments. As cost-minimizing agents, growers seek production systems-level solutions that utilize the cheaper inputs. Philip Martin, in his keynote talk at the 2024 "Changing Landscape of Farm Labor Conditions in the US" event, shared proxies for these resources, where imports (land), migrant workers (labor), and machine (capital) allocations motivate specialty crop growers' decisions. His observations were built on evidence that human resources employed by the agricultural industry may achieve economics of skills should growers choose to focus on recruitment, remuneration, and retention (Martin, 2017).

Growers echo Fisher and Martin by clarifying exactly where the solution point is in bringing along human skillsets and technical tools:

> The labor needed to drive a tractor is not what's killing me; the labor killing the weeds is what's killing me. If you're going to charge $1.4 million for a device, we're perfectly fine attaching it to a tractor that already has a power source and putting a human in charge of keeping that equipment safe. (Wilson, 2023b)

In the specialty crop world, labor is the number one explanation behind a grower's interest in alternative technologies. The driving forces may be the constantly changing regulations related to labor, degree of access to quality labor, unpredictable wage rates, limited training, housing, or medical care for employees in the community, etc., which affect a grower's decision to adopt a new production system. Growers who find ways to achieve skill economies year-round on the farm are much more likely to diversify through adoption of an

Figure 1. Economies of Skill Approach Examines the Technology and Human Co-Learning Environments to Better Identify Where Marginal Gains Exist Through Dynamic Evolutions Along Fresh Produce Supply Chain



Note: This example depicts the open-field grown tomato supply chain pictorially, from inputs to farms to processing to markets and marketers (graphic created by the author).

emerging technology, whether it be a new machine, an environmentally friendly technique, or a storage and distribution management process.

Adoption Hurdle: Change Is Great, but Transitions Are Costly

There is a need for improved understanding of the roles and dynamic interactions among participants in the fresh produce supply chain to improve industry coordination and competitiveness, expand U.S. market demand, and build in supply chain resiliency (Morgan et al., 2022). U.S. farms growing perishable and seasonal food have achieved gains through economies of scale and scope, largely dependent on production management decisions. Many produce farms have a corporate structure and grow nearly year-round on owned and leased land throughout the United States and abroad. Such operations have farms strategically located and follow the progression of seasons to provide a year-round supply of produce as demanded by retail and foodservice buyers. Medium-sized farm operators are finding ways to collaborate to meet buyer needs, and technology-driven tools offer savings in time and resources needed to gather market information. Given that market access and market share drive profitability, technologies built to gather and organize data along the supply chain, from farm to fork, are emerging that reduce the cost of knowing and empower economic agents to make timely, informed decisions (Morgan, 2023).

Author interviews with growers revealed that those who owe more on their capital than they own of their primary asset (land) did not have funds available to support a decision to adopt and further invest in automation or mechanization technology. Likewise, those who rented land did not find value in capital investments aimed at improving productivity of the land itself, as they themselves were not gaining the added long-run value and the landlord often raised the rent as increased returns were capitalized into their land's value. Educators and researchers alike need to listen when a grower tells us so: “Try to learn without losing too much. Farming is a science-based profession and anytime you modify practices it could pose a significant threat to your livelihood” (Wilson, 2023c). Growers add that while innovations are always attractive, the upfront and ongoing costs of adopting may result in near-term inability to pay bills.

Without a credible answer to “where are the technical minds and time needed to find and adjust to my farm needs?” most growers will not expend time and resources exploring alternative ways to doing things differently. The newest gadget might be capable of saving a grower many hours of headaches or generate substantial projected increases in the grower's bottom line, but the farm owner's major investment is in the land. In a recent focus group with large-scale Midwestern row crop growers, we discovered each participant actively supports shared long-run goals of sustainability and soil health but reminds researchers that their families need to put food on the table today. These growers also noted that they need advisors willing to stand in fields and equipment barns to assist in all stages of technological solutions development. Given diminishing numbers of Extension professionals, coupled with reduced programming budgets and increased workloads (Wang, 2014; Narine, Harder, and Zelaya, 2019), most farm advisors are in the form of input supplier representatives or consultants. Further, Lee et al. (2024) concluded that "With the current agricultural challenges and the increasing demand from farmers to use technology… it would be challenging to expect Extension change agents to promote agricultural innovations to clients without effective training (p. 21)."

In numerous Extension-led stakeholder meetings, growers clearly communicate that they are willing to pay exactly what a new piece of technology is going to add to their bottom line, no more and no less, which tracks with our economic model assumptions that growers make rational decisions. As economists we can look at it this adoption question differently. When a grower considers investing in any fixed asset, the decision is not limited to the purchase price, or whether they can cash flow the monthly payment, no matter how convincing an argument the salesperson tries to pencil out or the interest rate. Instead, their decision has everything to do with their perceptions of what the next new machine may be in the immediate future, which indicates their understanding that technologies are changing at faster and faster rates.

As educators it is imperative that we first understand the context facing an individual grower and frame the decision to adopt based on the farm's available human resources and real-time knowledge, skills, and abilities. Instead of asking what will they pay for XYZ tech, build in return on investment timelines that includes answers to "How does it plug into existing human skillsets? What are the synergies with existing equipment? How long until it becomes obsolete and what is the replacement plan? Does it require electricity or internet and is there another way to make sure we have backup energy sources?" These and many other key questions are all part of the decision making that extends well beyond the large amounts of data collected from farm equipment or smart applications offered by input suppliers (McFadden, Njuki, and Griffin, 2023). Viewed through the eyes of a grower, it is apparent that U.S. food supply chain vulnerabilities as identified by the USDA (2022) *Agri-food Supply Chain Assessment* are driven by disconnects, delays, and misunderstandings across the spectrum of available people, knowledge levels, and constrained skillsets.

Adoption Hurdle: Partnering with Intent

People working in agriculture are tasked with assessing the five major agribusiness risks, which include issues specific to production, marketing, human resource, legal and regulatory, and financial components (Neill and Morgan, 2021). It is critically important that educators recognize the entirety of our learner audience extends well beyond farm owners and managers, college students, or folks who just want to grow their own food. Indeed, our wider audience incorporates all who touch the global food and fiber system, all of whom need practical skills and a portfolio of expertise. Our dynamic perspective widens to recognize the importance of produce buyers and retail store managers who want their consumers to have the best produce yet have no exposure to food production realities, financial institutions, and venture capital investors who may see the opportunity but misread the regulations, policy makers tasked with describing social welfare across all economic agents, middle managers of global food companies tasked with sustainably sourcing foodstuffs, private consultants with narrow and wide-ranging degrees of knowledge depth, nongovernment organizations (NGOs) with a mission to advocate for human needs and wants, environmental activists with differing yet parallel goals to agriculture, all alongside a population dependent on health care professionals and community leadership. To create and capture skill economies, newly imagined partnerships and liaisons across this interrelated paradigm of actors await the dynamic thinkers and doers within our midst.

Adoption Hurdle: Learning By Doing

Traditional degree programs require large commitments of time and finances to complete and are focused on one or two major areas of study, and geographic access and practical applications are often limited. After conversations with members of the agricultural community, there is a clear need for foundational training in risk management that better prepares students to deal with dynamic challenges that demand holistic solutions under time constraints. Specifically, a recent panel of Southwest Florida producers identified and described major limiting factors when adopting technologies. First, producers struggle to locate and hire workers who can operate the technology and then collate the massive amount of data into a useful form (i.e., reliable information) needed to inform better decisions. Second, producers lack trained technicians who are available when needed to fix expensive machines when they break. In the absence of such technicians, producers must idle the broken machinery for extended periods, which generates revenue losses that can be exacerbated if market prices are declining day by day. Other growers shared that they are unable to retire from daily farm operations as they cannot find anyone qualified to take over their duties or interested in a lifelong career in production agriculture. Further evidence supporting their concerns are college scholarships offered by agricultural companies to high school students with the guarantee of employment after graduation that remain unfilled due to a lack of interest.

In Sum

After decades of delivering economic risk management extension programs, we are familiar with the need for shelf-ready programs built and delivered by trusted Extension professionals. Labor markets tell us they value and reward people whose skillsets are verified through assessments conducted by a third party, as this communicates the added value each graduate brings to their employer and/or clientele. We at the land-grant universities, research and education centers, and county offices tasked with managing change in our extension roles have a natural advantage in long-standing cultivated networks within rural communities, yet we are often bogged down by the weight of our own habitual ways of doing and standard metrics of success. Given our understanding of these pressure points along food supply chain, we are positioned to answer key questions, such as:

- Where is optimal placement of tech-savvy skilled humans along fresh produce supply chains?
- What is the optimal place to locate and develop technology-based fixes along the fresh produce supply chain?
- How can we optimize production systems to gain and maintain the attention of a workforce who values equitable sharing of business risks and entrepreneurial opportunities?
- Why limit the definition of labor input into agricultural production to hours worked in the field; instead, include things like the development of agricultural technologies?
- What are the marginal gains to investment in skill economies when expanded across different asset mixes, land and nonland?
- How may the framing of our labor resources as skill economies lead to improved farm owner choice sets available (including, but not limited to, tech adoption) to manage risks through diversification, collaboration, co-operation, etc.?

As extension economists, we are capable of “capitalizing on today’s strengths while building tomorrow’s niches (p. 869)” (Holt, 1989). With input from the clients and environments wherein we serve, we can (and DO!) attract learners and provide skills-based tools and training to people on the frontlines of change who must identify, manage, and mitigate elements of economic risks, known and unknown. Economies of skills that are built-in to the humans of our industry drives our capacity to co-create technologies and produce long-term competitive enterprise solutions. As Fisher (1951) stated, “These are not novel suggestions…The reasons for their rejection are too many… but technical infeasibility is not one of them (p. 491).” Now is the time for the agriculture industry to focus first on those factors that motivate human wants and needs and then how to manage production decisions with technical improvements. Bridging the gap between labor-sparing technologies and progressive fresh produce systems demands that we find “the will to continue to develop products that are not yet being demanded, but which we know are needed (P. 873)” (Holt, 1989).

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