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Overcoming the Nursery Industry Labor Shortage: A Survey of Strategies to Adapt to a Reduced Workforce and Automation and Mechanization Technology Adoption Levels

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Abstract. **US nurseries are experiencing a workforce shortage that is expected to intensify. A mixed-mode survey of decision-makers representing the US nursery industry was conducted in 2021. The survey assessed practices used in 2020 to elicit a better understanding of nursery approaches to the challenges presented by persistent labor scarcity. We compare our results with survey data collected ~15 years earlier at container nurseries. Survey responses revealed that nurseries were undertaking strategies that aimed to improve production efficiency, better recruit and retain employees, and secure other sources of labor to overcome this shortage. Specifically, more than 65% of surveyed US nurseries increased worker wages, and more than 55% of respondents adopted automation to address the labor shortage. Strategies in use by ≥23% of respondents may limit future growth or jeopardize long-term nursery survival. These include diversifying tasks of current employees, reducing production of labor-intensive plants, or delaying expansion plans. Survey results**

suggested that production tasks excluding irrigation were on average 31% automated or mechanized at container nurseries, an increase from 16% during the prior survey. Field nurseries were 35% automated or mechanized in 2020. Newly developed or yet-to-be developed automated and mechanized technology (AMT) that decision-makers perceive as being helpful were reported. This article explores linkages between nursery characteristics and AMT adoption and highlights research and extension programming initiatives that are needed to help growers make informed decisions regarding adopting automation.

Agricultural businesses have traditionally depended on manual labor, and the specialty crops sector is particularly reliant on workers to perform production tasks manually. Nursery production labor accounts for almost 35% of input costs (Hall 2023) and includes labor-intensive manual tasks such as planting, staking, tying, pruning, fertilizing, weeding, labeling, spacing, and transporting plants. This reliance on labor, coupled with the time-sensitive nature of many production tasks, makes the nursery industry particularly vulnerable to wage increases and labor scarcity. In fact, US nursery labor costs have increased in recent years, culminating with 2022 labor costs at nearly 170% of 2007 values (Hall 2023). Historically, nurseries have been able to maintain the workforce needed to support production due to adequate domestic labor for seasonal and year-round positions. However, in recent years, substantial shortages have emerged among both domestic and migrant workers. Domestic and foreign labor supplies no longer meet current labor demands.

The extent of the workforce scarcity and its effect on the US nursery industry is substantial. Nearly 80% of surveyed nurseries indicated that labor was their largest business challenge in 2018 (McClellan 2018b). More than 50% of responding nurseries reported that lack of qualified labor limited their ability to hire, with general crew labor and grower positions being the hardest to fill (Nursery Management 2018). The Department of Labor certified more than 300,000 farm jobs to be filled by workers from the H-2A (temporary agricultural employment of foreign workers) program in fiscal year 2021. This represents a 15% increase from fiscal year 2020, and more than a 217% increase from 2013. In 2022, the H-2A program appeared to expand regardless of the 6% increase in the Adverse Effect Wage Rate (Martin 2022). These numbers indicate the importance of the H-2A program as a source of labor for many nurseries and the US agricultural sector in general. Nonetheless, in the past 10 years greenhouses and nurseries have only represented an average of 9% of all US firms requesting H-2A workers (Simnitt et al. 2021).

Nursery operators express numerous concerns about the H-2A program. These concerns include the return on investment (ROI) in employee development. For example, many tasks require an investment of time and dollars for intensive, specialized training that requires years of continued employment to recoup. However, nurseries are burdened by the high hourly wage during this training with no guarantee of employing the same workers year after year, or even the opportunity to use workers for a full year. Additionally, growers are frustrated about the lack of control over required wage increases midseason that directly impact H-2A workers. Moreover, these raises lead to raises for non-H-2A employees to maintain equitable compensation across the nursery's workforce.

The unmet labor demand is exacerbated by a simultaneous increase in demand for specialty crop products driven by do-it-yourself home improvements (Campbell et al. 2020) and new housing construction. For example, 87% of garden centers reported that sales increased from 2019 to 2020 (Daly 2021; Nursery Management 2020). Additionally, in the United States, the average hourly wages rose to $30.40 in 2021 (Iacurci 2021), with fast food chains, national home improvement stores, and warehouses offering $15 per hour plus benefits (Rodda 2021). These wage rates, among jobs that are perceived to be more stable, reliable, comfortable, or less physically demanding, make it increasingly difficult to recruit from the domestic labor pool for physically challenging nursery tasks in uncontrolled outdoor environments. Moreover, the construction industry, also fueled by the recent housing boom, offers much higher hourly wages, $30.73, and directly competes with nurseries as they recruit to fill their seasonal workforce (American General Contractor Association 2019; Rodda 2021).

Nursery owners and operators have employed a number of strategies to ameliorate the workforce shortage and meet increasing product demand. For example, a national 2018 survey of nursery professionals found 40% were paying higher wages, 25% were adopting labor saving technologies, and 22% were training employees to improve their job-related skills (Rihn et al. 2022a). In this same survey, just 9% indicated that they were adding benefits, and 34% were not doing anything in response to labor shortages. The authors submit that due to the wording of this question, it was possible that these respondents did not have a labor shortage; however, the aforementioned statistics suggest that is not the case. Rather, this statistic may reflect uncertainty regarding specific changes that were made, lack of capital, or increased perceptions of risk associated with change decelerating the decision-making process—all pointing to a critical need to support this segment of US specialty crops.

The labor-reducing advantages of automation have been anecdotally noted by producers and reported in popular press. For example, potting machines are reported to reduce labor requirements dramatically. Hibernia Nursery (Apopka, FL, USA) reduced the 3 months required annually for potting to 1 month (Rodda 2021) by automating the potting process. Hibernia Nursery also found that automated pruning allowed them to reduce the time required to prune an acre from 80 man-hours to 4 man-hours. Similarly, Ridge Manor Nursery (Madison, OH, USA) installed two $16,000 automated rice hull applicators which reduced needed workers for this task by four (Nursery Management 2020). Ridge Manor Nursery reported that using extended conveyers increased labor efficiency, allowing them to load a semitrailer truck 30% faster with 33% fewer workers. In each case, owners and managers are making these adjustments not to eliminate current workers but rather to evolve their business to a new labor paradigm hallmarked by an insufficient workforce. These instances of adopting automation have not only helped ameliorate labor scarcity from a production efficiency standpoint but may also increase the appeal of nursery production to members of the limited current workforce. For example, at Ridge Manor Nursery, workers reported an increased level of enjoyment when loading trailers with the expanded conveyers and appreciated that it no longer created a physical strain on their bodies. Other technologies, such as horticultural forklifts (Trike™; AgroNomix, Oberlin, OH, USA), also appear to improve worker experience, making nurseries more attractive to current employees (McClellan 2018a; Nursery Management 2020). Moreover, nursery managers report that adopting automation allows them to create positions that are more appealing to potential employees (McClellan 2018a).

Nursery production is inherently reliant on a scarce and unreliable manual labor workforce. Therefore, the nursery industry must take opportunities to continue developing automation strategies and innovations that address this critical issue. An essential first step is evaluating current automation use and industry members' perceptions of current labor challenges and opportunities. Accordingly, a transdisciplinary group of research and extension professionals undertook a national nursery survey with the objectives of 1) identifying

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the strategies currently in use to address the labor shortage and 2) evaluating current adoption of automated and mechanized technology (AMT)s and the level to which each production task is automated.

Materials and Methods

The research reported here was part of a national inquiry conducted in 2021 investigating growers' use and perceptions associated with AMT in the prior year, 2020. The data were collected using a mixed-mode survey (i.e., paper and electronic survey versions) to maximize participation (Dillman et al. 2009). The electronic version of the survey was designed using Qualtrics (Provo, UT, USA). Before survey dissemination, the research protocol was approved by the lead institution's institutional review board (IRB), per current IRB protocol (IRB-20-05942-XM).

Sample. Nonprobability sampling techniques were used because random sampling of this population was not possible (Lamm and Lamm 2019; Warner et al. 2020) given a lack of a readily accessible nationwide sampling frame. The sample contact list included 1305 individuals who own or manage nurseries. Distribution revealed only 1225 individuals were listed with either a valid e-mail address, valid US Postal Service (USPS) postal address, or both types of contact information. The sample included 1017 valid e-mail addresses and 1181 valid USPS addresses (Table 1). The geographic distribution of the USPS sample is provided as an approximation of the total sample. However, readers are urged to use caution when interpreting these data because there may be responses from a state with no USPS addresses or more responses than there are sample members for a given state because of online responses.

The electronic survey was disseminated directly to research team members' contact lists, which generated 56 completed responses, and through state nursery associations, a trade publication, and the project team website (https://www.nurseryleap.com) that collectively generated another 35 electronic responses. A corresponding paper survey was distributed to nonrespondents and other individuals for whom the research team had no e-mail address but had mailing addresses from state department of agriculture licensing databases and from industry association member lists. The paper surveys generated 98 returned responses. Multiple contacts were used with an e-mail reminder and a replacement paper survey delivered to nonrespondents sent 2 weeks after the original mailing. In total, 189 completed surveys were received; the corresponding response rate was 14.1% and cooperation rate was 90.9% (American Association for Public Opinion Research 2020). A maximum of one response per firm was allowed. Potential survey participants were screened to include only those who were 18 years old or older, represented businesses with nursery production, and were decision-makers within their respective nurseries.

Survey instrument. The questions pertaining to the current inquiry (Table 2) addressed two objectives: 1) capturing nurseries' current strategies to address labor issues and 2) compiling the AMTs currently used and the percent of each task currently automated. Respondents selected strategies currently used to address labor issues from a series of provided responses. Respondents were asked to indicate whether they were already using AMTs provided in a list and were given the opportunity to add additional technologies to capture AMTs currently being used and those that need to be developed. AMTs were presented in groups pertaining to container growers, field growers, or mixed growers. The electronic version of the survey used display logic to show participants only those technologies that applied based on the percentage of their 2020 inventory reported as field or container grown. Specifically, respondents within the electronic survey were assigned to container or field grower groupings if they reported inventory of 76% or greater for either of these categories, and assigned to a mixed grower group if they had no more than 75% of their inventory in either of the other two production types. Visual cues were used in the paper survey to direct respondents to the appropriate group of AMTs. All lists of AMTs, statements, and tasks were developed based on a literature review and industry and researcher feedback to improve validity and identify meaningful factors to include in the survey instrument. This included an expert panel review by members of the industry and academia before conducting the survey (Vaske 2008).

We compare results for Objective 2 to those obtained during a previous regional study. Posadas (2018) conducted verbal interviews with 88 owners or operators of wholesale container nurseries from nine southern states (Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Texas) from 2003 to 2009. Coker et al. (2010) reported results from the same survey, but for the collection period 2003 to 2008. We refer to this survey as being conducted in 2006 (the median year of the full data collection period) and as a 15-year period between the Posadas survey and the current study to improve readability. Additionally, results were not divided by nursery size for these previous publications. We provide this clarification to aid readers and to facilitate an accurate interpretation of the comparisons that are presented. Results for irrigation-related AMTs are published separately because they constitute a significant data set and required more discussion to relate to the existing literature.

Data analysis. Data from the electronic and paper-based surveys were input and merged into a single dataset with consistent response values and labels. The sample was considered both as a whole (all nursery responses) and by two nursery size groups: 1) less than or equal to $1.4 million in annual sales (n = 73; 50.3% of the sample) and 2) more than $1.4 million in annual sales

Table 1. Geographic distribution of the US Postal Service (USPS) sample to which the survey was sent in 2021 and asking about practices used in 2020 to assess automated, semiautomated, and mechanized nursery technologies (AMTs). Geographic distribution of nursery decision-makers receiving the survey by e-mail or accessing it by the www.nurseryleap.com website is not accessible.

State	Members in USPS sample
Alabama	8
Arkansas	1
Arizona	8
California	43
Connecticut	5
Delaware	1
Florida	284
Georgia	5
Hawaii	1
Idaho	1
Illinois	9
Indiana	1
Iowa	1
Kansas	2
Kentucky	3
Louisiana	6
Maryland	5
Massachusetts	2
Michigan	9
Minnesota	1
Missouri	4
New Hampshire	1
New Jersey	10
New Mexico	1
New York	5
North Carolina	22
Ohio	18
Oklahoma	14
Oregon	79
Pennsylvania	5
South Carolina	4
Tennessee	583
Texas	9
Virginia	10
Vermont	2
Washington	12
Wisconsin	6
Total sample	1181

(n = 72; 49.7% of the sample), hereafter referred to as "below-median nurseries" and "above-median nurseries," respectively. The $1.4 million in annual sales was selected as a threshold of firm size given that value was the median reported annual sales among respondents.

Descriptive statistics included means and standard deviations. All descriptive statistics and mean separation analyses were conducted using statistical software (Stata ver. 17.0; StataCorp, College Station, TX, USA). Pairwise t tests, analysis of variance and Tukey's honest significance test were used to assess significance across sub-samples. Mean separation was conducted at a significance level of alpha = 0.05.

Results and Discussion

Sample demographics. Sample demographics are given for paper surveys mailed to USPS addresses (Table 1). The geographic distribution of e-mail and website samples is not known. The USPS sample is weighted to

Table 2. Description of study variables, question, question formats, and response options in a survey of decision-makers representing the US nursery industry conducted in 2021 and asking about practices used in 2020 to assess automated, semiautomated, and mechanized nursery technologies (AMTs) to elicit a better understanding of nursery approaches to the challenges presented by persistent labor scarcity.

Variable	Strategies to address labor shortages	AMTs currently used[i]	Percentage of tasks currently automated	Perceived helpfulness of AMTs
Question	Which of the following are you doing, or doing more of, to address labor shortages?	For each item below, please indicate how unlikely or likely you would be to adopt each technology or whether you are currently using the technology.	Please indicate the percent of each task that is automated at your nursery on a per year basis. Responses do not need to sum to 100%. If you do not use automation to complete that task, please record 0%.	For each line, please indicate how helpful automating the following tasks would be for reducing labor at your nursery.
Question format	Multiple choice, check all that apply	5-point Likert scale, with additional response option[ii]	Write-in, paper survey; slider question, electronic survey	5-point Likert scale[iii]
Response options	I am not experiencing labor shortages[iv] Adopting labor-saving technology Paying higher wages Training employees to improve skills Adding employee benefits Applying for or already using H2A labor Putting expansion plans on hold Scaling back my operation High-skill labor (managers, etc.) doing more low-skill/manual labor Reducing production of labor-intensive crops Increasing outsourcing (e.g., reducing in-house propagation to purchase more liners, hiring subcontractors, etc.) Adopting LEAN processes Other (please list) ___________ Nothing[iv]	Tying machine (during production; e.g., Max Tapener)[v, vi] Foliage trimmer/pruner[v, vi] Root pruner [v, vi] Granular fertilizer applicator[v, vi] Tractor/truck/wagon to move product[v, vi] Conveyer belts[v, vi] Liquid fertilizer injector[v, vi] Substrate mixer[v] Potting machine[v] Robotic plant spacers[v] Forklift to move and space product[v] Trike™ horticultural forklift to move and space product[v] Mechanical liner setter/planter[vi] Mechanical stake installer[vi] Laser guided pesticide sprayer (e.g., GPS tracking, crop sensing, or variable-rate)[vi] Lifter or shaker[vi] Tree spade[vi] Pneumatic c-ring fastener for burlapping[vi] Balled and burlapped (B&B) tree handler: Tree Boss, Tree Jaws®, etc. to move B&B Mechanical bundler (post-harvest)[vi] Forklift to move B&B[vi] Other automation for container nursery: ___________[v] Other automation for field nursery: ___________[vi]	Potting into containers Pruning/trimming Planting in the field Inventory tracking Weed control – mechanical removal, chemical control, mulching, etc. Labeling Pest monitoring/control/applications to control insects and diseases Mixing and loading container substrate Employee training Harvesting Pulling orders Transporting plant material (e.g., moving and spacing plants Shipping Fertilizer application Other (please list) ___________	Propagation Harvesting Mixing and loading container substrate Potting into containers Planting in the field Pruning/trimming Pulling orders Shipping Transporting plant material (e.g., moving, spacing plants) Weed control – mechanical removal, chemical control, mulch, etc. Inventory tracking Labeling Employee training Monitoring/spraying insects and diseases Other (please list) _______

[i] Irrigation AMTs were also present in the survey but will be published separately because they constituted a significant volume of closely related information.
[ii] Current adoption was derived from a question also soliciting response to likelihood of adoption using a 5-point Likert scale (very unlikely = −2, unlikely = −1, neither unlikely nor likely = 0, likely = 1, and very likely = 2). An additional response "Currently using it" was also an answer option.
[iii] Perceived helpfulness was derived from responses using a 5-point Likert scale (not at all helpful = 1, slightly helpful = 2, moderately helpful = 3, very helpful = 4, extremely helpful = 5).
[iv] "I am not experiencing labor shortages" and "Nothing" were set as mutually exclusive in the electronic version, that is, survey participants could not select other responses if either of these were selected.
[v] AMTs that applied to container growers.
[vi] AMTs that applied to field growers.

the southeastern United States; Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, Tennessee, and Virginia compose ∼77% of the sample.

Respondent demographics. The current research is a portion of a larger project. Respondent demographics are described in more detail by Rihn et al. (2022b). In brief, respondents (referred to as "nursery producers" here after) heavily represented nursery-predominant businesses, with 80% of participants reporting that nursery production was responsible for 76%

or more of their sales. Just 19% represented firms for which nursery production was between 1% and 75% of their sales. Nearly half of survey respondents represented the Southeast with 42% from Alabama, Florida, Georgia, Mississippi, and Tennessee. Just over half of all respondents indicated their sole production method is container production (51%). Other production systems represented included field only (26%), and those with both field and container, which were referred to as mixed operations (23%). Survey respondents produced foliage plants (15%), palms (13%), herbaceous perennials (50%), evergreen trees and shrubs (62% and 64%, respectively), deciduous trees and shrubs (78% and 69%, respectively), and propagules (80%). Respondents averaged having nearly 24 years in green industry decision-making positions, and as of 2020, represented nurseries that were established on average 38 years ago. Responding nurseries had average annual sales of $5.7 million.

Strategies to address the labor shortage. Respondents indicated their strategies to address the labor shortage by either enhancing efficiency, rewarding current employees, or securing other sources of manual labor. Below-median and above-median nurseries differed in which strategies they used (Table 3). More above-median nurseries ($P < 0.004$) indicated that they increased wages (84% vs. 47%), added benefits (44% vs. 20%), adopted lean production practices (40% vs. 17%), and applied for or already used H-2A labor (39% vs. 14%) relative to below-median nurseries. Adopting labor-saving technology (68% vs. 47%), training employees to improve their skills (60% vs. 33%), and reducing production of labor-intensive crops (49% vs. 30%) were also being implemented at a higher percentage by above-median nurseries ($P < 0.025$) compared with below-median nurseries. Interestingly, 64% of below-median nurseries responded that they were not experiencing a labor shortage compared with just 13% of above-median nurseries ($P = 0.002$). There was no effect of nursery size on highly skilled labor performing manual tasks, putting expansion plans on hold, increasing outsourcing, or scaling back their operation ($P > 0.05$).

Below-median nurseries may benefit from an overall reduced need for labor and may be able to rely on family members and their personal network to supply or supplement their relatively low labor needs compared with above-median nurseries. This may at least partially explain the 4.9-fold difference in below-median nurseries' reporting that they were "not experiencing a labor shortage" (Table 3). A previous survey conducted among southern container nursery operations that ranged in annual sales from <$250,000 to more than $2 million, found that 66% of respondents indicated that labor was "available" or "highly available" (Posadas 2018). It is impossible to compare the results of these two surveys directly based on nursery size because Posadas (2018) did not break down the total sample by annual sales. However, the total sample decrease from 66% in 2006 to 26% (Table 3) appears to signify a substantial reduction in available workers occurring in the 15-year period between surveys. Since 2018, the percentage of nurseries adding benefits increased from 9% (Rihn et al. 2022a) to 44% for above-median nurseries and 20% for below-median nurseries. In the present survey, 27% of nurseries are using high-skill labor to perform manual tasks regardless of nursery size. This practice is common in small businesses where employees have many responsibilities; however, it may be less common and therefore less accepted by employees at large nurseries where workers may be focused on specific teams and activities. Large nurseries may have more capital to support wage raises and increased benefits, labor-saving improvements such as automation, and the capacity to offer employee training compared with below-median nurseries. Velandia et al. (2021b) reported larger Tennessee nurseries use more H-2A labor than smaller Tennessee nurseries. This may be explained by larger nurseries having the resources to navigate and afford the process of hiring workers through the H-2A program (Velandia et al. 2021a).

The trend for below-median and above-median nurseries alike to adopt measures that could curtail long-term nursery growth as well as have a negative impact on surrounding communities is of concern. In particular, nurseries responded that they are reallocating highly skilled labor for more menial tasks (27%), putting expansion plans on hold (23%), and scaling back their operation (15%) (Table 3). These measures seem counter to achieving long-term business goals and indicate that management decisions, such as assigning high-skill workers to more labor-intensive tasks, could further exacerbate the labor issue by serving as the impetus for skilled labor to seek other employment opportunities (Rihn et al. 2022a).

Current use of AMTs. Below-median and above-median nurseries are differentially integrating about half of the surveyed AMTs (Table 4). Specifically, above-median nurseries are using trucks or tractors with wagons, granular fertilizer applicators, potting machines, liquid fertilizer applicators, forklifts, tying machines, substrate mixers, conveyer belts, and "other" field automation at a greater percentage than below-median nurseries ($P < 0.05$).

Some of the greatest differences in automation use between above-median and below-median nurseries are among plant handling (and ancillary tasks) and plant transport tasks (Table 4). For example, above-median nurseries use tractors or trucks with wagons, 86%, and forklifts, 60%, more than below-median nurseries, 71% and 36%, respectively. Additionally, above-median nurseries use potting

Table 3. Strategies used by nurseries to address their labor shortfall as determined by a survey of decision-makers representing the US nursery industry conducted in 2021 and asking about practices used in 2020 to assess automated, semiautomated, and mechanized nursery technologies (AMTs) to elicit a better understanding of nursery approaches to the challenges presented by persistent labor scarcity.

	Total sample		Below median (≤$1.4M in sales)		Above median (>$1.4M in sales)		
Response to labor shortages	Mean (%)[i]	*SD*	Mean (%)	*SD*	Mean (%)	*SD*	Significance[ii]
Paying higher wages	66	0.48	47	0.50	84	0.37	<0.001
Adopting labor-saving technology	56	0.50	47	0.50	68	0.47	0.013
Training employees to improve skills	45	0.50	33	0.47	60	0.49	0.002
Reducing production of labor-intensive crops	38	0.49	30	0.46	49	0.50	0.025
Adding employee benefits	29	0.46	20	0.41	44	0.50	0.004
Adopting lean processes	28	0.45	17	0.38	40	0.49	0.004
Applying for or already using H-2A labor	27	0.45	14	0.35	39	0.49	<0.001
High-skill labor doing more low-skill/manual labor	27	0.45	30	0.46	25	0.43	0.481
Not experiencing labor shortages	26	0.44	64	0.49	13	0.34	0.002
Putting expansion plans on hold	23	0.42	25	0.44	20	0.41	0.488
Increasing outsourcing	21	0.41	14	0.35	28	0.45	0.052
Scaling back my operation	15	0.35	19	0.40	12	0.32	0.236
No. of observations	154[iii]	.[iv]	73	.	72	.	.

[i] % = valid percent (number of respondents who selected the given answer option / number of respondents who answered the question).
[ii] Significance was tested using analysis of variance and Tukey's honestly significance test at a significance level of 0.05.
[iii] Not all respondents answered the income question; therefore, not all were categorized as above-median or below-median. Consequently, the total is not the sum of below-median + above-median.
[iv] Indicates no value is presented.

Table 4. Nursery use of automation and mechanization nurseries as determined in a survey of decision-makers representing the US nursery industry conducted in 2021 asking about practices used in 2020 to assess automated, semiautomated, and mechanized nursery technologies (AMTs) to elicit a better understanding of nursery approaches to the challenges presented by persistent labor scarcity. The effect of nursery size (above- and below-median annual sales) and type (predominately container, predominately field, or mixed) are presented at a significance level of 0.05.

	Total sample		Below median (≤$1.4M in sales)		Above median (>$1.4M in sales)			Cont. grown (≥76% inventory in container)		Field grown (≥76% in field)		Mixed operations (mix of production methods)				
Technology	Mean (%)[i]	*SD*	Mean (%)	*SD*	Mean (%)	*SD*	*P*[ii]	Mean (%)	*SD*	Mean (%)	*SD*	Mean (%)	*SD*	Cont.-field *P*	Cont.-mixed *P*	Field-mixed *P*
Tractor/truck/wagon	73	0.45	71	0.46	86	0.35	0.029	77	0.43	66	0.48	73	0.45	0.377	0.889	0.707
Granular fertilizer applicator	51	0.50	48	0.50	65	0.48	0.035	51	0.50	45	0.50	58	0.50	0.757	0.732	0.403
Potting machine	47	0.50	26	0.44	79	0.41	0.000	48	0.50	—[iii]	—	46	0.50	—	0.853	—
Liquid fertilizer injector	46	0.50	36	0.48	64	0.48	0.001	57	0.50	23	0.43	48	0.51	0.001	0.565	0.032
Forklift	44	0.50	36	0.48	60	0.49	0.003	39	0.49	49	0.51	48	0.51	0.996	0.541	0.502
Tree spade	41	0.50	45	0.50	50	0.51	0.661	—	—	51	0.51	33	0.47	—	—	0.065
Mechanical liner setter/planter	36	0.48	32	0.47	53	0.51	0.068	—	—	38	0.49	35	0.48	—	—	0.707
Tying machine (during production)	35	0.48	32	0.47	50	0.50	0.023	44	0.50	28	0.45	27	0.45	0.088	0.124	0.997
Substrate mixer	35	0.48	23	0.43	53	0.50	0.002	34	0.48	—	—	37	0.49	—	0.803	—
Conveyer belts	33	0.47	14	0.35	61	0.49	0.000	40	0.49	11	0.31	42	0.50	0.001	0.955	0.002
B&B tree handler	33	0.47	37	0.49	47	0.51	0.387	—	—	43	0.50	25	0.44	—	—	0.065
Foliage trimmer/pruner	30	0.46	32	0.47	35	0.48	0.683	38	0.49	19	0.40	25	0.44	0.060	0.240	0.797
Root pruner	30	0.46	36	0.49	37	0.49	0.966	—	—	23	0.43	23	0.43	—	0.970	—
Mechanical bundler (post-harvest)	13	0.34	13	0.34	15	0.36	0.852	—	—	15	0.36	12	0.32	—	—	0.626
Lifter or shaker	13	0.34	18	0.39	12	0.36	0.440	—	—	26	0.44	2	0.14	—	—	0.000
Pneumatic c-ring fastener	10	0.30	11	0.31	9	0.29	0.811	—	—	11	0.31	10	0.30	—	—	0.868
Trike™ horticultural forklift	9	0.29	6	0.23	17	0.38	0.107	14	0.35	—	—	8	0.27	—	0.235	—
Other field automation	7	0.25	4	0.20	14	0.35	0.040	10	0.30	4	0.20	4	0.19	0.346	0.420	0.996
Mechanical stake installer	5	0.22	3	0.16	6	0.24	0.498	—	—	4	0.20	6	0.24	—	—	0.734
Robotic plant spacers	4	0.20	4	0.20	7	0.25	0.609	4	0.21	—	—	4	0.19	—	0.866	—
Other container automation	4	0.20	1	0.12	8	0.28	0.051	4	0.21	6	0.25	2	0.14	0.518	0.755	0.855
Laser guided pesticide sprayer	3	0.17	0	.[iv]	6	0.24	0.133	—	—	2	0.15	4	0.19	—	—	0.623
n (no. of observations)	189[v]		73		72			90		47		52				

[i] % = valid percent (number of respondents who selected the given answer option / number of respondents who answered the question).

[ii] Significance was tested using analysis of variance and Tukey's honestly significance test at a significance level of 0.05.

[iii] Indicates no response, generally because the technology was not possible for the production system.

[iv] Indicates no value is presented.

[v] Not all respondents answered the income question; therefore, not all were categorized as above-median or below-median. Consequently, the total is not the sum of below median + above median.

Cont. = container.

machines (79% vs. 26%), conveyer belts (61% vs. 14%), and substrate mixers (53% vs. 23%) more commonly than below-median nurseries. Posadas (2018) did not categorize respondents by nursery size but reported that 41% of nurseries filled containers mechanically. Therefore, the increase in potting machine adoption since 2006 appears to be primarily by larger nurseries. More prevalent use of these AMTs by larger nurseries may be explained by the greater capital expense of these technologies. For example, adopting potting machine technology includes an initial inlay of capital of $50,000 or more (in Dec 2022), and necessary infrastructure changes such as covered workspace and three-phase electricity for semiautonomous potting machines. This increase may also reflect findings from analyzing the present survey data using the Theory of Planned Behavior, which revealed a positive relationship between growers' perceptions of approval from other growers and intent to adopt plant-handling AMTs (Warner et al. 2022a). Perhaps larger growers have more interaction with their peers than smaller growers or are more competitive regarding aligning with their peers' image of the ideal grower.

Conveyers are newer technologies for the green industry. According to the 2006 survey, conveyers were used to move plants from the potting area at ~9% of nurseries; however, less than 2% of nurseries used conveyers for other tasks (Coker et al. 2010). By 2020, conveyers had already become as widely adopted as forklifts by above-median nurseries (Table 4). Given their low level of adoption in the recent past, perhaps their application to and compatibility within nursery production is not widely recognized by smaller nurseries, nor may be the ruggedness or survivability of this equipment in an outdoor environment. Observability (of the outcomes associated with adopting a technology) can be an important predictor of adoption of innovation (Rogers et al. 2019) yet was not linked to AMT adoption (Warner et al. 2022a). Perhaps observability is scale-dependent, with small nurseries requiring examples of other small nurseries using specific pieces of automation.

Automated and mechanized technologies that assist with agrochemical application, such as granular fertilizer applicators and liquid fertilizer injectors, were among the most heavily adopted AMTs but were adopted at different levels by above-median and below-median nurseries (Table 4). Specifically, both granular and liquid fertilizer applicators are used by 65% vs. 48% and 64% vs. 36%, of above-median and below-median nurseries, respectively. Coker et al. (2010) found that fertilizer was applied directly by manual labor either by hand or by the bucket and spoon method at nearly 80% of nurseries. Since 2006, adoption of automated fertilizer application technology has reduced manual applications of granular and liquid fertilizers by 39% and 24%, respectively, at below-median nurseries. Fertilizer applicators and injectors are low-cost AMTs, which may have contributed to this increase in adoption. The high capital investment may negatively influence nursery decision-making for other automation. Nursery producers responded that purchase and installation cost was the highest ranking barrier to adopting automation in the present survey, with below-median nurseries indicating this was a greater barrier than above-median nurseries (Rihn et al. 2022a).

Some technologies that were not adopted differently by above-median and below-median nurseries include tree spades (41%), mechanical planters (36%), balled-and-burlapped plant handlers (33%), foliage trimmers (30%), and root pruners (30%) (Table 4). The nonsignificance may be attributed to some AMTs being essential to completing field production tasks regardless of nursery size. For example, hand digging large trees (i.e., greater than 3 inches in caliper) is not feasible for the typical nursery (Davidson et al. 1999), regardless of nursery size.

Automation that was adopted by 15% or less of nurseries with no difference in adoption rate by above-median and below-median nurseries included mechanical bundlers, lifter/shakers, pneumatic c-ring fasteners, horticultural forklifts, mechanical stake drivers, robotic spacers, "other" container automations, and laser-guided pesticide sprayers (Table 4). Robotic spacers, the only widely known AMT for spacing plants in container production, were used by just 4% of nurseries in 2020. Robotic spacers were not specifically listed in the 2006 survey; however, 9% of nurseries responded that they were using mechanized spacing (Posadas 2018). These results suggest that nurseries are declining in their adoption of spacing automation, indicating previously adopted technologies may not have adequately met the needs of growers or were too expensive to support broader adoption.

The type of production system influenced whether certain AMTs were adopted (Table 4). More container nurseries (57%) and mixed nurseries (48%) adopted liquid fertilizer injectors than field nurseries (23%; $P \leq 0.032$). Additionally, field nurseries (11%) currently use fewer conveyers than either container (40%) or mixed nurseries (42%; $P \leq 0.002$). However, testimonials or articles that feature other field nurseries adopting portable conveyers, such as the popular press article on Willowbend Nursery (McClellan 2018a), may encourage other field nurseries to consider adopting this form of automation. Warner et al. (2022a) found that intention to adopt plant handling AMTs was predicted entirely by injunctive norms, e.g., approval, from other growers and customers, when these variables overpowered other reliable theory-based predictors of behavior, demonstrating the importance of social influences on adoption.

Percent of task automated: Predominately container nurseries. Tasks related to mixing substrate and filling containers with substrate were roughly 29% automated in 2006 (Posadas 2018). Collectively, these tasks were 55% automated in 2020 (Table 5). Potting into containers was 47% automated in 2020, whereas placing liners in containers was just 9% automated in the previous survey. Moving and spacing containers was 38% automated in 2020, whereas moving and transporting plants after potting ranged from 15% to 32% in 2006, depending on subtask. Spacing was 4% automated in 2006. The increased automation of these tasks is not surprising given that plant handling and plant transport are known to be repetitive and labor intensive. Ingram et al. (2017) found that potting, transporting, and assembling and loading orders were responsible for nearly 80% of the labor costs in the production of #3 'Green Beauty' boxwood (*Buxus microphylla* var. *japonica*).

The increase in automated movement of plants may be partially explained by the use of portable conveyer belts, which have become more popular since 2006 when just ≤1.5% of nurseries were using them except in conjunction with potting machines (Coker et al. 2010). Automation to space plants is primarily, if not entirely, due to the use of the robotic spacer, HV-100 (Harvest Automation, Billerica, MA, USA). This spacer was trialed by a relatively small number (~30) of highly visible nurseries and has been prominently featured on nursery tours since 2006 (Harvest Automation 2016). At Centerton Nursery (Bernville, PA, USA), spacing robots more accurately spaced on an offset pattern, resulting in elimination of wider than intended spacing and reducing production space requirement by 10 houses, in addition to established labor savings (Gohil 2019). However, as discussed earlier, robotic spacing has not been widely adopted. Warner et al. (2022a) found that compatibility (i.e., product or technology alignment with existing nursery infrastructure, values, and goals) was the most important predictor of current and future adoption of AMTs. Potting machines generally require three-phase electricity and, along with associated conveyers and hoppers, can require a large structure in which to operate, all of which require a significant financial investment. Yet adoption of substrate handling AMTs increased by 93% and potting AMTs by 422% from 2006 to 2020 despite the known barrier of high initial purchase cost and the significance nursery producers place on compatibility with existing infrastructure (Rihn et al. 2022b; Warner et al. 2022a). Robotic spacers require a relatively smooth production surface and both robotic spacers and horticultural forklifts require that the surface be free of aboveground irrigation lines and other physical barriers, either for the movement of the AMT or to prevent damage to irrigation lines or other structures. The relatively high potting machine adoption may reveal strong alignment with firms' values (e.g., working conditions) and objectives (e.g., high consistency in product or the sheer gains in efficiency) that outweigh barriers or perceived incompatibility in other areas. The cost or perceived incompatibility with current nursery infrastructure may be a barrier for horticultural forklifts (Trike™) and robotic spacers, given their relatively low adoption.

Fertilizer application by predominately container producers was 47% automated in 2020, compared with just 16% in the 2006

Table 5. Percentage of individual nursery tasks that were automated or mechanized by predominately container nurseries as determined in a survey of decision-makers representing the US nursery industry conducted in 2021 asking about practices used in 2020 and compared with data previously collected over several years (median year = 2006) to better understand nursery adoption of automated, semiautomated, and mechanized nursery technologies (AMTs) over time.

	2020			2006
	Total sample[i]			Total sample[ii]
Nursery task	Mean (%)[iii]	*SD*	Task	Mean (%)
Mixing and loading substrate	55	42	Mixing substrate	28
			Filling containers	29
Potting into containers	47	40	Placing plant liners into containers	9
Fertilizer applications	47	38	Fertilizer applications	16
Moving and spacing plants	38	36	Moving containers from potting to transport vehicle for movement within the nursery	15
—	.[iv]	.	Transporting containers to field	32
—	.	.	Spacing plants	4
—	.	.	Removing containers from transport vehicle and placing in the field	3
Weed control - mechanical removal, herbicide applications, mulching, etc	35	33	—	.
Inventory tracking[v]	27	33	—	.
Monitoring pests, pesticide applications	27	36	Pesticide applications	25
Pruning	25	27	Pruning	13
Shipping	23	30	Picking up plants from holding area or trailers and loading onto transport or delivery vehicles	11
Labeling	20	31	—	.
Employee training	17	27	—	.
Pulling orders	16	25	Removal of plants from transport vehicle and placing in hold area awaiting shipment	8
All tasks	31	.	All tasks	16

[i] Observations from predominately container growers (>75% of wholesale inventory in containers), all nursery sizes combined.
[ii] Source = Posadas (2018). Observations from decision-makers representing container nurseries in eight southeastern US states (Alabama, Florida, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee) that spanned $250,000 to $2,000,000 in annual gross sales. Survey was conducted by phone interview after soliciting participation by mail. To improve readability, we refer to this survey as being conducted in 2006 (the median year of the full data collection period).
[iii] % = valid percent (number of respondents who selected the given answer option / number of respondents who answered the question).
[iv] Indicates no value is presented.
[v] Without the three new tasks in the 2021 survey, employee training, inventory tracking, labeling, the mean of all worker tasks = 35%.

survey (Table 5). The 194% increase in automated fertilization application across the two survey time periods represents a substantial shift in automation adoption. Fertilizer applicators (Fertil Fertilizer Dispenser; Simeoni Tecnogreen, Sacile, Italy; Fertileeze granular applicator; Fertileeze®, Hendersonville, NC, USA) represent an opportunity for nurseries to improve efficiency due to their low cost ($200–$550), minimal infrastructure modification requirements, and their immediate ability to eliminate a repetitive task that often strains workers. Weed control, including mechanical removal, herbicide applications, and mulching, was just 35% automated in 2020. Monitoring pests and pesticide applications to control insects and diseases were 27% automated in 2020 compared with 25% automated pesticide application in 2006. Like fertilization, low-cost AMTs are commercially available to help reduce the time required to make pesticide applications as well as the physical toll on workers when applying pesticides. For example, battery operated backpack sprayers at $275 (417 Li; Solo, Newport News, VA, USA) and gravity fed granular applicators at $50 (Spread-Rite® G; PBI Gordon Corp., Shawnee, KS, USA) are available and would nearly entirely mechanize the task. Yet these relatively low-cost AMTs are not widely adopted although hand-weeding is estimated to cost more than $11,000 per acre (Ingram et al. 2016). Another example of commercially available automation that is beneficial to nursery crops producers is intelligent, variable-rate spray technology. This technology was commercialized in 2019 and automates pesticide application from air-assisted sprayers (Smart Apply® Intelligent Spray Control System™; Smart Apply Inc., Indianapolis, IN, USA) (Zhu et al. 2017). Sprayers equipped with this technology sense the crop in real time and actuate only those nozzles that are needed in response to the crop's presence, size, and density, thereby reducing pesticide volume sprayed by more than 70% compared with the standard 100 gallons per acre in a field nursery (Fessler et al. 2021). This technology reduced pesticide application time by 27% to 32% and labor and fuel by 28% in an orchard when compared with the conventional constant-rate air-assisted sprayer (Manandhar et al. 2020). The percentage of automated insect and disease monitoring and control was largely unchanged since the prior survey, 27% vs. 25%, although growers had a range of technologies and price points available to them in the 2020 survey, including options with unbiased, favorable ROI calculations as published in Manandhar et al. (2020).

Inventory tracking was not included in the previous survey but was 27% automated in 2020 (Table 5). This is notable because inventory technology and software were not thought to be used in the nursery trade or used enough to warrant inclusion in the 2006 survey. Additionally, the current technology is considered expensive, yet this task is automated at levels similar to weed control, monitoring insects and diseases, pesticide applications, pruning, and shipping in 2020. Participants in all regions of the United States strongly voiced the need for improved inventory management strategies during listening sessions (Fulcher A, unpublished data). Inventory tracking is especially challenging from a labor quality and scarcity standpoint. Growers cited the difficulty in finding individuals knowledgeable of plant identification and quality who also possess the experience necessary to conduct accurate inventory assessments and projections based on anticipated growth. They also cited the transient nature of live plants, which may grow or die, thus necessitating repeated assessments as a factor that makes this a time-intensive task. Radio frequency identification technology has been tested on bare-root liners and container crops (Fernandez et al. 2014). Despite low maximum payload and the challenge of miscounts and overcounts when assessing crops from above, application of this technology to nursery crop production continues to advance (Quino et al. 2021a, 2021b).

Recently, nursery producers have experimented with sensors connected to a monitor that detects and accounts for each plant as it is potted (ScoreBoard System; AgroNomix, Oberlin, OH, USA). One limitation of this AMT is that it will not address changes in inventory availability over time, for example, from dead, slow-growing, or poor-quality plants. Further innovation is needed so that nurseries have affordable inventory AMTs uniquely suited for their needs, such as capable of providing real-time, cloud-based inventory, assessing and grading plant quality, and detecting and removing dead or undersized plants from the count.

Pruning was reported as being 25% automated in the 2020 survey, whereas in 2006, it was just 13% automated, representing an increase of 92% in the 15-year period (Table 5). Growers have had access to horizontal bar-type mowers for trimming a bed of liners, which are often modified or made by in-house mechanics. However, only recently have automated machines that prune individual plant canopies to a range of shapes been available in the United States. Like fertilizing and herbicide applications, pruning is repetitive and physically demanding work. Chemical pruning, i.e., use of plant growth regulators, is common for greenhouse crops but less so for nursery crops (Interregional Working Group 4 2023), making wider adoption of a mechanized or automated solution that much more urgent. In fact, during national listening sessions held in 2020, growers were asked "In what part of your operation is the biggest opportunity to implement automation and related technologies?". Their responses ranked pruning second only after plant transport tasks (Fulcher A, unpublished data). Moreover, growers who had already adopted pruning and potting machines reported that product consistency, quality, and timeliness of both the production task and subsequent crop scheduling were of substantial benefit in addition to the labor efficiencies of automated pruning and potting. This benefit was heightened with respect to contract growing—that is, a large batch of plants must finish at the same time or when creating scheduling windows of distinctly staggered crops (e.g., when blooming is critical). Although automated pruning machines are expensive, ∼$50,000 (in Jul 2022), a positive aspect identified in listening sessions is that existing pruning AMTs are compatible with the typical nursery infrastructure (Warner et al. 2022a).

Tasks that fall within the plant transport cluster generally have low adoption. For example, "Picking up plants from holding area or trailers and loading onto transport or delivery vehicles" was reported as 11% automated in 2006, and "Shipping" was reported as 23% automated in 2020 (Table 5). Likewise, pulling orders was 8% automated in 2006, compared with 16% automated in 2020. Like transporting plants following potting, the use of conveyer belts and, to a lesser extent, horticultural forklifts (Trike™) may be the reason for the increase. Additionally, the use of point-of-sale racks for shipping, which has been encouraged as a more labor-efficient system for plant transport (Spirgen 2019) and widely adopted in recent years, has likely facilitated the use of existing AMTs (e.g., forklifts). Ingram et al. (2017) found that assembling orders and loading trucks was nearly 52% of the cost of labor for #3 boxwood production. This highlights another instance of the disconnect between need and potential benefit. Plant transport is a labor-intensive task, yet few AMTs for this task are commercially available and those that are available have a low adoption rate. Perhaps the uneven nature of the nursery floor, both the surface and topography, is an infrastructure compatability barrier, adversely affecting adoption of certain plant handling and plant transport AMTs (Warner et al. 2022b). McClellan (2022) reported that Decker's Nursery (Groveport, OH, USA) had to make changes to the surface of the nursery floor, in addition to other significant infrastructure changes, to accommodate the use of horticultural forklifts (Trike™).

Labeling and employee training were 20% and 17% automated, respectively, in 2020 (Table 5). These tasks were not included in 2006 study. Some online programs exist for training employees, including various pesticide certification trainings, and programs such as the University of Tennessee Original and Advanced Tennessee Master Nursery Producer programs (Marble et al. 2016a, 2016b), and the University of Florida's Greenhouse Training Online (Fisher 2021). Considering the timing of the survey (administered in 2021 about 2020 nursery practices), it is possible that enhanced online offerings due to the COVID-19 pandemic caused a higher affirmative response (Wright et al. 2021). Labeling exemplifies a repetitive, low-skill task that, if automated, could reallocate scarce labor to a more engaging task. Panoramic Farm, a North Carolina, USA, nursery, recently added an in-line inkjet printer that prints directly on containers immediately af-ter potting as the containers move down the potting line. Consequently, employees previously dedicated to pre-printing and later
placing labels onto containers perform more engaging tasks and tasks that add more value to the production system, such as driving a forklift or a tractor (LEAP Sustainability 2020). The in-line inkjet printer was anecdotally reported to be a more cost-effective solution than an automated adhesive label applicator, which would have produced a similar result at 5 times the cost.

Percent of task automated: Predominately field nurseries. A similar set of questions was asked about AMTs used in field production in 2020. The survey conducted in 2006 (Posadas 2018) was not intended for field production, therefore no comparison with the survey conducted in 2021 is presented. Harvesting was the single most heavily automated task in field production (56%), followed by weed control (51%; Table 6). The proportion of weed control that is automated in field production is nearly 50% greater than the portion of this same task that is automated in container production (35%; Tables 5 and 6). This may be because tractors and all-terrain vehicles are already in use in field production, plants and rows are spaced accordingly, further facilitating the use of cultivators, manure spreaders for mulch, traditional sprayers, and "low-volume controlled droplet" applicators (e.g., Enviromist; Micron Group, Herefordshire, UK), for weed control.

Monitoring for pests and making pesticide applications were listed as a single task in the 2020 survey and were 47% automated (Table 6). At the time of publication, there is no commercialized automation of pest scouting

Table 6. Percentage of individual tasks that were automated or mechanized by predominately field production nurseries as determined in a survey of decision-makers representing the US nursery industry conducted in 2021 asking about practices used in 2020 to better understand nursery adoption of automated, semiautomated, and mechanized nursery technologies (AMTs).

		Total sample[i]	
Nursery task	No. of observations	Mean portion that is automated (%)[ii]	*SD*
Harvesting	39	56	36
Weed control (mechanical removal, herbicide applications, mulching, etc.)	38	51	37
Fertilizer applications	37	49	40
Planting into the field	39	49	37
Monitoring pests, pesticide applications	38	47	40
Transporting plant material (e.g., moving plants)	37	46	43
Shipping	36	24	34
Pruning	34	23	31
Inventory tracking	37	21	31
Labeling	36	21	31
Employee training	36	19	29
Pulling orders	37	13	28
All tasks	.[iii]	35	35

[i] Among predominately field production nurseries (>75% of wholesale inventory in field production), all nursery sizes combined.

[ii] % = valid percent (number of respondents who selected the given answer option / number of respondents who answered the question).

[iii] Indicates no value is presented.

for nursery crops, although opportunity exists for drones, robots, cell phone applications, and other technologies to advance this production task. Scouting is recommended to be performed as a dedicated activity; however, workers often monitor for pests concurrently with other tasks (LeBude et al. 2012). Therefore, designing scouting AMTs to either operate separately (e.g., dedicated continuous scouting) or coupling scouting with other routine tasks, such as by mounting the device on a frequently used tractor, may offer additional efficiencies, allowing producers to redeploy labor smartly while scouting effectively.

Pesticide applicators used in nursery crop production are necessarily mechanized, whether a gravity-fed sprayer, boom sprayer, or an orchard or canon-style air-blast sprayer. However, only a few commercialized sprayers are truly automated, for example, "low-volume controlled droplet" applicators (Enviromist), precision spray systems equipped with a laser sensor (Smart Apply® Intelligent Spray Control System™), or an ultrasonic sensor (SmartSpray; Durand Wayland, LaGrange, GA, USA). Conversely, measuring and mixing chemicals are entirely manual tasks, although experimental systems are in development. Continued transformative research that leads to a commercially available, automatic inline injection system to mix agrochemical concentrates and water in real time is needed because these tasks involve potential exposure to undiluted active ingredients (Zhang et al. 2020a, 2020b).

Fertilizer application was 49% automated in field nurseries in 2020, similar to container nurseries (47%; Tables 5 and 6). Planting was 49% automated (Table 6). Although a large, mechanical planter is often used to create a furrow, many laborers often work in conjunction with a mechanical planter to plant a crop. For example, workers unbundle and prune bare-root liners and remove container liners from pots. Other workers ferry wagons with prepped liners to the planting site. Workers hand the prepared liners to workers on the setter, who manually place the plants in the furrow, while other workers walk behind the setter and straighten liners and firm the soil around them. One additional worker operates the tractor that pulls the setter.

Transporting plant material was 46% automated (Table 6). Due to the large size of field nurseries (i.e., often 100 or more acres), tractors typically pull wagons to production sites either for planting in the field or when harvesting balled and burlapped plants. Wagons are traditionally loaded and unloaded by hand, although portable conveyers assist with this task at an increasing frequency. Willowbend Nurseries (Perry, OH, USA) is using telescoping conveyers (MaxxReach®; FMH Conveyers, Jonesboro, AR, USA) at their docks to eliminate the need for workers to walk each armload of bare-root liners to the front of the shipping container, making this task more efficient (McClellan 2018a). Much like racks have improved the labor efficiency of loading small container crops (Spirgen 2019), telescoping conveyers and similar technologies have the potential to dramatically improve loading efficiency of field-grown crops.

Pruning is 23% automated at field nurseries in the United States (Table 6), similar to 25% at container nurseries (Table 5). Most nurseries have crews of five to eight workers with manual pruners or shears that trim large blocks of shrubs at a time. A portion of this task can be automated and labor reallocated to tasks that are not easily automated to adapt the constraints of a reduced workforce. Some field nurseries have motorized, gantry-style mechanized pruners that require a driver, and, at some nurseries, a single worker walking behind with shears to clean up any missed branches. Although human-operated pneumatic and battery-operated pruners are available, a commercialized AMT to prune individual branches does not exist for nursery crops or other tree crops. An automated pruner would allow producers to prune trees efficiently to a uniform and symmetrical shape that would increase grade and consequently the price. A custom root pruner allowed a nursery in Oklahoma, USA, to reduce the number of employees needed for hand pruning bare-root liners in preparation for potting from 25 to 30 employees to three (Bryant J, personal communication). At a McMinnville, TN, USA, nursery, a single employee with a \$50,000 gantry pruning machine replaced a crew of four workers, allowing them to be reassigned to other, nonautomated tasks. Pruning expense was reduced ~\$0.10/plant, and the AMT had an ROI of 2 years based on use on just one of the two crops they pruned using the gantry pruner (Hines T, personal communication). These examples demonstrate both the effectiveness of AMTs at addressing the labor shortage and the potential to alleviate it further with pruning AMTs, as other specialty crop operations have. For example, California grape producers face labor shortages and rising labor costs similar to the US nursery industry. In Lodi, the California region leading in the mechanization of grape production, 69% of vineyards use machines to preprune and 46% remove leaves mechanically (Gray 2020). Vineyard pruning AMTs could provide platforms that manufacturers serving the nursery industry can efficiently adapt for field production of trees and shrubs, facilitating cost-effective options and ultimately adoption.

Inventory tracking, labeling, employee training and pulling orders are all less than 21% automated (Table 6). The current approach and future opportunities for field production are largely as described for container production above.

Needed automation advancements. Growers wrote in newly and yet-to-be developed automation to identify other automation needs. Among predominately container producers, autonomous tractors and sprayers, automated transplanters, and irrigation stations for wagons to pass through immediately following transplanting, including conveyer-based stations, were the most common responses. Other responses included an automated container label applicator, an all-terrain container spacing machine, and an automated inventory system. Responses affiliated with container production appear to reflect both a strong demand for an automated sprayer and lack of awareness that such a product (e.g., Smart Apply® Intelligent Spray Control System™) is commercially available. This suggests that observability and trialability are low for recently introduced AMTs and that communication from growers who have adopted these AMTs, in addition to general product marketing, may not be fully reaching producers. There is a need to improve or increase social diffusion to accelerate adoption of new and existing AMTs because producers are not only unaware of them but are currently not experiencing the economic returns AMTs can provide. Extension-led field days and demonstrations, as well as multimedia resources featuring grower experiences with technology, could help alleviate this. Predominately field producers did not write in any forms of automation meeting the aforementioned criteria. Mixed operations listed facial recognition time clocks, which are available and being adopted on a limited basis at nurseries, automated grading and loading systems, container and tray dispensers, and arthropod and disease monitoring technologies. A weeding robot was also mentioned and may reflect either lack of awareness of existing weeding robots (Robocrop in-row weeder; Garford Farm Machinery Ltd., Deeping St. James, Peterborough, UK) or a reluctance or inability to devote the capital resources necessary to acquire this technology. However, Willowbend Nursery (Perry, OH, USA) is using these robotic weeders in an effort to position themselves to survive current and future labor shortages and reported reducing the number of employees from 40 to 15, thereby reducing their labor expenses by \$300,000 to \$400,000 (McClellan 2018a).

The nursery industry is positioned to take advantage of automation. Posadas (2018) found that decision-makers 30 to 69 years of age tend to adopt more nursery mechanization compared with those aged $\geq$70 years. Nursery decision-makers responding to the present survey averaged nearly age 57 years, which is within the age range likely to embrace AMTs. Additionally, Posadas (2018) also found that nurseries with larger annual sales had more automation. Specifically, mechanization of nursery tasks exceeded the benchmark group and increased with increasing sales by 14.2%, 24.0%, and 34.8% in nurseries with annual sales of \$500,000 to 999,999 (\$635,281 to \$1,269,291), \$1,000,000 to \$1,999,999 (\$1,270,562 to \$2,541,122), and $\geq$\$2,000,000 (\$2,541,124), respectively (inflation adjusted values in parenthesis). In the present survey, nearly 62% of respondents had annual sales of $\geq$\$500,000, suggesting they fall within an annual gross sales range that would support adopting AMTs. Lastly, Posadas (2018) found that each unfilled position would lead to an increase in mechanization by 0.54% and 0.37% for full-time and part-time positions, respectively.

Considering that in the present survey 36% of below-median nurseries and 87% of above-median nurseries indicated that they are experiencing a labor shortage, continued and expanded adoption of automation is expected in the future. In addition to the nursery demographics that suggest widely adopting automation is necessary and inevitable, Fulcher et al. (2021) reported that nursery producers in Tennessee, USA, surveyed in 2020 expected a 17% increase in sales over the next 5 years. In light of the COVID-19-induced demand for plants (Campbell et al. 2020) that developed immediately after the Tennessee survey, this may be an underestimation and is likely not limited to Tennessee nurseries but rather a nationwide trend. Exchanging capital for unavailable workers (i.e., investing in automation to replace those not applying for unfilled positions) may be the best way for growers to navigate a scarce workforce in tandem with an increased demand for plants.

The survey highlights use of expensive and inexpensive AMTs that are currently available, as well as yet-to-be developed AMTs that nursery decision-makers perceive as being needed. Producers are initiating innovation to address the labor shortage, but comprehensive, widespread federally funded research is essential for continued, substantive advancement in AMT development and adoption. Moreover, the adoption of AMTs may require complex production changes, nursery design evolution that relies less on available labor trends and more on accommodating automation adoption, and economic considerations that extension professionals can help producers assess and prepare. Reduced perceptions of complexity of an innovation is expected to increase adoption (Rogers et al. 2019), and this relationship has been documented specifically with regard to nursery AMTs (Warner et al. 2022b). For example, the need for low-labor pruning solutions is so great that recently a US grower contracted with a manufacturer to develop a custom pruning system that prunes multiple rows of plants at the same time. Automated and mechanized technologies such as this may create a need for greater production block uniformity. Specifically, there may be a maximum permitted grade change, and uniformity and length parameters for row width and distance between rows within a block. Once in place, these infrastructure changes may drive additional adoption of automation for planting. The type and age of a plant, and therefore the desired size and shape, may need to be the same throughout a block to minimize adjustments during use and maintain maximum efficiency. A model outlining characteristics of the nursery of the future needs to be developed for the industry to adapt to automation, much as has been done for viticulture at the University of California–Davis "touch-free" experimental vineyard (Gray 2020). Given that some nursery crops have production periods exceeding 3 years, just implementing a compatible production block layout could take several years across a nursery. Other changes, such as removing production houses, grading, and rebuilding houses with entrances wide enough to accommodate horticultural forklift (Trike™) traffic, for example, could be expensive, time-intensive, and prevent or interrupt production on existing sites. It is hypothesized that AMTs may reduce producer flexibility and lend themselves more to large-scale nurseries as has been experienced in row crop production (Duffy 2009; MacDonald et al. 2018). Ultimately, the nursery industry may become a more dichotomous industry with many small, specialized nurseries and a few very large nursery conglomerates, similar to poultry production and row crop agriculture (Duffy 2009). Similarly, substantial consolidation, especially since the Great Recession, and concomitant adoption of automation, have been occurring in the US greenhouse industry (Drotleff 2019).

The nursery industry should cautiously consider trends from other forms of agriculture as it continues to invest in AMTs. Larger farms more fully use both their labor and their labor-saving automation (Duffy 2009). For many forms of technology, the costs are fixed and thus the more plants that are produced, the lower the cost of the technology per unit. Yet technology is often a large capital expense. If production costs increase but nursery income does not compensate for the increase in costs (e.g., by reducing labor expenses), then growers must produce more plants to make the same income. The need to produce on more acres can lead to a continued, escalating investment in automation to maintain profits, known as the "technology treadmill," with the threat of going out of business looming for those nurseries that do not repeatedly reinvest in technology (Cochrane 1993).

Additional research and outreach are needed to accelerate automation adoption as a path toward nursery sustainability in the face of a limited and shrinking workforce. Unbiased, economic analyses are essential to allow growers operating nurseries across a range of scales to determine the ROI for specific pieces of automation before making large capital investments. These assessments should lead to tools that give individual nurseries the ability to assess each AMT's utility within the confines of their nursery's economic and physical layout characteristics. Additionally, more research is needed to better understand seeming inconsistencies in grower behavior related to automation adoption. For example, potting and substrate handling AMTs were adopted at relatively high percentages and had some of the largest increases since 2006—422% and 93%, respectively. However, these are among the most expensive forms of AMT, and purchase cost is the highest ranking barrier for nursery producers considering adopting automation (Rihn et al. 2022b). Adopting these AMTs requires a purchase and possibly additional space such as a new building. While seemingly a barrier, a new building has a known, established cost in the form of a quote. Additionally, the construction could be outsourced. In contrast, renovating existing infrastructure [e.g., removal of solid-state irrigation from the nursery floor to allow the use of a horticultural forklift (Trike™)] may represent a less well-defined cost and a task that would fall on the nursery's employees. Regardless of size, less than 10% of nurseries have adopted horticultural forklifts. Further investigation is needed to better understand the effect of nursery size on propensity to adopt AMTs, given that average adoption across all types of automation was greater for above-median (38%) than below-median nurseries (24%), and significantly so for nearly half of the 22 technologies (Table 4). Rihn et al. (2022b) found a positive relationship between crop uniformity and quality and the likelihood of AMT adoption. Perhaps smaller nurseries have inherently more varied crops, less discriminating or perhaps more loyal customers, or, given their lower existing automation, benefit less from the consistency afforded by additional automation. However, it is concerning that below-median nurseries are adopting these AMTs at a slower pace than their above-median counterparts, given the labor-intensive nature of plant transport tasks.

Automation adoption may have both positive and negative ramifications for labor dependency, diversity of plant inventory, production costs, and crop quality and uniformity. Consumers may be asked to pay the increased cost of AMT adoption through higher prices for plants produced using automation. Therefore, it is important to understand their perceptions about AMTs on plant quality, worker retention, employee well-being, living wages, and environmental costs (i.e., agrochemical pollution, CO_2 generation, and global warming potential). Posadas (2012) and Krahe and Campbell (2016) found a neutral effect of automation on employee retention (i.e., no workers were lost). However, Posadas (2018), in an analysis of data collected from 2003 to 2009, found a slight loss of workers as an effect of automation adoption. An updated analysis is necessary given the change in workforce availability. Additionally, the commercial implications of automation as well as consumer preference for these effects need further study to define their perceptions accurately and understand how the nexus of consumer perceptions and AMT adoption impact long-term nursery sustainability.

Respondents were limited to the southeast in the Posadas (2018) paper and included different firms and respondents than in this article. Therefore, there are limitations to comparing these two datasets, and our comparisons should be interpreted carefully. Sample size was considered adequate in the current work but could be improved, increasing power of the analysis and allowing for smaller differences to be detected.

Conclusions

Nursery production entails numerous repetitive manual tasks, including planting, fertilizing, pruning, weeding, staking, transporting inherent to numerous tasks, and inventory management. US nurseries are experiencing a simultaneous increase in demand for product and decrease in available labor, both domestic and foreign. Thus, nurseries are approaching a critical decision point: to invest in automation and expansion for the future or compete with those who have for the remaining limited workforce. Automation of nursery production tasks, as in other industries, may also create more desirable positions through less physically demanding or repetitive tasks, and instead offer more engaging tasks with more responsibilities, ultimately leading to greater worker satisfaction. This may also increase the ability of nurseries investing in AMTs to attract workers. Automation may necessitate a suite of comprehensive production and site changes to accommodate specialized AMTs and may decrease production system flexibility. Extension and research initiatives are identified that will not only assist growers in navigating these capital intensive, relatively permanent decisions but also provide necessary guidance to the Extension professionals who support the US nursery industry, industry associations, policymakers, allied suppliers, and others. As nursery producers weigh AMTs as a solution to replace an increasingly insufficient workforce, they may also want to consider how expansion may play a role in optimizing automation, potential pitfalls, and how expansion and consolidation may influence long-term sustainability at both the individual nursery and the industry-wide, national level.

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