Perceptions of Precision Agriculture Technologies in the U.S. Fresh Apple Industry

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ADDITIONAL INDEX WORDS. *Malus domestica*, technology adoption, tree fruit

SUMMARY. Advances in precision agriculture technologies provide opportunities to improve the efficiency of agricultural production systems, especially for high-value specialty crops such as fresh apples (*Malus domestica*). We distributed an online survey to apple growers in Washington, New York, and Michigan to elicit stakeholder perceptions of precision agriculture technologies. Findings from this study demonstrated that growers are willing to adopt precision agriculture technologies when they receive results from applied research projects and are engaged with active extension programs. The availability of customized services and purchasing and rental options may minimize the effects of the economies of size that create barriers to adopting increasing access to technologies. Finally, respondents deemed collaborative efforts between industry and academic institutions crucial for adapting the innovation to better address the needs of growers.

Precision agriculture technologies have been successfully applied in a number of U.S. crop production systems over the past few decades (Gebbers and Adamchuk, 2010). Early applications focused on yield monitors and global positioning satellite technology for annual row crops (Schimmelpfennig and Ebel, 2011). Recent advances in soil sensing (Rossel et al., 2011), crop sensing (Roberts et al., 2012; Zhang and Kovacs, 2012), and data analytics (Landrum et al., 2015; Tien, 2013) have set the stage for the next wave of precision agriculture applications (Lowenberg-DeBoer, 2015). However, the adoption of more advanced precision agriculture technologies has generally lagged behind other agricultural technology developments (Schimmelpfennig and Ebel, 2011), with relatively few producers using remote sensing, soil sensing, or variable rate application technologies. Lagged adoption has been attributed to several factors, including capital requirements (Pierpaoli et al., 2013; Schimmelpfennig and Ebel, 2011), insufficient agronomic research tailored to precision agriculture (Bramley and Trengove, 2013; Cambouris et al., 2014), and lack of grower time and technical expertise for information-intensive management (Aubert et al., 2012; Griffin et al., 2004; Pierpaoli et al., 2013; Schimmelpfennig and Ebel, 2011).

The adoption of precision agriculture technologies has been particularly slow for many specialty crops, such as the U.S. tree fruit industry (Schimmelpfennig and Ebel, 2011). However, many commercial firms recognize that these technologies have the potential for use in tree fruit production. A variety of precision agriculture services are available, including remotely sensed canopy maps (Digital Harvest, Pendleton, OR), precision soil mapping and pre-planting nutrient management (AgVerdict, San Francisco, CA), and sensor-based irrigation management (METER Group, Pullman, WA). Although high-value tree fruit industries invested substantial capital in expensive technologies like high-density orchard plantings, engineered trellis systems, and high-capacity sorting and storage equipment and facilities, growers lack confidence in precision agriculture technologies that have not demonstrated horticultural improvements, labor efficiency, fruit yield, quality, or—ultimately—profits.

Despite the higher value of tree fruits compared with annual row crops, little precision agriculture research exists for tree fruit systems (Aggelopoulou et al., 2013). Research of precision agriculture for Florida citrus (*Citrus* sp.) has addressed nutrient spatial variability (Mann et al., 2011c; Schumann, 2010; Zaman et al., 2005; Zaman and Schumann, 2006), soil physical properties (Mann et al., 2010, 2011b), and citrus management zone delineation (Mann et al., 2011a). Work regarding deciduous tree fruit like apples and orchards has addressed spatial variability (Turker et al., 2011; Vega et al., 2013) and zone-based management in Greece (Aggelopoulou et al., 2011a; Aggelopoulou et al., 2010, 2011b, 2013; Papageorgiou et al., 2013). Scattered studies exist for other perennial crops such as olive [*Olea europaea* (Fountas et al., 2011)], pear [*Pyrus communis* (Perry et al., 2010, 2018)], and kiwifruit [*Actinidia deliciosa* (Woodward and Clearwater, 2012)].

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.4536	lb	kg	2.2046

Received for publication 25 Oct. 2018. Accepted for publication 16 Jan. 2019.

This research was funded by the Washington State University (WSU) College of Agriculture Human and Natural Resources (CAHNRS) Emerging Research Issues (ERI) Internal Seed Funding Program, 2016 project "Sensor-Based Precision Orchard Management." The Principal Investigator is David J. Brown, WSU Crop and Soil Sciences Department.

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https://doi.org/10.21273/HORTTECH04214-18

The production value of fresh apples in the United States was \$3.1 billion in 2016. The top three apple-producing states were Washington, New York, and Michigan, with annual production values of \$2.26 billion, \$0.26 billion, and \$0.21 billion, respectively (U.S. Department of Agriculture, 2017). Apples are a high-value crop, with improved cultivars selling at premium prices. High-density plantings require a substantial initial investment and ongoing management expenses, with positive cash flows often deferred 4 years or more after orchard establishment. For example, establishing a new 'Gala' orchard costs ≈\$9500/acre (initial one-time cost) and more than \$3500/acre for horticultural management (recurrent operating cost including activities such as pruning, training, thinning, irrigation, and labor); these costs do not include harvest or fixed costs for trellis, irrigation, land, insurance, and equipment (Galinato et al., 2016). Establishment and management costs are similarly high for other woody perennial crops. Additionally, the lack of availability of seasonal labor, which accounts for ≈46% of production costs, places further pressure on orchard profitability (Galinato et al., 2016). Given such high management costs and value for high-quality products, there is substantial potential for precision agriculture technologies to improve labor and resource efficiency, horticultural practices, fruit quality, and profits for apples and related crops (D. Brown, personal communication). In fact, there is evidence from studies of other high-value crops such as wine grape (*Vitis vinifera*) indicating that variable rate applications of inputs imply greater economic and environmental benefits compared with uniform management (Arno et al., 2009).

This study investigated the industry's outlook regarding precision agriculture from multiple perspectives, such as where precision agriculture could be more impactful, state of familiarity with and use of precision agriculture, the role of agricultural service companies and consultants in facilitating access, and benefits derived from the technology. We expect such information will be useful to researchers and extension educators because it will allow them to more effectively plan and perform their activities to increase the adoption of precision agriculture for tree fruit production.

Materials and methods

In Nov. and Dec. 2017, we surveyed apple growers in Washington, Michigan, and New York regarding the 2017 apple production season. The survey was administered online via survey software (Qualtrics, Provo, UT) using electronic mailing lists managed by extension educators at Washington State University, Michigan State University, and Cornell University. Institutional Review Board (IRB) approval was granted by the Washington State University Office of Research Assurances to the project "Assessment of the Perceptions for Precision Agriculture Technologies by U.S. Apple Producers" (IRB 16877). The electronic mailing lists consist of 350 apple operation contacts in New York, 1200 in Washington, and 325 in Michigan. We obtained a total of 119 responses: 49 from New York, 43 from Washington, and 27 from Michigan.

We devised the survey questions using input from industry representatives and extension educators. Respondents were asked to rank the top three challenges they encounter in fresh market apple production, to report their familiarity with three precision agriculture technologies (remote sensing for canopy mapping, precision soil mapping and nutrient management, and sensor-based irrigation management), and to indicate whether they used any of the technologies. The survey also asked respondents to rank the top three benefits and top three concerns they perceive from adopting precision agriculture technologies. In addition, respondents were asked about the number of years during which they had used such technologies, and whether they were considering investing in these technologies. Finally, respondents were asked to select their most trusted source of information regarding applying precision agriculture technologies, and to indicate the value of agricultural service companies' and consultants' expertise for guidance and implementing precision agriculture technologies. Data were analyzed using different empirical specifications according to the dependent variable in the model or question of interest.

CHALLENGES ENCOUNTERED IN FRESH APPLE PRODUCTION. We chose an ordered probit model to analyze growers' perceived challenges in apple production because the response variable characterizing the importance of challenges was discrete and ordinal. Respondents were asked to select their top three from a list of 11 challenges. The most important challenge was assigned a value of 11, the second most important was assigned a value of 10, and the third most important was assigned a value of 9. Challenges not considered among the top three were assigned a value of 6 (the median of 1 and 11). This method has been used for previous research to elicit the level of importance for product attributes (Davis and Gillespie, 2004; Greene and Hensher, 2008). It is assumed that a producer's challenge ranking is associated with an underlying utility level of satisfaction or perceived benefits. Producers ranked challenges according to the level of benefits they would receive if a solution to that challenge were provided (Yue et al., 2013, 2014a, 2014b, 2014c). The producers' utility function was represented by the following:

$$
\begin{aligned}
U_{ij}^{challenge} = {} & \alpha_0 + \alpha_1 Laborharvest_i \\
& + \alpha_2 Laborpreharvest_i \\
& + \alpha_3 Laborsupervisor_i \\
& + \alpha_4 Pestdisease_i + \alpha_5 Weather_i \\
& + \alpha_6 Water_i + \alpha_7 Postharvest_i \\
& + \alpha_8 Foodsafety_i \\
& + \alpha_9 Newcultivars_i \\
& + \alpha_{10} Markets_i + \alpha_{11} Other_i \\
& + \beta_{12} Size_i + \beta_{13} Washington_i \\
& + \beta_{14} Michigan_i \\
& + \beta_{15} NewYork_i \\
& + \beta_{16} Univresearcher_i \\
& + \beta_{17} Agservice_i \\
& + \beta_{18} Othergrowers_i \\
& + \varepsilon_{ij}^{challenge}; i = 1, \ldots, 119 \text{ (n)};
\end{aligned}
\quad [1]
$$

where α_j is the producer's marginal utility from solutions to challenges j (j = availability/cost of labor for harvest activities; availability/cost of labor for preharvest activities; availability/cost of intermediate supervisory labor, both harvest and preharvest; pests and diseases; weather; water; postharvest handling; food safety; productivity and profitability of available scion and rootstock cultivars; competing markets; and other challenges); β_{12} is the marginal utility from the size of the operation; β_{13}, β_{14}, and β_{15} are the marginal utility from the state (Washington, Michigan, and New York, respectively) in which the operation is located; β_{16}, β_{17}, and β_{18} are the marginal utility from the most trusted sources (university researchers and extension educators, agricultural service providers, and other growers, respectively) of information for applying precision agriculture technologies; and ε_{ij} is the error term, which is assumed to follow a normal distribution with a mean of 0 and standard deviation of σ_E.

When estimating model coefficients with Eq. [1], we selected the "other" challenge category as the base variable for interpretation. In this type of model, to avoid perfect multicollinearity, one must use a base variable for comparison. That is, the estimated coefficients of the challenges are all relative to the base variable "other." Similarly, for the binary state variables, New York was omitted and treated as the base variable. Challenges with positive statistically significant coefficients were more likely to be chosen as most important compared with the "other" category, and challenges with negative statistically significant coefficients were less important. To predict the probability that a challenge would be ranked in each ranking category (i.e., first, second, and third most important), we estimated the marginal effects. In other words, a marginal effect of 0.49 (as presented, for example, in Table 2) suggested that the category "availability/cost of labor" for harvest had a 49% chance of being chosen as the top challenge in relation to the "other" category.

Familiarity with and use of precision agriculture technologies. We used a separate binary probit model to analyze how familiar growers were with precision agriculture and the use of precision agriculture. The goal was to identify factors that could influence familiarity with and the use of precision agriculture technologies for fresh apple production. We chose this model because the response variable was discrete and binary (e.g., 1 = if they were familiar with or used the technology; 0 = otherwise). The probability that the respondent was familiar with or used a precision agriculture technology was calculated as follows:

$$Prob(Y = 1|x) = \Phi(x'\gamma) \qquad [2]$$

where Φ is the cumulative normal probability distribution; x is a vector of variables, including the size of the operation, the state in which the apple operation is located (e.g., Washington, Michigan, and New York); the source of information regarding precision agriculture technologies (e.g., university researchers and extension educators, agricultural service providers, and other growers); and γ is the vector of parameters to estimate. For the state in which the operation is located, the variable New York was omitted and was considered as the base variable. Similarly, "other growers" was the omitted variable among sources of information. As previously explained, statistical significance should be interpreted as relative to the base variable. To predict the probability with which a factor will impact the familiarity with or use of precision agriculture technologies, we estimated the marginal effects.

Benefits and concerns associated with precision agriculture technologies. We used a separate ordered probit model to analyze factors impacting the perceived benefits and another model to analyze factors impacting the perceived concerns associated with precision agriculture use. The response variable (i.e., the importance of benefits/concerns) was discrete and ordinal. The survey asked respondents to identify their top three perceived benefits and concerns from a list of five benefits and six concerns related to adopting precision agriculture technologies. The most important benefit was assigned a value of 5, and the second most important was assigned a value of 4. The benefits not considered among the top three were assigned a value of 3 (the median of 1 and 5). The concerns were assigned values in a similar manner. The producer benefit function was represented by the following:

$$\begin{aligned} U_{ij}^{benefits} = {} & \eta_0 + \eta_1\, Thinning_i + \eta_2\, Nutrient_i \\ & + \eta_3\, Pruning_i + \eta_4\, Irrigation_i \\ & + \eta_5\, Other_i + \theta_1\, Size_i \\ & + \theta_2\, Washington_i + \theta_3\, Michigan_i \\ & + \theta_4\, NewYork_i \\ & + \theta_5\, Univresearcher_i \\ & + \theta_6\, Agservice_i + \theta_7\, Othergrowers_i \\ & + \varepsilon_{ij}^{benefits};\ I = 1, \ldots, 119\ (n), \end{aligned}$$

where η_j is the producer's marginal utility from benefits j [j = improvement in effectiveness (labor hours, chemical costs vs. thinning quality) of green fruitlet thinning, nutrient application based on the real-time needs of each plant, improvement in effectiveness (labor hours vs. pruning quality) of dormant pruning, better targeted irrigation programs, and other)]; θ_1 is the marginal utility from the size of the operation; θ_2, θ_3, and θ_4 are the marginal utility from the state (Washington, Michigan, and New York, respectively) in which the operation is located; θ_5, θ_6, and θ_7 are the marginal utility from the most trusted providers (university researchers and extension professionals, agricultural service providers, and other growers, respectively) of information about applying precision agriculture technologies; and $\varepsilon_{ij}^{benefits}$ is the error term, which is assumed to follow a normal distribution with a mean of 0 and standard deviation of σ_E.

The producer's concern function was represented by the following:

$$\begin{aligned} U_{ij}^{concern} = {} & \vartheta_0 + \vartheta_1\, Cost_i + \vartheta_2\, Service_i \\ & + \vartheta_3\, Technical_i + \vartheta_4\, Results_i \\ & + \vartheta_5\, Donotsee_i + \vartheta_6\, Other_i \\ & + \kappa_1\, Size_i + \kappa_2\, Washington_i \\ & + \kappa_3\, Michigan_i + \kappa_4\, NewYork_i \\ & + \kappa_5\, Univresearcher_i \\ & + \kappa_6\, Agservice_i + \kappa_7\, Othergrowers_i \\ & + \varepsilon_{ij}^{concerns};\ i = 1, \ldots, 119\ (n), \end{aligned}$$

where ϑ_j is the producer's marginal utility from potential solutions to concerns related to precision agriculture technology j (j = cost of the service, customer service of the provider, availability/cost of technical expertise, reliability/quality of results to drive decisions that improve management, do not see a benefit, and other); κ_1 is the marginal utility from the size of the operation; κ_2, κ_3, and κ_4 are the marginal utility from the state (Washington, Michigan, and New York, respectively) in which the operation is located; κ_5, κ_6, and κ_7 are the marginal utility from the most trusted providers (university researchers and extension professionals, agricultural service providers, and other growers, respectively) of information about applying precision agriculture technologies; and $\varepsilon_{ij}^{concerns}$ is the error term, which is assumed to follow a normal distribution with a mean of 0 and standard deviation of σ_E.

Investment consideration in precision agriculture

TECHNOLOGIES. We used a binary probit model to depict factors that could influence the investment consideration for precision agriculture technologies. The model was chosen because the response variable was discrete and binary (e.g., 1 = if they would consider the investment; 0 = otherwise). The probability function and vector of explanatory variables were similar to Eq. [2]: size of the apple operation; state in which it is located (Washington, Michigan, and New York); and source of information regarding precision agriculture technologies (university researchers and extension professionals, agricultural service providers, and other growers). To predict the probability that a factor will impact the investment consideration, we estimated the marginal effects. A Z-test was used for all econometric specifications to infer whether a coefficient estimate was statistically significant at $P \leq 0.1$, 0.05, or 0.001. Parameter estimates for all econometric specifications in this study were estimated using STATA (StataCorp, College Station, TX).

Results and discussion

SUMMARY STATISTICS. The largest farms in terms of acreage were in Washington (average farm size, 369 acres), followed by Michigan (255 acres) and New York (176 acres). Across all states, the average size of our response sample was 266 acres. According to the 2012 Census of Agriculture, Washington had 2839 apple farms with a total of 174,152 acres, each with an average size of 61 acres. Michigan had 1584 apple farms with a total of 43,240 acres, each with an average size of 27 acres. New York had 1365 apple farms with a total of 47,148 acres, each with an average size of 35 acres (U.S. Department of Agriculture, 2014). Regarding the number of years of experience with precision agriculture technologies, Washington growers had the most experience (average, 9 years), followed by Michigan (7 years) and New York (6 years). Overall, respondents had an average of 7 years of experience.

Our sample size might not have been representative of the total number of apple operations in each of the three states surveyed. However, it is noteworthy that the average size of the operations was larger than those reported by the census. This means that growers responding to our survey were likely the early adopters of precision agriculture technologies. The seminal work performed by Feder (1980) and Feder and O'Mara (1981) explained that larger agricultural operations were more likely to adopt innovations. Larger operations are better positioned to invest in innovation, information gathering, and learning. Moreover, the rate of return for innovations is higher for larger operations. Larger operations tend to exhibit a better capacity to bear risk given their more professional management and higher degree of division of labor (Diederen et al., 2003). Most empirical studies found a positive relationship between the size of the perennial crop operations and the adoption of innovations (Gallardo and Brady, 2015; Gallardo and Sauer, 2018; Lu et al., 2016).

CHALLENGES FACED IN FRESH APPLE PRODUCTION. The availability of labor for harvest activities was the most important challenge for U.S. apple growers compared with the other challenge categories (regulatory demands, new marketable cultivars available nonexclusively to all growers, fire blight, farm succession, and government intervention) (Table 1). The decrease in the number of immigrant farm workers, especially from Mexico (Charlton and Taylor, 2016; Taylor et al., 2012), has led to a decrease in available labor pools for specific orchard tasks that require critical masses of labor, such as harvest. If not for temporary worker programs for immigrants such as H2A, a generalized labor shortage would negatively affect the economic profitability of labor-intensive apple production (Brady et al., 2016; Zahniser et al., 2012). H2A is a temporary agricultural worker program that allows U.S. employers of agents who meet specific regulatory requirements to bring foreign nationals to the U.S. to fill temporary agricultural jobs (U.S. Department of Homeland Security, 2018). Other labor-related challenges that ranked high in importance were availability/cost of labor for preharvest activities (fourth in importance) and intermediate supervisory labor (sixth in importance). This is relevant to our research problem because it is likely that a combination of innovative technologies from different disciplines (e.g., plant breeding, horticultural management, mechanical engineering, computer systems, robotics, and others) will facilitate the successful implementation of automated alternatives for a range of orchard activities (Gallardo and Sauer, 2018). For example, technologies like remote sensing would

Table 1. Coefficient estimates from the ordered probit model of the ranking of challenges for fresh apple production based on responses of an apple grower survey in Washington, New York, and Michigan in 2017.

Variable	Coefficient estimate (SE)
Availability/cost of labor for harvest activities	2.13*** (0.24)
Weather	1.83*** (0.23)
Pests and diseases	1.52*** (0.26)
Availability/cost of labor for preharvest activities	1.38*** (0.27)
Competing markets	1.37*** (0.29)
Availability/cost of labor for intermediate supervisory labor	1.17*** (0.31)
Productivity/profitability of available scion and rootstock cultivars	0.82*** (0.41)
Food safety	0.35* (0.44)
Water	–5.59*** (0.03)
Postharvest handling	–0.31 (0.73)
Size in acres	0.001(0.06)
Washington	0.003 (0.065)
Michigan	0.001 (0.072)
University researcher/extensionist	0.005 (0.073)
Agricultural service providers	0.005 (0.072)
Log likelihood	–2,817.57
Observations (no.)	1,309

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.

inform the development of more uniform tree canopies and fruit placement within the canopy, which would greatly enhance the efficiency of automated harvesting machines (D. Brown, personal communication).

Weather was ranked second in importance, followed by pests and diseases (Table 1). Both are significant daily challenges throughout the entire year for perennial tree fruit producers. Short-term changes in weather can affect many biotic and abiotic aspects of apple production. For example, longer-term shifts like warmer summer temperatures, erratic precipitation patterns, and extended growing seasons might favor additional generations per season for insect pests and insect disease vectors and alter pathogen lifecycles. Warmer winters could increase the survival of spring insect populations. Earlier springs could lead to the earlier arrival of migratory insects (New York State Energy Research and Development Authority, 2011). In 2012, Michigan's apple crop was reduced by 90% as a result of advanced floral development from early heat accumulation followed by episodic spring frost events, resulting in the largest apple crop loss since the 1940s (Michigan Apple News, 2012).

Competing markets was ranked fifth in importance (Table 1). Per capita domestic demand for U.S. fresh apples has stagnated since the 1980s at 16 to 19 lb/year (Perez, 2016). In contrast, fresh apple exports increased from an average of 607 million pounds during the 1980s to 2.3 billion pounds during the 2014–15 marketing season. Export markets are becoming increasingly important to the U.S. apple industry because the processing market has declined and domestic production of fresh apples has outpaced domestic demand (Perez, 2016). With large volumes, a wide range of cultivars, and high fruit quality, the United States has established a strong presence in international markets (Perez, 2016). In terms of export value, the United States is the leading fresh apple exporter in the world, surpassing China and Poland, although those countries have export volumes larger than that of the United States. Because U.S. apple production is expected to increase, particularly in Washington, export markets will continue to be crucial for the U.S. apple industry (Perez, 2016).

Productivity/profitability of available scion and rootstock cultivars was ranked seventh in importance. To reverse stagnant U.S. domestic demand for fresh apples, the industry opted to produce a wide array of cultivars with improved fruit quality attributes to meet the expectations and preferences of consumers (Gallardo et al., 2018). Offering a wide selection of cultivars with superior quality could also enhance the U.S. fresh produce presence in international markets (Perez, 2016).

Food safety was ranked eighth in importance. In 2011, the U.S. Congress passed the Food Safety Modernization Act to safeguard public health by ensuring that the food supply is safe from microbial, physical, and chemical contamination (U.S. Food and Drug Administration, 2018). As a result, commercial-scale apple growers must comply with a series of regulations, including tracing their produce from farms to retail stores and implementing and documenting a plethora of safety procedures during every step of the operation (Washington State University, 2018).

Water was ranked less important than the other challenge categories. Although apple production in the semi-arid interior valleys of Washington requires irrigation, orchards in Michigan and New York, which are located in cooler climates that have historically received greater precipitation throughout the growing season, received no supplemental water. However, this situation is changing rapidly given the deleterious effects of periodic drought on fruit growth, market pressure to produce high-quality fruit, and the significantly higher costs to establish high-density orchards. Subsequently, early and significant yields are required during years 3, 4, and 5 to repay the establishment investment (Robinson et al., 2013). Another benefit from an adequate water supply is improved uptake of calcium and other nutrients from the soil, thereby benefiting tree health and potentially improving control of physiological disorders like bitter pit (Robinson et al., 2013).

"Postharvest handling" was not significantly different in importance from the "other" category, which is not particularly surprising given that our respondents were focused on production aspects, even though postharvest fruit quality can be greatly affected by preharvest practices and conditions. Postharvest handling encompasses a wide array of practices originating in the orchard and continuing through the entire postharvest supply chain, including quality evaluations, storage regimes, sanitation practices, food safety, pathology, handling and packing practices, transportation, and marketing/exporting. Advancements in storage technologies have greatly increased the amount of time apples can be stored yet still maintain desirable fruit quality characteristics (Postharvest Information Network, 2016).

The size (in acres) of the apple operation, the state in which it is located, and providers of information were not statistically significant, indicating these factors did not impact the respondents' ranking of challenges. Table 2 reports the marginal effects of each challenge. "Availability/cost of labor" for harvest activities was 49% more likely to be ranked the most important challenge compared with the "other" challenge category. Similarly, "weather" was 38% more likely, "pests and diseases" was 28% more likely, "availability/cost of labor for preharvest activities" was 23% more likely, "competing markets" was 23% more likely, "availability/cost of labor" for intermediate supervisory labor was 18% more likely, and "productivity/profitability" of available scion and rootstock cultivars was 10% more likely to be ranked as the most important challenge compared with the "other" challenge category. "Water" was 8% less likely to be ranked most important compared with the "other" challenge category; "food safety and postharvest handling" was as likely as the "other" challenge category to be ranked most important.

FAMILIARITY WITH AND USE OF PRECISION AGRICULTURE TECHNOLOGIES. The size of the operation was statistically significant and positive for familiarity with and use of precision agriculture technologies (Table 3). Principal operators of orchards with at least 266 acres were 20% more familiar with precision agriculture technologies and 31% more likely to have used a precision

Table 2. Marginal effects of the ordered probit model regarding the ranking of challenges encountered in fresh apple production based on responses to a survey of apple growers in Washington, New York, and Michigan in 2017.

Variable	Top challenge (SD)	Second-ranked challenge (SD)	Third-ranked challenge (SD)	Fourth-ranked challenge (SD)	Fifth-ranked challenge (SD)	Sixth-ranked challenge (SD)	Seventh-ranked challenge (SD)	Eighth-ranked challenge (SD)	Ninth-ranked challenge (SD)	Tenth-ranked challenge (SD)	Eleventh-ranked challenge (SD)
Availability/cost of labor for harvest activities	0.49*** (0.06)	0.18*** (0.022)	0.03* (0.02)	–0.07*** (0.02)	–0.09** (0.02)	–0.01*** (0.01)	–0.10*** (0.01)	–0.10*** (0.01)	–0.09*** (0.01)	–0.09*** (0.01)	–0.07*** (0.09)
Weather	0.38*** (0.05)	0.20*** (0.02)	0.06*** (0.01)	–0.04** (0.02)	–0.08*** (0.02)	–0.09*** (0.01)	–0.09*** (0.01)	–0.09*** (0.01)	–0.09*** (0.01)	–0.08*** (0.01)	–0.07*** (0.01)
Pests and diseases	0.28*** (0.06)	0.19*** (0.03)	0.08*** (0.01)	–0.02 (0.02)	–0.06*** (0.02)	–0.07*** (0.02)	–0.08*** (0.01)	–0.09*** (0.01)	–0.08*** (0.01)	–0.08*** (0.01)	–0.07*** (0.01)
Availability/cost of labor for preharvest activities	0.24*** (0.06)	0.18*** (0.03)	0.09*** (0.02)	–0.01 (0.02)	–0.05*** (0.02)	–0.07*** (0.02)	–0.08*** (0.01)	–0.08*** (0.01)	–0.08*** (0.09)	–0.08*** (0.01)	–0.06*** (0.01)
Competing markets	0.23*** (0.06)	0.18*** (0.03)	0.09*** (0.02)	–0.01 (0.02)	–0.05*** (0.02)	–0.07*** (0.02)	–0.08*** (0.02)	–0.08*** (0.01)	–0.08*** (0.01)	–0.08*** (0.01)	–0.06*** (0.01)
Availability/cost of labor for intermediate supervisory labor	0.20*** (0.06)	0.16*** (0.04)	0.09*** (0.02)	0.01 (0.02)	–0.04 (0.02)	–0.06*** (0.02)	–0.07*** (0.02)	–0.07*** (0.02)	–0.07*** (0.01)	–0.07*** (0.01)	–0.06*** (0.01)
Productivity/profitability of available scion and rootstock cultivars	0.10 (0.06)	0.11* (0.06)	0.08*** (0.03)	0.02*** (0.01)	–0.02 (0.02)	–0.04 (0.03)	–0.05* (0.03)	–0.06*** (0.03)	–0.06*** (0.02)	–0.06*** (0.02)	–0.05*** (0.01)
Water	–0.08*** (0.02)	–0.15*** (0.02)	–0.19*** (0.03)	–0.16*** (0.02)	–0.12*** (0.01)	–0.09*** (0.01)	–0.07*** (0.03)	–0.06*** (0.02)	–0.04*** (0.01)	–0.03*** (0.01)	0.98*** (0.01)
Food safety	0.03 (0.04)	0.04 (0.06)	0.04 (0.05)	0.02 (0.02)	0.001 (0.001)	–0.01 (0.02)	–0.02 (0.03)	–0.02 (0.03)	–0.03 (0.03)	–0.03 (0.03)	–0.03 (0.03)
Postharvest handling	–0.02 (0.03)	–0.03 (0.07)	–0.04 (0.08)	–0.07 (0.02)	–0.01 (0.03)	0.0002 (0.01)	0.01 (0.01)	0.02 (0.03)	0.02 (0.05)	0.03 (0.08)	0.04 (0.11)

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.

agriculture technology in their orchard at least once compared with orchards with less than 266 acres. The location of an operation was statistically significant and positive for the use of precision agriculture technologies. Compared with growers in New York, growers in Washington (Michigan) were 27% (21%) more likely to have used precision agriculture technologies. Overall, survey results suggested that an operation's scale positively impacted familiarity with and use of precision agriculture technologies.

BENEFITS AND CONCERNS ASSOCIATED WITH PRECISION AGRICULTURE TECHNOLOGIES. Effectiveness of green fruitlet thinning was the most important perceived benefit from the use of precision agriculture technologies compared with the other categories (robotic harvest, improved database for decision management, lack of autonomous equipment, directed accurate spraying, improved returns, more reliable pest and disease management information, stress detection from mite/aphid feeding, platform-assisted horticulture activities, and imaging of buds for estimating return bloom) (Table 4). The "effectiveness of green fruitlet thinning" was 56% more likely to be ranked as the top benefit compared with the "other" benefit category (Table 4). Currently, the precision thinning method of estimating the fruit abscission response to chemical thinners (Greene et al., 2005) depends on tedious caliper measurements of hundreds of individually tagged fruitlets. This method is highly informative but time-intensive, thus limiting adoption and characterization of the diversity of localized effects on fruit set. Survey results suggest that the U.S. apple industry would value technology that provided rapid, automated measurements of fruitlet growth and estimates of the fruit set.

Table 3. Coefficient estimates and marginal effects for the probit models depicting familiarity and use of precision agriculture technologies for fresh apple production based on responses to a survey of apple growers in Washington, New York, and Michigan in 2017.

	Familiarity		Use	
Variable	Coefficient estimate (SE)	Marginal effect (SD)	Coefficient estimate (SE)	Marginal effect (SD)
Size	1.02** (0.45)	0.20** (0.09)	0.81*** (0.27)	0.27*** (0.08)
Washington	–0.05 (0.37)	–0.01 (0.07)	0.64*** (0.28)	0.21*** (0.09)
Michigan	–0.24 (0.39)	–0.05 (0.08)	–0.003 (0.33)	–0.001 (0.11)
University researcher/ extensionist	–0.17 (0.39)	–0.03 (0.08)	0.24 (0.32)	0.08 (0.11)
Agricultural service provider	0.19 (0.43)	0.04 (0.09)	0.94*** (0.34)	0.31*** (0.10)
Log likelihood	–42.46		–69.75	
Observations (no.)	119		119	

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.

Table 4. Coefficient estimates and marginal effects of the ordered probit model on the ranking of benefits of adopting precision agriculture technologies for fresh apple production based on responses to a survey of apple growers in Washington, New York, and Michigan in 2017.

		Marginal effect				
Variable	Coefficient estimate (SE)	Top benefit (SD)	Second-ranked benefit (SD)	Third-ranked benefit (SD)	Fourth-ranked benefit (SD)	Fifth-ranked benefit (SD)
Effectiveness of green fruitlet thinning	1.76*** (0.20)	0.56*** (0.06)	0.05*** (0.02)	–0.10*** (0.02)	–0.28*** (0.03)	–0.24*** (0.02)
Nutrient application based on real-time needs	1.66*** (0.18)	0.53*** (0.06)	0.06*** (0.02)	–0.10*** (0.02)	–0.27*** (0.03)	–0.23*** (0.02)
Effectiveness of dormant pruning	1.38*** (0.1885)	0.43*** (0.06)	0.08*** (0.02)	–0.07*** (0.02)	–0.23*** (0.03)	–0.21*** (0.02)
Targeted irrigation programs	1.06*** (0.17)	0.32*** (0.06)	0.08*** (0.01)	–0.04** (0.02)	–0.19*** (0.03)	–0.17*** (0.02)
Size in acres	0.001 (0.01)	—	—	—	—	—
Washington	–0.01 (0.11)	—	—	—	—	—
Michigan	0.01 (0.11)	—	—	—	—	—
University researcher/ extensionist	0.01 (0.12)	—	—	—	—	—
Agricultural service providers	0.01 (0.12)	—	—	—	—	—
Log likelihood	–844.34					
Observations (no.)	595					

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.
— = test not performed.

Table 5. Coefficient estimates and marginal effects of the ordered probit model on the ranking of concerns from adopting precision agriculture technologies for fresh apple production based on responses to a survey of apple growers in Washington, New York, and Michigan in 2017.

Variable	Coefficient estimate (SE)	Marginal effect: Top concern (SD)	Second-ranked concern (SD)	Third-ranked concern (SD)	Fourth-ranked concern (SD)	Fifth-ranked concern (SD)	Sixth-ranked concern (SD)
Reliability/quality of results	1.38*** (0.12)	0.40*** (0.04)	0.11*** (0.02)	–0.05*** (0.02)	–0.14*** (0.02)	–0.17*** (0.02)	–0.15*** (0.01)
Cost of the service	1.37*** (0.12)	0.39*** (0.04)	0.11*** (0.02)	–0.05*** (0.02)	–0.14*** (0.02)	–0.17*** (0.02)	–0.15*** (0.01)
Availability/cost of technical expertise	1.04*** (0.11)	0.28*** (0.04)	0.11*** (0.01)	–0.02 (0.01)	–0.10*** (0.02)	–0.14*** (0.02)	–0.13*** (0.01)
Customer service of provider	0.45*** (0.11)	0.10*** (0.03)	0.06*** (0.02)	0.01** (0.005)	–0.04*** (0.01)	–0.07*** (0.02)	–0.07*** (0.02)
Do not see significant benefit	–0.93*** (0.11)	–0.12*** (0.01)	–0.13*** (0.02)	–0.09*** (0.02)	–0.001 (0.01)	0.10*** (0.01)	0.25*** (0.04)
Size in acres	0.002 (0.09)	—	—	—	—	—	—
Washington	–0.003 (0.09)	—	—	—	—	—	—
Michigan	0.005 (0.10)	—	—	—	—	—	—
University researcher/ extension professional	0.002 (0.10)	—	—	—	—	—	—
Agricultural service providers	0.005 (0.11)	—	—	—	—	—	—
Log likelihood	–1.142						
Observations (no.)	714						

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.

— = test not performed.

Nutrient application based on real-time needs was ranked the second most important benefit. Compared with the "other" benefit category, this variable was 53% more likely to be ranked the most important benefit (Table 4). To ensure a consistently high yield of high-quality fruit, trees must maintain optimal nutrient ratios; therefore, prescriptive nutrient application is important (D. Brown, personal communication).

"Effectiveness of dormant pruning" was ranked third in importance and was 43% more likely than the "other" category to be ranked as the most important benefit. The canopies of modern high-density orchard systems have been transitioned to narrow, accessible planar canopies with high light interception to improve fruit size, color, and taste characteristics such as sweetness. Decreases in labor availability throughout the United States have encouraged the use of mechanical pruning (Robinson et al., 2013) based on techniques and equipment used in Europe (Miranda Sazo et al., 2010). Traditionally, pruning was conducted during the dormant period for physiological reasons and labor efficiency; however, the relative ease and rapidity of mechanical pruning expand alternatives. Mechanical pruning in late spring, when 10 to 12 leaves have emerged on extension shoots, promotes less regrowth, greater flower bud formation, herbaceous shoots that can be easily cut, and decreased fungal infections (S. Musacchi, personal communication). Appropriate timing and application of pruning additionally reduce or prevent the development of blind wood and ensure sufficient light penetration to color fruit and improve quality (S. Musacchi, personal communication), but additional investigation is required to optimize management protocols.

"Targeted irrigation" was ranked fourth in importance and was 32% more likely than the "other" benefit category to be ranked as the most important perceived benefit from precision agriculture technology. Irrigation, as previously explained, is essential for the establishment and productivity of apple trees, especially in high-density orchards. Irrigation management commonly relies on meteorology-based evapotranspiration models, volumetric soil moisture, and soil water potential sensors (Arbat et al., 2008). Evapotranspiration models developed for row crops have been shown to inaccurately estimate water use of apple trees (Dragoni et al., 2005; Dragoni and Lakso, 2011). Conventional direct measurements of tree physiological status can be time-consuming and expensive to implement (Masseroni et al., 2016; Osroosh et al., 2016).

The acreage of the apple operation, the state in which it is located, and sources of information were not statistically significant, indicating that these factors did not impact respondents' ranking of perceived benefits.

Regarding concerns about adopting precision agriculture technologies, the reliability/quality of results was ranked as most important compared with the other concern categories (time-management, reliance on high-speed Internet connection, lack of autonomous equipment, annual fees, time needed to achieve precision management) (Table 5). "Reliability/quality" of results was 40% more likely to be ranked as the most important concern compared with the "other" concern category. This corroborates the issue mentioned previously: insufficient field research for precision agriculture discourages the adoption of precision agriculture technologies for tree fruit (Bramley and Trengove, 2013; Cambouris et al., 2014). Increased investment in applied field research projects that test and demonstrate the benefits of precision agriculture technologies, coupled with active extension programs to appropriately disseminate research findings, could reduce grower concerns and accelerate adoption.

"Cost of service" ranked second in importance among concerns and was 39% more likely to be ranked the most important concern compared with the "other" concern category (Table 5). As observed by Pierpaoli et al. (2013) and Schimmelpfennig and Ebel (2011), lagged adoption of precision agriculture technologies might be the result of the considerable capital investment in equipment and skilled personnel required to interpret and implement the data. Research projects focusing efforts on high-value industries with substantial capital for technology investments could be a positive avenue for advancing and extending the knowledge of precision agriculture technologies to tree fruit. The apparent scale barrier to the adoption of innovations such as precision agriculture could be overcome by introducing purchasing and rental options and by providing customized services (Lu et al., 2016).

"Availability/cost of technical expertise" was ranked as the third concern and was 28% more likely to be ranked as the most important concern compared with the "other" category (Table 5). Literature regarding the economics of technology adoption indicated that customized services as well as collaborative efforts between industry and local institutions are crucial for adapting innovation to the needs of local growers (Gordon et al., 2018; Lu et al., 2016; Taylor and Zilberman, 2016).

The category of "do not see significant benefits" was ranked lower in importance compared with the "other" category, and it was 93% less likely to be the most important concern. This demonstrated that the apple industry recognizes the benefits associated with precision agriculture but still requires applied research to demonstrate the extent of such benefits.

INVESTMENT CONSIDERATION FOR PRECISION AGRICULTURE TECHNOLOGIES. The size of the operation had a positive effect on the consideration of investment in precision agriculture technologies (Table 6). Operations with 266 acres or more were 18% more likely to consider investing in such technologies. Although the data suggest that smaller operations are less likely to invest, the relative difference was not large. Furthermore, as mentioned, economic literature about adopting new technologies demonstrated that scale barriers can be overcome by introducing purchase and rental options, by providing customized services (Lu et al., 2016), and by providing smaller-scale producers with ready access.

IMPORTANCE OF AN AGRICULTURE SERVICE COMPANY OR CONSULTANT EXPERTISE FOR GUIDANCE AND IMPLEMENTATION. Results of frequency distribution showed that most growers (43; 35% of respondents) cite the expertise of their agriculture service or consultant as extremely important, followed by very important (42; 34%) and important (26; 21%) (Table 7). Ten growers were neutral about the topic, one deemed the expertise unimportant, and one did not reply. There were no salient differences among states regarding the average importance rating based on a scale of 1–7 (1 = extremely unimportant; 7 = extremely important). The average rating of importance ranged from 5.74 to 5.96. On average, growers highly ranked the expertise they receive, with an average importance of 5.9. This signals that growers trust service companies to share information that would facilitate the adoption of new technologies, thereby corroborating that collaboration between industry and academic institutions is crucial to adapt innovation to the needs of growers (Gordon et al., 2018; Lu et al., 2016; Taylor and Zilberman, 2016).

Summary and conclusions

Advances in precision agriculture technologies—especially in the areas of computer hardware and software, sensors, and data analytics—have created new opportunities for their application in crop production. Although precision

Table 6. Coefficient estimates and marginal effects of the probit model depicting factor impacting the investment consideration in precision agriculture technologies in fresh apple production, based on responses to a 2017 survey of apple growers in Washington, New York, and Michigan.

Variable	Coefficient estimate (SE)	Marginal effect (SD)
Size	0.52* (0.27)	0.18** (0.09)
Washington	0.12 (0.29)	0.04 (0.10)
Michigan	–0.25 (0.31)	–0.09 (0.11)
University researcher/extension professional	0.10 (0.31)	0.04 (0.11)
Agricultural service provider	0.27 (0.33)	0.09 (0.11)
Log likelihood	–72.23	
Observations (no.)	119	

*, **, ***Significant via Z-test at $P \leq 0.10$, 0.05, or 0.01, respectively.

Table 7. Frequency distribution of the importance of agriculture service company or consultant expertise for guidance and implementation by region based on responses to a survey of apple growers in Washington, New York, and Michigan in 2017.

	Frequency of respondents marking a particular category								
State[z]	Extremely important = 7	Very important = 6	Important = 5	Neutral = 4	Unimportant = 3	Very unimportant = 2	Extremely unimportant = 1	Does not apply	Avg importance
WA	18 (42%)	11 (26%)	9 (21%)	4 (9%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	5.95
MI	7 (26%)	12 (44%)	6 (22%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	1 (4%)	5.74
NY	17 (35%)	17 (35%)	11 (22%)	4 (8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	5.96
Total (avg)	43 (35%)	42 (34%)	26 (21%)	10 (8%)	1 (0.8%)	0 (0%)	0 (0%)	0 (0%)	5.90

[z] WA = Washington; MI = Michigan; NY = New York.

agriculture technologies have been extensively applied to row crops, their use has lagged in tree fruit crops. Given the high value of these crops and the increasing challenges regarding labor and horticultural management, applied research and extension activities have the potential to increase profitability.

In our online survey conducted in three states with the highest apple production by volume (Washington, New York, and Michigan), we found that the major challenges affecting the apple industry were related to labor and weather. Precision agriculture technologies offer solutions to these challenges across a broad array of production activities, from orchard establishment to crop production and protection from pests and diseases. These technologies enable simultaneous improvements in the consistency of yield and fruit quality. Despite the present low level of adoption, growers strongly supported research and extension activities that address labor-related and weather-related challenges. Such activities would also address their major concerns about the reliability or quality of results and costs of service.

One limitation of this study was the small sample size of apple operations surveyed. However, our respondent sample exhibited operations larger than the average, as reported by the U.S. Census. This implies that we obtained responses from the early adopters of precision agricultural technologies. Seminal work regarding agricultural economics concluded that adoption of innovations follows an S-shape curve (Griliches, 1957). At early stages of diffusion of an innovation, a small percentage of the total population of adopters ("early adopters") are the ones likely investing in the new technology. For an innovation to be massively adopted, it is crucial that extension professionals and stakeholders share research-based information regarding the benefits and use of the innovation with the early adopters. This group will disseminate the information, which will trigger and bolster the propagation of information. Additionally, this group will be imitated, that is, the benefits of the innovation would be inadvertently communicated to others, thus propelling imitative behavior and adoption (Frattini et al., 2013).

Apparent adoption barriers associated with economies of size could be minimized if purchasing and rental options (along with customized services) could increase access to technology. Finally, apple growers are aware of the importance of collaborating with agriculture service companies and academic institutions to adapt technologies to their specific needs.

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