A Current View of High Tunnel Tomato Production in New England

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KEYWORDS. greenhouse, grower, high tunnel, production practices, survey, tomato

ABSTRACT. **High tunnel tomatoes are a high-value crop for many vegetable growers in New England. We conducted a survey to gain a better understanding of grower concerns, production practices, infrastructure, yield, and revenue for tunnels growing in-ground, trellised, and irrigated hybrid "slicer" tomato cultivars. We found that top grower concerns were soil fertility and plant diseases (cited by 51% and 45% of growers, respectively). At least two-thirds of tunnels were managed with organic practices, produced winter greens after tomatoes, had manual roll-up sides and large endwalls for passive ventilation, had horizontal air flow (HAF) fans for air circulation, had plants that were not lowered, used fertigation, relied on passive pollination, were sprayed to manage disease, and used biocontrols for insect pests. Approximately one-half the tunnels had air heating systems, had grafted plants, had not been rotated out of tomatoes, had nonthinned flower clusters, used Geronimo and/or Rebelski cultivars, had a plant density of 4 to 6 ft^2/stem, and were mulched with black plastic and/or landscape fabric. Total yield reported by growers was 0.74 to 5.35 lb/ft^2, with an average of 2.18 lb/ft^2. The average marketable yield was 1.78 lb/ft^2. The average retail price was \$4.56/lb. Tunnels with the 10 highest yields averaged 3.15 lb/ft^2 or twice the average of other tunnels. Practices in the high-yielding tunnels that also had an adoption rate 50% or greater than the rate in the low-yielding tunnels included automatic roll-up sides, air heating, grafted plants, and HAF fans.**

High tunnels are semi-permanent, plastic-covered greenhouse structures that are widely used by vegetable growers in New England (Table 1). Farmers who grow vegetables in high tunnels report earlier and higher yields and improved crop quality (Bruce et al. 2019; Fitzgerald and Hutton 2012; Galinato and Miles 2013). Originally designed with a relatively small, simple infrastructure and crop management practices (Wells and Loy 1993), high tunnels are now deployed with a wide variety of infrastructure features and crop management systems.

Tomatoes (*Solanum lycopersicum*) are especially suited to, and thus widely grown in, high tunnels. Compared with many other vegetable crops, tomatoes can effectively use the vertical growing space in a tunnel when trellised. Significantly higher yield can be obtained in tunnels compared with outdoor fields, and the harvest can be extended before and after the outdoor growing season (Bruce et al. 2019). The use of high tunnels can extend the growing season of organic tomatoes, reduce plant defoliation by early blight (*Alternaria solani*), and produce larger and more marketable fruit compared with field-grown fruit (Rogers and Wszelaki 2012). In eastern North Carolina, high tunnels advanced a summer tomato crop by 3 to 4 weeks via protection from low temperatures, earlier accumulation of growing degree days, and greater ability to manage the growing environment (O'Connell et al. 2012). Increased degree day accumulation in high tunnels can result in tomato harvest beginning 1 month or more earlier than that in the field (Reeve and Drost 2012; Singh et al. 2021).

The return on investment from a tomato high tunnel is typically rapid. Case studies of nine Michigan farms found that under some management practices, the structures paid back in 2 years (Conner et al. 2010). On an individual farm, the payback period depends on the cost of construction, operating costs, crop yields, and net revenues, all of which can vary. The construction cost of a specific type of tunnel and crop prices in specific markets for tomatoes are factors that growers may not have much influence on, but operating costs and yield can be influenced by grower decisions about infrastructure selection and crop management practices.

The 2022 US Census of Agriculture provides data regarding greenhouse tomato production for each state, along with floriculture crops (Table 39, USDA National Agricultural Statistics Service 2024). Statewide data regarding the acreage of vegetables harvested is also reported (Ibid, Table 36). Most farms that sell vegetables in New England are small-scale or medium-scale, and they typically use high tunnels rather than glass greenhouses. Assuming that most tunnel tomato production takes place on farms that also report selling fresh market (field) vegetables, it is possible to use Census data to estimate the percentage of vegetable farms that grow greenhouse (i.e. high tunnel) tomatoes (Table 1).

The US Department of Agriculture Natural Resources Conservation Service (NRCS) has provided funding for high tunnel construction since 2010 and required that the tunnels must be used to grow food crops in the soil. From 2010–18, the NRCS funded the construction of 1878 high tunnels in New England (Table 2). Using 2022 US Census of Agriculture data, we estimated there are 928 tunnels growing greenhouse tomatoes in the region (Table 1), which is just 49% of the NRCS-funded tunnels. Many high tunnels on vegetable farms are constructed without NRCS funding. Thus, it appears that Census data significantly under-represent greenhouse (high tunnel) tomato production in New England. Thus, it appears that Census data significantly under-represents greenhouse (high tunnel) tomato production in New England, especially given that not all high tunnels on vegetable farms are constructed with NRCS funding.

Many factors are associated with optimizing yield and quality of tunnel tomatoes. The optimal investment in

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Table 1. Number of New England farms selling fresh market vegetables and greenhouse tomatoes from the 2022 US Department of Agriculture Census of Agriculture state reports. Assuming that "greenhouse tomatoes" represents high tunnel tomato production, and that "greenhouse tomato" production takes place on farms that report selling field vegetables, these data can be used to estimate the percentage of vegetable farms that sell high tunnel tomatoes.

State	Farms selling fresh market (field) vegetables	Farms selling greenhouse (tunnel) tomatoes	Percent of vegetable farms selling greenhouse (tunnel) tomatoes	Avg farm acreage of fresh market (field) vegetables	Area (ft^2) greenhouse (tunnel) tomato production	Avg tunnel tomato area (ft^2) per farm
CT	887	146	16.5	7.7	415,704	2,857
MA	1436	195	13.6	11.6	631,612	3,239
ME	1197	252*	21.1	20.3	431,592*	1,713
NH	522	119	22.8	5.8	288,868	2,427
RI	298	46	15.4	6.1	107,146	2,329
VT	728	170	23.4	5.3	567,426	3,338
New England	5,068	928	18.3	11.1	2,442,348	2,632

* Excluding one farm with a 42-acre glass greenhouse, which is atypical.
CT = Connecticut; MA = Massachusetts; ME = Maine; NH = New Hampshire; RI = Rhode Island; VT = Vermont.

infrastructure and management time depends on a farmer's goals and capacity. Information about what peers are doing (i.e., benchmarking) can help growers understand options for improving production in ways that fit their farm. However, data are lacking about what constitutes "typical" practices. The purpose of this study was to assess the range of practices currently used in tomato high tunnels and identify practices that distinguish high-yielding tunnels from those with lower yields.

Methods

In Apr 2024, 90 growers who had worked with the University of Vermont Extension on previous high tunnel tomato projects were invited via e-mail to participate in a 37-question survey by completing a Google form. Qualitative and quantitative data were collected. Each farm provided their data from a single high tunnel that is passively ventilated with in-ground production of trellised "slicer" tomato cultivars using drip irrigation. Tunnels could be managed with conventional or organic methods but should have been in production for at least 3 years.

Forty-seven growers, primarily from Vermont (n = 35) as well as those from all other New England states plus eastern New York, completed the survey (Fig. 1). These growers were informed that after the growing season, they would be asked to report yield data from the tunnel identified in their survey response. In Oct and Nov 2024, yield reports were requested and 40 growers provided usable yield data.

Results

Production context. Tunnels were categorized as follows: 70% (n = 33) were certified organic; 17% (n = 8) followed organic practices but were not certified organic; 75% (n = 35) of the tomato tunnels were also used to grow winter greens; 55% (n = 26) of the tunnels were not rotated out of annual tomato production; 38% (n = 18) of the tunnels were planted to tomatoes for more than 10 years; 23% (n = 11) had grown tomatoes for 7 to 10 years; and 38% (n = 18) had grown tomatoes for 3 to 6 years.

Thirty-eight percent (n = 18) of tunnels were 30 ft × 96 ft, with 2880 ft^2 of growing area. Twenty-three percent (n = 11) of tunnels are 21 to 27 ft × 96 ft, with 2016 to 2592 ft^2 of growing area. The average tunnel size was 3227 ft^2, the smallest tunnel size was 1344 ft^2, and the largest tunnel size was 9000 ft^2 (Fig. 2).

Grower concerns. An open-ended question asked growers to identify their top three concerns or issues with high tunnel tomato production. Soil fertility and plant diseases were the top concerns (cited by 51% and 45% of growers, respectively) (Table 3).

Cultivars and plant management. 'Geronimo' was grown in 40% (n = 19)

Table 2. Number, area, and value of high tunnel funding provided by US Department of Agriculture Natural Resources Conservation Service in New England and New York from 2010–19. Data provided by LeRoy Hall, Data Services Branch.

	Tunnels completed	Square footage completed	Payments, completed tunnels	Tunnels planned	Square footage planned	Obligated, planned tunnels	Total Tunnels	Total square footage	Total paid and obligated
CT	214	487,305.4	$2,021,767	37	90,244.0	$410,442	251	577,549.4	$2,432,209
ME	532	1,075,212.7	$4,225,069	193	473,860.1	$2,162,903	725	1,549,072.8	$6,387,972
MA	293	690,556.2	$2,770,036	62	156,688.1	$729,072	355	847,244.3	$3,499,108
NH	378	712,072	$2,935,707	53	129,204.1	$580,625	431	841,276.1	$3,516,332
NY	475	991,936	$3,242,753	92	224,689.1	$1,046,203	567	1,216,625.1	$4,288,956
RI	138	309,005.4	$1,248,560	47	104,942.0	$483,157	185	413,947.4	$1,731,717
VT	323	711,351.5	$2,536,072	101	267,995.1	$1,239,493	424	979,346.6	$3,775,565
Total	2,139	4,490,134	$16,958,197	548	1,357,379	$6,241,453	2,687	5,847,512	$23,199,650

Economics and Policy Analysis Division Farm Production and Conservation Business Center, US Department of Agriculture, Beltsville, MD, USA, 20 Nov 2018. Data Source: NRCS ProTracts Data FY18.
CT = Connecticut; MA = Massachusetts; ME = Maine; NH = New Hampshire; NY = New York; RI = Rhode Island; VT = Vermont.

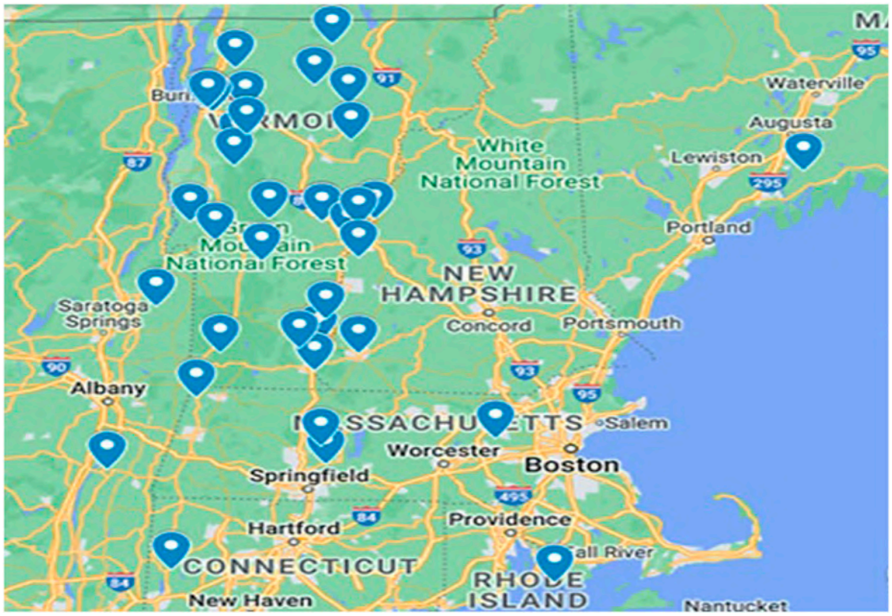

Fig. 1. Location of 47 farms that completed the high tunnel tomato survey.

of tunnels. 'Rebelski' was grown in 26% (n = 12) of tunnels. 'Big Beef' was grown in 17% (n = 8) of tunnels. 'Caiman' was grown in 15% (n = 7) of tunnels. 'Big Dena' and 'BeOrange' were grown in 11% (n = 5) of tunnels. Additionally, 51% (n = 24) of farms used grafted tomato plants. 'Maxifort' was the most widely used root stock (n = 15), followed by 'DR0141TX' (n = 6), 'Fortamino' (n = 3), and 'Estamino' (n = 2).

Seventy-one percent of tunnels relied on passive pollination and 19% had purchased bumblebee hives. In 68% (n = 32) of tunnels, the trellised plants were not lowered. In 15% (n = 7) of tunnels, the trellised plants were lowered once or twice. In 17% (n = 8) of tunnels, the trellised plants were lowered three times or more. In 47% (n = 22) of tunnels, fruit clusters were not thinned. In 25% (n = 12) of tunnels, fruit clusters were thinned to five fruits. In 19% (n = 9) of tunnels, fruit cluster were thinned to four fruits. In 8% (n = 4) of tunnels, fruit clusters were thinned to three fruits per cluster.

Plant density ranged from 2.6 to 9.6 ft^2 per stem or leader. Forty-nine percent (n = 23) of tunnels had a density between 4 and 6 ft^2 per stem. The average density was 5.5 ft^2 per stem. The correlation between stem density and reported total yield was R^2 = 0.11 (Fig. 3).

Growth period. Transplants were set into the tunnels from 15 Mar to 1 Jun. Approximately half the growers set transplants in late March or April, and half set them in May (Fig. 4).

After transplants were set, the tomato crop grew for 76 to 214 d, with an average of 160 d (Fig. 5). The correlation between days of growth and total yield was R^2 = 0.11 (Fig. 6).

Ventilation, circulation, and heating. For passive ventilation, 79% (n = 37) of tunnels had manual roll-up sides, 64% (n = 30) had large endwall doors, 43% (n = 20) had endwall gable vents, 19% (n = 9) had automatic side vents, and 17% (n = 8) had ridge vents. Additionally, 62% (n = 29) of tunnels had HAF fans.

Forty-seven percent (n = 22) of tunnels were unheated, 32% (n = 15) had propane heat, 11% (n = 5) had fuel oil heat, and 6% (n = 3) had wood pellet heat. Cord wood heat and natural gas heat were each used in 2% (n = 1) of tunnels. Fifteen percent (n = 7) of tunnels had root zone heating systems. Nine percent (n = 4) of tunnels used shadecloth.

Growers provided the total area of passive ventilation openings in the tunnels. Using the tunnel area dimensions provided, the ratio of ventilation openings to floor area was calculated. Ratios ranged from 0.17 to 0.64, with an average of 0.26. Four percent (n = 2) of tunnels had a ratio below 0.2, 23% (n = 11) of tunnels had a ratio between 0.2 and 0.29, 26% (n = 12) of tunnels had a ratio between 0.3 and 0.39, 26% (n = 12) had a ratio between 0.4 and 0.49, and 6% (n = 3) of tunnels had a ratio greater than 0.5. The correlation between the ventilation ratio and total yield was R^2 = 0.7 (Fig. 7).

Plant nutrition. To manage fertility, 64% (n = 30) of growers used the long-term high tunnel soil test, 40% (n = 19) used a field soil test, and 19% (n = 9) used a tissue (leaf) analysis. Twenty-one percent of growers (n = 10) added the same materials each year, 66% (n = 31) of growers injected fertilizers into the drip irrigation system, and 21% (n = 10) of growers applied foliar fertilizers. A

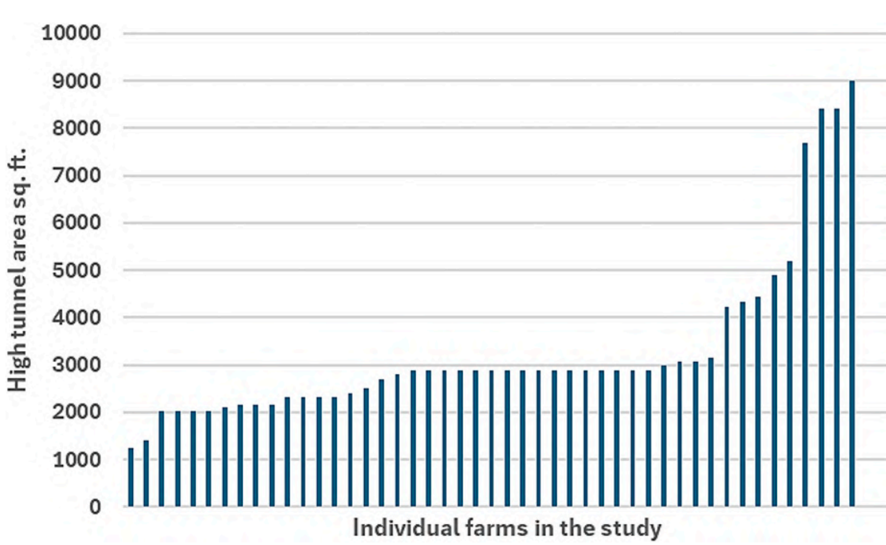

Fig. 2. The total area (ft^2) of each high tunnel on the 47 farms in the survey.

Table 3. Percentage and number of growers citing high tunnel tomato concerns or issues.

Concern or issue identified by growers	Percent of growers citing	Number of growers citing
Soil fertility	51	24
Diseases	45	21
Pests	19	9
Yield	17	8
Aphids	15	7
Irrigation	13	6
Pruning/trellising labor	13	6
Botrytis	11	5
Environmental control	9	4
Green shoulder	9	4
Salts	9	4
Sclerotinia	6	3
Cultivars	6	3
Hornworm	4	2
Labor	4	2
Leaf mold	4	2
Soil pH	4	2

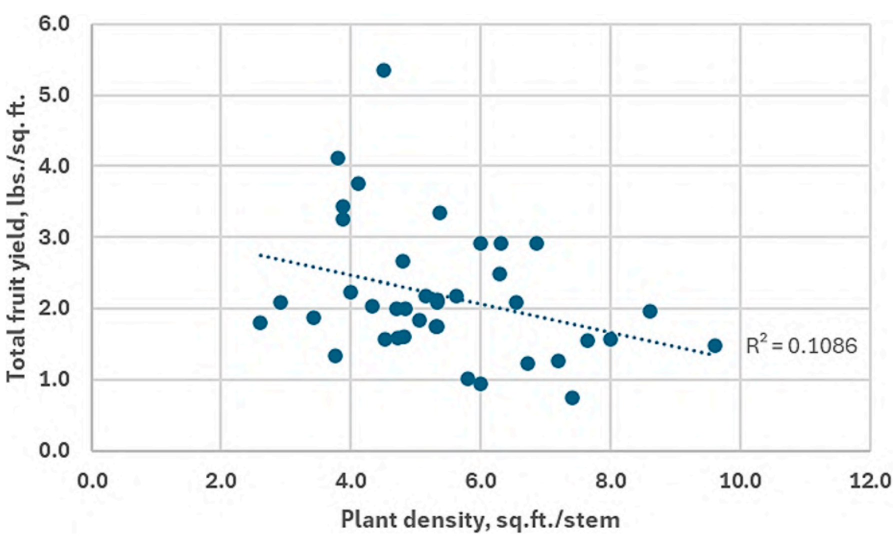

Fig. 3. The relationship between plant density (number of stems or leaders) and total tomato yield as reported by 40 farms.

variety of soil amendments were used: 72% (n = 34) of growers applied compost and 66% (n = 31) applied potassium as a single-nutrient fertilizer (Table 4).

Irrigation and mulching. An average of one drip irrigation line per 2.2 linear ft of tunnel width was used, and the range was one drip line per 0.9 linear ft to one drip line per 5.0 linear ft of tunnel width. The correlation between drip line density and total yield was R^2 = 0.13 (Fig. 8).

A variety of surface mulches were used (Table 5). Fifty-eight percent (n = 27) of tunnels had landscape fabric or black plastic mulch under tomato plants, 21% (n = 10) of tunnels had bare soil, 11% (n = 5) had green or infrared transmitting plastic, and 11% (n = 5) had organic residues as mulch.

Insect and disease management. In 67% of tunnels, biological controls were used to manage insect pests. The most widely used were *Aphidius* spp. in 34% (n = 16) of tunnels, *Aphidoletes* spp. in 30% (n = 14) of tunnels, lady beetles (*Hippodamia convergens*) and habitat plants, which were both used in 23% (n = 11) of tunnels. Additionally, 15% of tunnels (n = 7) used banker plants. Ninety-two percent of tunnels were sprayed to control disease, primarily for powdery mildew (*Oidium neolycopersici*), gray mold (*Botrytis cinerea*), leaf mold (*Fulvia fulvia*), and bacterial diseases.

Yield. Tomato yield was reported for 85% (n = 40) of tunnels in the study. Of these, 21 yields were measured and 19 were estimated. Total yield ranged from 0.74 to 5.35 lb/ft^2, with an average of 2.18 lb/ft^2. Forty-five percent (n = 18) of tunnels yielded 2.03 to 2.92 lb/ft^2, 35% (n = 14) of tunnels yielded 1.02 to 1.97 lb/ft^2, 10% of tunnels yielded 3.25 to 3.76 lb/ft^2, 5% (n = 2) yielded more than 4 lb/ft^2, and 5% (n = 2) yielded less than 1 lb/ft^2.

The reported percentage of total yield that comprised seconds or culls ranged from 0% to 40%, with an average of 18.4%; most growers estimated rather than measured seconds or cull yields. The average marketable yield (total yield minus seconds or culls) was 1.78 lb/ft^2. Fifty-one percent (n = 24) of growers weighed harvested fruit, 28% (n = 13) of growers did not measure yield, and 19% (n = 9) estimated yield based on sales records. Forty-nine percent (n = 23) of growers did not know how much yield to expect, 13% (n = 6) expected 2 lb/ft^2, 11% (n = 5) expected 3 lb/ft^2, 6% (n = 3) expected 4 lb/ft^2, 11% (n = 5) expected 5 lb/ft^2, and 11% (n = 5) expected 6 lb/ft^2.

Revenue. Retail prices reported by 40 growers ranged from \$3 to \$7.50/lb, with an average price of \$4.56/lb. Thirty-two percent (n = 13) of growers charged \$4/lb, 24% (n = 10) of growers charged \$4.50/lb, 24% (n = 10) of growers charged \$5/lb, 11% (n = 5) of growers charged more than \$5/lb and 7% (n = 3) of growers charged less than \$3/lb. Some growers (n = 6) did not report retail prices because they relied on community-supported agriculture markets that did not charge by the pound or because they only sold wholesale.

Based on an average tunnel growing area of 3227 ft^2, average marketable yield of 1.78 lb/ft^2, and average retail price of \$4.56/lb, the average annual gross revenue from a tomato high tunnel was \$26,193.

Discussion

We found some areas of consistency in high tunnel tomato production practices among farms and other

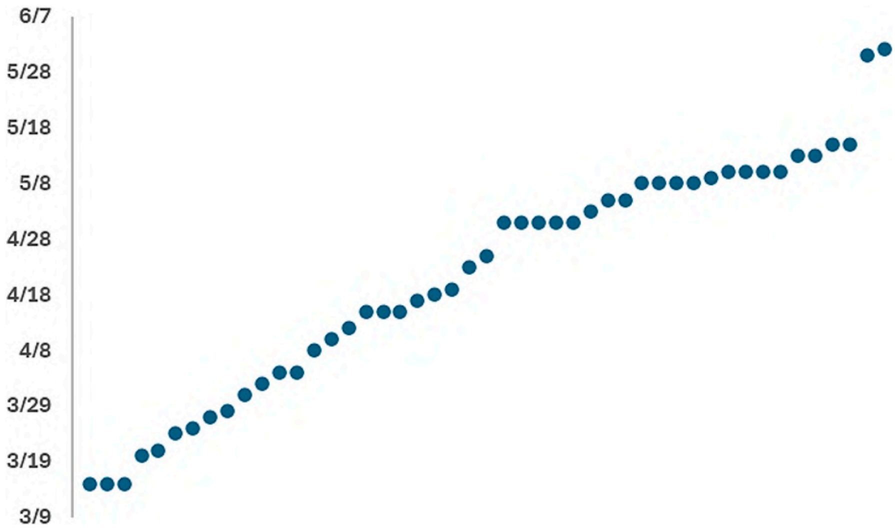

Fig. 4. The date when tomato transplants were set into the soil in 47 high tunnels.

areas with a moderate or high level of variation.

Production context. Seventy percent of the 47 tunnels were certified organic, which made sense because a requirement for participation in the survey was the use of in-ground production, which is a practice associated with organic tunnels. Most respondents were from Vermont, which has robust organic farming activity including 1.66 million ft^2 of certified organic greenhouse production (Vermont Organic Farmers 2022).

Tunnel size was similar on many farms. Sixty-one percent of tunnels were between 2010 and 2512 ft^2 in area, and most were 96 ft long, with widths of 21 to 26 ft. This size may optimize the construction cost of the growing area because multiple smaller tunnels require duplication of equipment such as heaters, pumps, and fans, while larger tunnels may require stronger (costlier) frames. The most common tunnel length was 96 ft, which accommodates a popular plastic covering size. Larger sizes can be challenging to handle and install. Tunnel widths greater than 30 ft, may not have optimal lateral air flow (Cornell University 2025), especially with an upright crop, such as trellised tomatoes, that reduces internal air flow.

A lack of annual rotation out of tomatoes and double-cropping with winter greens in the same season were common. Sixty-two percent of tunnels had been planted to tomatoes for 7 years or more, and 75% of tunnels grew winter greens after tomatoes. Greater use of annual crop rotation and/or fallow periods could benefit many tunnels, especially because plant disease was a top concern cited by growers and insect pests were a notable concern.

Grower concerns. Plant disease, soil fertility, and insect pests were the greatest concerns. Sixty-six percent of growers cited “diseases,” “Botrytis,” “Sclerotinia.” and/or “leaf mold” as top concerns. “Soil fertility,” “pH,” and “salts” were cited by 62% of growers as top concerns. “Pests,” “aphids,” and “hornworm” were cited by 38% of growers as top concerns. Some issues, for example, lack of ventilation, air circulation, and/or adequate irrigation, were not easily associated with reduced crop performance via observation alone; therefore, they may not have been cited by growers as concerns, even if they warranted improvement.

Cultivars and plant management. ‘Geronimo’, which was found in 40% of tunnels, was the most widely planted cultivar, and ‘Maxifort’, which was found in 63% of tunnels with grafted plants, was the most widely used rootstock cultivar. We did not assess attributes that drove grower cultivar preferences.

Only 51% of tunnels had grafted plants that could improve yields in tunnels with low soil nutrient availability and/or soil-borne diseases. An on-farm trial in Maryland found that grafted ‘Big Beef’ plants exceeded the yield of nongrafted plants by an average of 5.15 lb per plant in one year and by an average of 3.5 lb per plant in another year (Lantz 2018). “Primo Red” tomato scions grafted onto “Maxifort” rootstock out-yielded ungrafted plants at 16-, 20-, and 24-inch in-row spacings in a central New York high tunnel. The additional cost of grafted transplants was offset by higher yields, resulting in higher net revenues (Reid et al. 2023). A survey of 46 high tunnels on 26 farms in the Northeast did not find that grafting significantly increased yield (Maden 2024). These farms had optimized soil fertilization using the long-term high tunnel soil test. On-farm research in Ohio found that grafted tomato plants grown in the ground in high tunnels had lower levels of root pathogens than those of ungrafted plants (Testen et al. 2021).

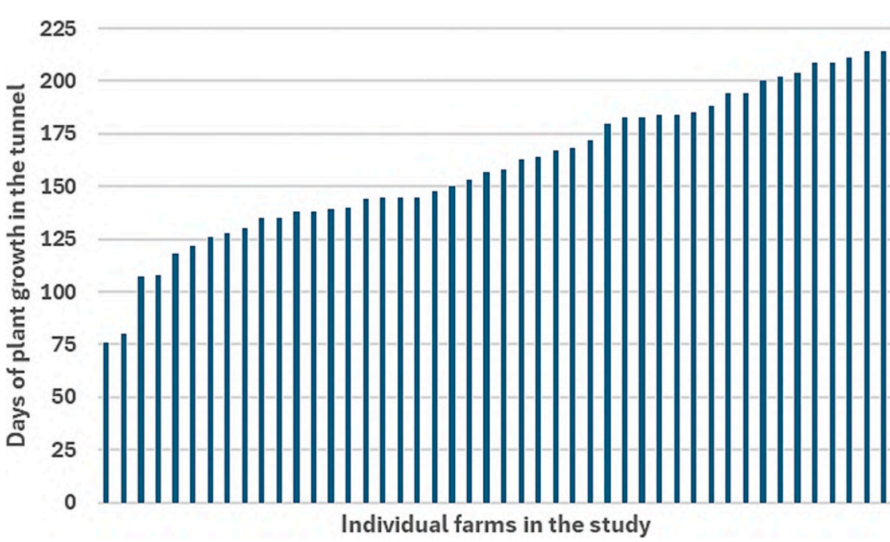

Fig. 5. The number of days tomato plants grew in 47 high tunnels.

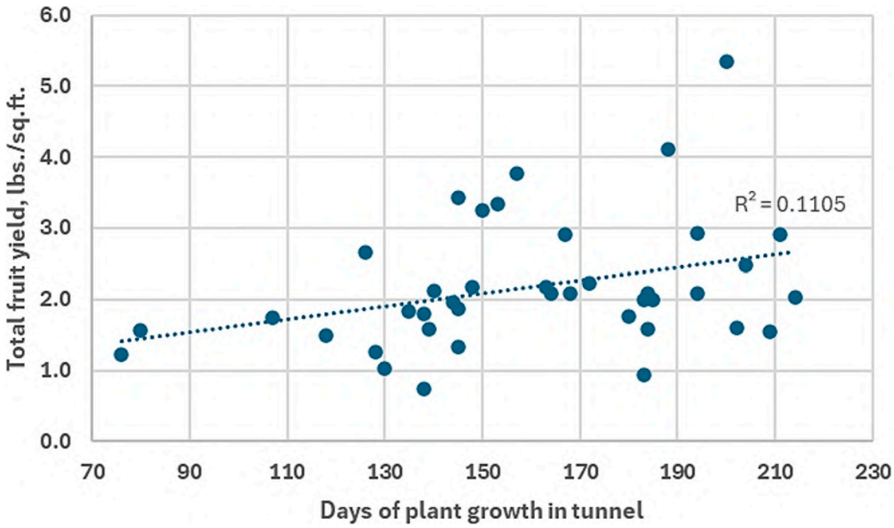

Fig. 6. The relationship between days of plant growth in the high tunnel and total tomato yield reported by 40 farms.

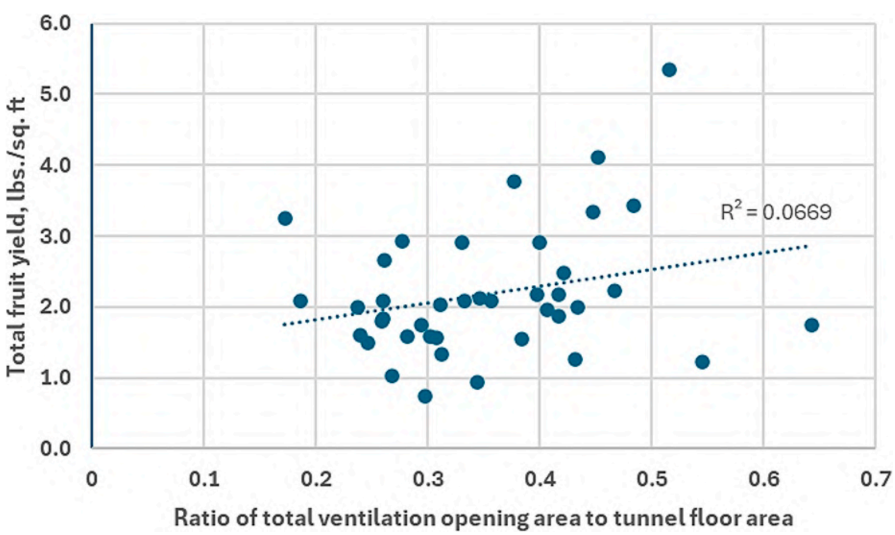

Fig. 7. The relationship between the ventilation ratio (total area of openings/ tunnel square footage) and tomato total yield as reported by 40 farms.

Trellised tomato plants were lowered in only 32% of tunnels. Lowering requires labor, so the cost may not have been justified except for a long-season tomato crop for which late fruit could not be reached from the ground without a harvest aide such as ladder or cart.

Fruits clusters were thinned in 53% of tunnels, and 84% of those were thinned to four or five fruits, presumably to obtain larger size and/or balance the fruit load. Research in New Hampshire compared the effect of pruning to three or six fruit per cluster, with and without the removal of every other cluster on 'Big Beef' tomato in high tunnels (Roman and Sideman 2022). Vegetative growth was significantly increased by reducing fruit load; however, this was not correlated with increased yield, and extra growth required additional labor for trellising and sucker removal. Thinning 'Jet Star' and 'Lola' tunnel tomato plants to three fruit per cluster significantly increased fruit size, but not yield, compared with leaving six fruit or not thinning (Mitchell et al. 2019). Neither of those studies thinned to four or five fruit, as performed in 45% of tunnels in our study.

Only 19% of tunnels used purchased bumble bees for tomato pollination, which can improve greenhouse tomato pollination and yield (Morandin et al. 2001). The benefits were likely greatest in early planted tunnels when passive ventilation and, thus, air movement were limited by cold outdoor temperatures.

Plant density. A wide range of plant (stem) density among tomato tunnels is not unusual. Maden (2024) surveyed 46 tomato high tunnels in the Northeast and found that stem density ranged from 3 to 10 ft^2/stem. Densities of 3.7 to 4.3 ft^2/stem significantly increased yield. In a Virginia high tunnel planted with 'Crimson Red 145307' a stem density of 10 ft^2 significantly outyielded densities of 7.5, 5.0 and 3.75 ft^2. Plants were in a sandy loam soil with a single drip line per bed. The authors hypothesized that insufficient irrigation played a role in decreased yield for the high-density treatments (Torres-Quezada and José Gandini-Taveras 2023). Tunnels in our study had an average density of 5.5 ft^2/stem, and the top 10 yielding tunnels had an average density of 4.5 ft^2/stem (Table 6), which was closer to optimal densities found by Maden (2024). This suggested that yield could be improved in some tunnels by reducing plant density. However, high plant density, especially with inadequate ventilation and/or air

Table 4. Percentage and number of high tunnels using different types of soil amendments.

Soil amendment identified by growers	Percent of tunnels using	Number of tunnels using
Compost	72	34
Potassium sulfate or chloride	66	31
Blended N–P–K fertilizer	47	22
Seed meals	38	18
Peatmoss	30	14
Chilean nitrate	23	11
Sul-po-mag	21	10
Epsom salts	19	9
Bone meal	19	9
Calcium or potassium nitrate	11	5
Fish emulsion	9	4
Manure	6	3

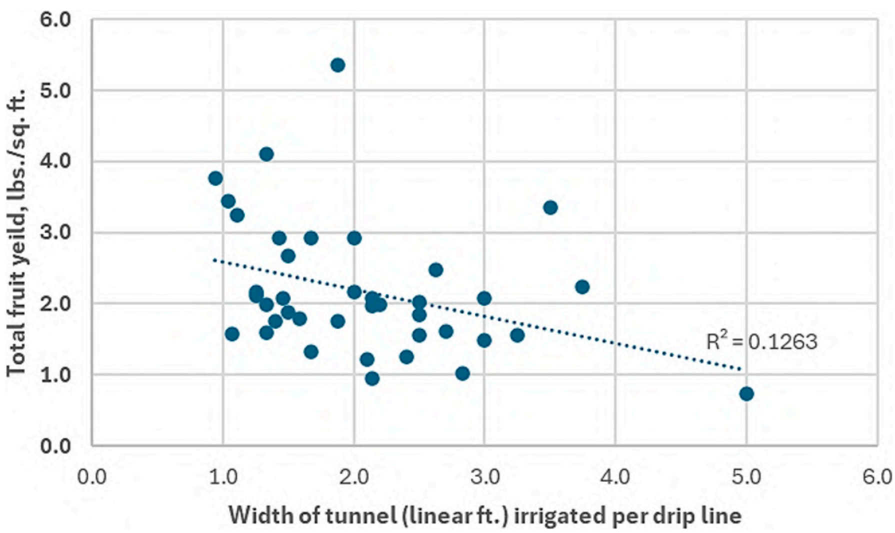

Fig. 8. The relationship between the number of drip lines per linear foot of high tunnel width and total tomato yield as reported by 40 farms.

Table 5. Percentage and number of tunnels with different soil surface mulches under tomato plants.

Mulch under tomato plants	Percent of tunnels	Number of tunnels
Landscape fabric	30	14
Black plastic	28	13
None (bare soil)	21	10
White plastic	9	4
Hay or straw	9	4
Green infrared transmitting plastic	2	1
Wood chips	2	1

circulation, can increase the risk of disease, which was a top concern of growers.

Growth period. The tomato transplant date ranged evenly among tunnels, from early March to the beginning of June. Early planting dates allowed growers to capture high prices and secure local markets (Conner et al. 2010; Hunter et al. 2012; Reeve and Drost 2012). Tunnels without supplemental heat usually ripen between 4 and 5 weeks before field tomatoes (Knewtson et al. 2010; Reeve and Drost 2012). The planting date can have no effect on overall yield (Rogers and Wszelaki 2012), but later planting dates may sacrifice early season yield (Hunter et al. 2012).

We found the correlation between the number of days growing in the tunnel and total yield was weak ($R^2 = 0.11$). This may have been because plants did not benefit from additional growing time when planted early into cold soil. High tunnel tomatoes transplanted in soil colder than 12 °C (53.6 °F) had inadequate nutrient uptake, reduced vigor, and lower yield (Gent 1992). We did not collect soil temperature data, but many of the unheated tunnels were planted early. Of the 22 unheated tunnels, 13 had plants set from 1 May to 10 May, and two others had them set in April.

Ventilation, circulation, and heating. Ventilation may have been inadequate in many tunnels. Fifty-seven percent of tunnels had a ventilation ratio (area of passive ventilation openings to tunnel floor area) below 0.35. The American Society of Engineers recommends that the total area of ventilation openings should be equal to 35% of the floor area in a passively-ventilated greenhouse (Bartok 2013). Ridge vents help optimize passive ventilation because of their location at the tunnel peak; however, only 17% of tunnels had ridge vents.

Adding or increasing the size of gable vents in endwalls, increasing door size in endwalls, and adding ground post extensions to increase side wall opening area are options that can increase ventilation openings. Adequate ventilation is critical to avoid high humidity, which promotes foliar diseases, which was a top concern of growers.

The relationship between the ventilation ratio and reported total yield was weak ($R^2 = 0.07$). This may have occurred because air exchange in passively ventilated greenhouses was difficult to optimize when manually controlled. The ratio provided a benchmark for optimizing the size of ventilation openings; however, if openings are not automated, then they may not provide timely ventilation. Typically, growers open side vents in the morning and close them at night, without adjusting for changes in outdoor temperature during the day. Only 19% ($n = 9$) of tunnels had automated side ventilation. Any natural ventilation system should have the

Table 6. Comparison of tunnel attributes and production practices between top-yielding tunnels and all others based on grower-reported total yield.

	Top 25% tunnel yields ($n = 10$)	Lowest 75% tunnel yields ($n = 30$)	Percent difference
Tunnel attribute			
Total yield (lb/ft^2)	3.47	1.75	99
Stem density (ft^2)	4.50	6.30	29
Tunnel width per drip line (ft)	1.64	2.29	28
Length of growing season (days after transplanting)	169.1	156.7	8
Ventilation ratio (total area of openings/total floor area)	0.37	0.35	7
Tunnel production practice			
Automatic ventilation	60%	10%	500
Air heating system	80%	37%	118
Grafted plants	70%	37%	91
HAF fans	80%	53%	50
High tunnel soil test	80%	63%	26

HAF = horizontal air flow.

means to open partially or fully in response to inside temperature, with automatic control of such systems being highly recommended. Incremental opening and closing should also be possible (American Society of Agricultural Engineers 2003).

Air circulation may be inadequate in some tunnels. Thirty-eight percent of tunnels lack HAF fans that mix air to provide uniform temperatures and humidity, thus preventing foliar diseases by reducing stagnant air and moisture buildup on leaves (Koths and Bartok 1985). The HAF fans also promote uniform CO_2 distribution, potentially enhancing photosynthesis and fruit yield. The use of HAF fans was found to stimulate greenhouse tomato seedling growth to an extent roughly equivalent to CO_2 enrichment at 1000 ppm (Thongbai et al. 2010). Temperature, humidity and CO_2 gradients in a tomato greenhouse are greatest when it's sunny, and HAF fans significantly improve uniformity of all three (Fernandez and Bailey 1994). In the field, we observed HAF fans that were often improperly located or sized. Properly installing HAF fans is a low-cost practice with a high potential for improving crop performance.

Growers noted unusually hot temperatures in tunnels during the 2024 growing season. Very few tunnels (8%) had shadecloth to help address this concern and avoid associated reductions in fruit yield or quality. Shadecloth can reduce tunnel temperature by 3 to 4 °F when light intensity is high, and it can reduce the number of unmarketable fruit attributable to skin cracks; therefore, cloth providing shade of 30% or less is recommended (Guan 2016).

Fifty-three percent of tunnels have air heating systems. Air heat allows plants to be set earlier by avoiding the risk of cold injury. Below 60 °F, nutrient deficiencies may occur because plants cannot absorb some elements at cool temperatures (Snyder 2016). Tomato plants in tunnels with air heat grew for an average of 18 d more than those in unheated tunnels. Root zone heat is used to promote growth of plants set in tunnels early in the growing season, when soil is cold. Heating the air does little to warm the soil in early spring because heat rises. Only 15% of tunnels had root zone heat; however, approximately half of the farms set their plants in the tunnel before mid-May, when soil was likely to still be cool. A greenhouse study in Quebec found that increasing soil temperature from 57 to 71 °F increased tomato yield by 36% to 47%, with transplants set 24 Apr through 6 May (Trudel and Gosselin 1982). Using root zone heat could increase yield even for growers already using air heat.

Plant nutrition. Compost was applied in 72% of tunnels. Compost can vary significantly in nutrient content and maturity (Mangan et al. 2013), and we observed that few farmers had their compost analyzed before application. Thirty-six percent of growers were not using the long-term high tunnel soil test offered by University of Maine, which measures immediately available water-soluble nutrients using the saturated media extract as well as reserve nutrients using the modified Morgan's extract (Maden and Grubinger 2023). Test results include measures of available nitrogen and soluble salts. The test results come with nutrient recommendations calibrated for tunnel crop yields, which are higher than those in outdoor fields. Eighty-one percent of growers did not use tissue testing to monitor the nutrient status of tomato plants. Using this low-cost practice, especially early in the growing season, could help growers assess and optimize fertilization.

Irrigation and mulching. All tunnels had drip irrigation, which was a prerequisite for survey participation. However, the number of drip lines varied considerably. The number of drip lines per linear foot of tunnel width was used to compare tunnels across a variety of planting and drip line arrangements. Tunnels ranged from one drip line per 0.9 linear ft to one drip line per 5.0 linear ft of tunnel width. We found that the correlation between the number of drip lines per linear foot of tunnel width and total yield was weak ($R^2 = 0.11$). However, the top 10 yielding tunnels had a 28% greater density of drip lines (Table 6). A survey of 46 tunnels in the Northeast in 2020 and 2021 found that three or four drip lines per row of tunnel tomatoes significantly improved yield compared with a single drip line per row (Maden 2024). The optimal number of drip lines in a tunnel will completely wet the potential crop rooting area, and that number is likely to vary with soil texture, soil organic matter, plant arrangement, and irrigation system output.

Fifty-seven percent of tunnels had plastic mulch or (plastic) landscape fabric as mulch; the others were bare or had organic residues as mulch. Twenty-seven tunnels with plastic mulch reported an average total yield of 2.3 lb/ft^2, and 13 tunnels with bare soil or organic mulches reported an average total yield of 1.92 lb/ft^2, which was a 17% reduction. Plastic mulches in high tunnels can promote growth by increasing soil temperature, reducing weed emergence, and reducing evaporation of water from soil (Jett 2013). Reduced loss of soil moisture may also reduce the incidence of foliar disease such as late blight (Shtienberg et al. 2010).

Insect and disease management. Diseases were a top concern cited by growers, and 92% of tunnels were sprayed for disease management. The extent to which growers managed cultivar selection, plant density, ventilation, and air circulation to avoid foliar diseases was not known. Additional research into the efficacy of these practices could benefit grower decision-making. Thirty-three percent of tunnels did not release beneficial insects to manage insect pests, suggesting the need for additional outreach regarding the topic. More outreach regarding the benefits of "plant-mediated integrated pest management systems" (Skinner et al. 2019) is also needed because only 23% of tunnels had habitat plants and only 15% had banker plants.

Yield and revenue. Total yield reported by growers ranged from 0.74 to 5.35 lb/ft^2. The top few yields were known to be from farms that specialized in tunnel tomatoes, and the lowest few yields were known to be from highly diversified farms that did not attempt to optimize their tunnels for tomatoes. The average marketable yield of 1.78 lb/ft^2 was consistent with that of other high tunnel tomato studies in the temperate United States. Tunnel tomato yields reported in eight outreach publications and enterprise budgets between 2004 and 2013 ranged from 1.26 lb/ft^2 to 2.89 lb/ft^2, with an average of 2.20 lb/ft^2 (Galinato and

Miles 2013). Four experienced tunnel growers in western Washington estimated that the marketable tomato yield was an average of 2.25 lb/ft^2, with a density of 4.0 ft^2/stem, which was 402% of estimated yields of field-grown tomatoes and three times more profitable (Galinato and Miles 2013). An on-farm high tunnel trial in Nebraska with 'Big Beef' and 'Big Dena' planted at 4 ft^2/stem yielded approximately 3.9 and 4.0 lb/ft^2, respectively (Practical Farmers of Iowa 2019). A survey of 46 tunnels on 26 Northeast farms in 2020–21 found that the average yield was 3.12 lb/ft^2. These farms had optimized fertilization using the long-term high tunnel test (Maden 2024). A 2018 study aggregated data from five organic farms in Vermont that grew both grafted and nongrafted slicing tomatoes in high tunnels. The average yield per plant, at an unspecified density, was 19.7 pounds. If the density had been 5.5 ft^2/stem, then the average yield would have been 3.6 lb/ft^2. The average net profit reported was \$3598 per 1000 ft^2, equivalent to \$156,513 per acre (Miller 2019).

In comparison with tunnel yields and revenue, the 5 year yield average for outdoor fresh market field tomatoes in New England was 9260 lb per acre from 2020–24, and the average price was \$2.21 per lb (NASS 2025), which was equivalent to \$20,465 in gross revenue per acre.

Many growers in this study did not have accurate measures of yield. Only 51% of growers weighed their tunnel tomato harvests, and 49% stated they did not know how much yield to expect. It is difficult to assess changes or improvements in production practices without an accurate baseline for comparison. Growers would benefit from assistance with practical methods to track yields, such as setting up reporting forms for employees to count trays harvested or weighing fruit production from a subset of representative plants.

Comparing high-yielding and low-yielding tunnels. Our data suggest that certain groups of practices are associated with higher yields. We examined the extent to which management practices differed between the highest-yielding tunnels and all others (Table 6).

High-yield tunnels have a higher average plant density (4.5 ft^2/stem) than that of low-yield tunnels (6.3 ft^2/stem). The initial cost of additional plants is low, but they add to labor costs for pruning, trellising, and harvesting.

High-yield tunnels have more drip lines per linear foot of tunnel width (1.64 ft) than low-yield tunnels (2.29 ft). In a 30-ft-wide tunnel, this is equivalent to 18 (vs. 13) drip lines. The cost of adding drip lines to an existing irrigation system is low.

High-yield tunnels have a longer growing season, with an additional 12.4 d. High-yield tunnels have 7% more ventilation opening area than that of low-yield tunnels.

High-yield tunnels have a 500% greater adoption rate of automated ventilation than low-yield tunnels. Investing in automated ventilation has potential for rapid returns. For example, at an average retail price of \$4.50/lb, the average revenue for a 30 × 96 ft high-yield tunnel is \$44,971, and the average revenue for a low-yield tunnel is \$22,680. Adding automation to side ventilation costs approximately \$3000, which would be paid back in less than 1 year with a 15% yield improvement in a low-yield tunnel.

High-yield tunnels have a 118% greater adoption rate of air heating systems than low-yield tunnels. Daylength is longest in June; therefore, heating to produce larger plants and increase photosynthesis in early summer could improve biomass production and yield.

High-yield tunnels have 91% greater adoption of grafted plants than low-yield tunnels. Grafting can help overcome soil limitations to plant growth, but grafted plants, whether purchased or produced, add cost because of the labor required to produce them.

High-yield tunnels have a 50% greater adoption rate of HAF fans than low-yield tunnels. The fans cost several hundred dollars each and last a long time. Typically, four fans per tomato tunnel sufficiently mix and circulate air. Proper sizing and placement of fans are important, and we observed that some growers installed fans improperly; therefore, the full benefits were not realized.

High-yield tunnels have a 26% greater adoption rate of the long-term high tunnel soil test than low-yield tunnels. Using this test helps optimize fertilization because the recommendations are tailored to high tunnel yield expectations. The cost is \$30 plus shipping and labor to collect the sample. Grower feedback regarding the impact of using this test and following the fertilizer recommendations has been positive (Maden 2024).

Conclusions

The adoption of one or more key practices could lead to improved yield on many farms growing high tunnel tomatoes. These practices are optimizing plant density, drip line density, and the area of passive ventilation openings; adding automated ventilation, air and ground heating systems, and horizontal air flow fans; and using grafted plants and the long-term high tunnel soil test. Economic returns on the adoption of practices depend on the management capacity of farmers and the revenue generated by additional tomato production. To evaluate the impact of new practices, growers need to accurately measure yield.

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