Organic Apple Production in High Tunnels

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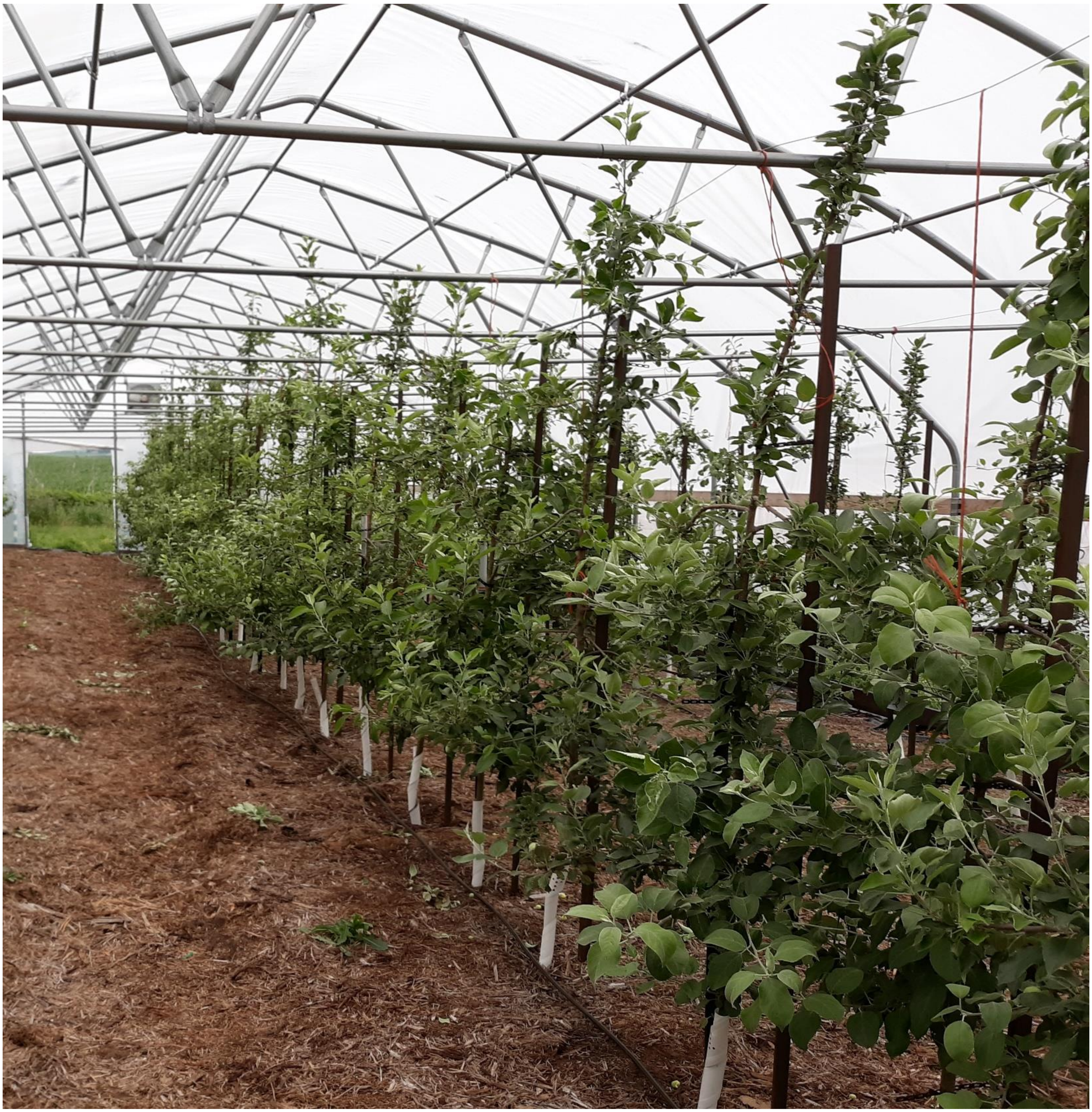


Summary

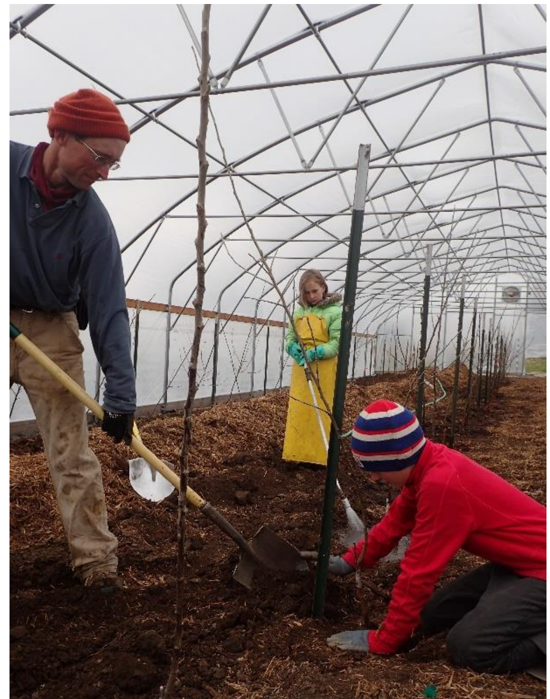
We evaluated the feasibility of growing organic apples in high tunnels. The trees grew vigorously and fruited quickly. As expected, most diseases were rare or absent in the tunnels; but insect damage occurred at broadly similar levels to the damage in outdoor orchards. Sunburn, soft flesh, and off-flavors were common in the fruit of many varieties, presumably because of the hot environment within the tunnels. Overall, we concluded that high tunnel cultivation of organic apples is difficult to justify because of the costs of high tunnel construction and maintenance, heat-related fruit defects, and the need for sprays to control insect damage. If high tunnel cultivation is feasible, it seems essential to focus on heat-adapted, high-yielding varieties, such as Suncrisp in our study. This report contains a detailed description of our growing methods, observations, expenses, and yields.

Background and Objectives

Locally produced organic apples are in demand, but most organic apples are produced in desert areas of Washington, where the dry climate reduces infection from fungal diseases such as apple scab. In the north central U.S., wetter weather favors disease, and most organic apple growers grow disease-resistant varieties and/or spray organic fungicides such as sulfur. Disease-resistant varieties can be difficult to market if they are not the most flavorful varieties or if they are not familiar to consumers. Organic fungicide sprays are expensive, require frequent re-application, and can have negative effects on apple trees, beneficial insects, and the environment.

We evaluated the profitability of organic apples grown in unheated polyethylene-covered high tunnels. Trees in tunnels are protected from rain and should therefore suffer less disease. Tunnels can also ameliorate severe weather, provide better growing conditions, and thus improve yields. Although high tunnels are expensive to build, many growers already have tunnels or can construct them at low cost with USDA-NRCS EQIP grants. We compared seven apple varieties in our project: high tunnels may be best suited to disease-susceptible varieties which are difficult to grow outdoors but which command a high market price.

Research Methods



Planting trees in tunnel 1

We established the high tunnel plantings in April 2019,and this three-year study was conducted in the 2019, 2020, and 2021 growing seasons.

Organic. Our entire farm is certified organic by MOSA (mosaorganic.org) and only organic methods were used in this research.

Planting Arrangement. There were thirteen trees of each variety in each tunnel, along with 1-2 border trees at each end of each row. (Data from border trees is not included in this report). Within each tunnel, the 91 non-border trees were arranged randomly, with varieties randomly interspersed. Trees were planted 3' apart within the row, with 11-12' between rows.

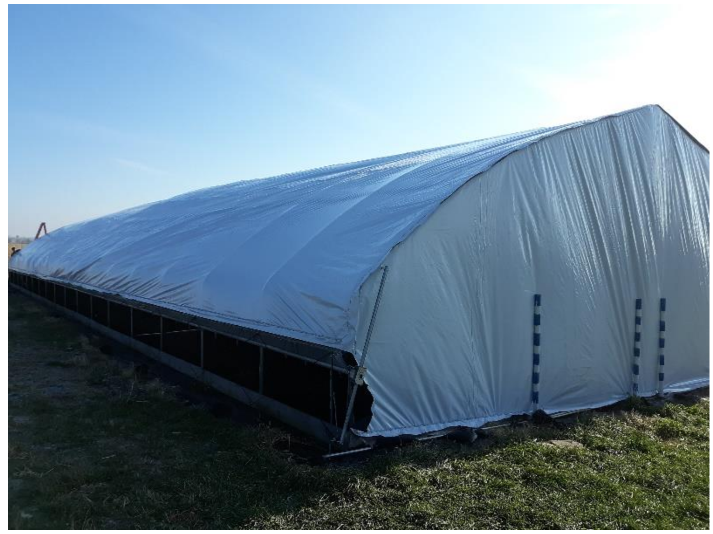
Varieties. We selected seven apple varieties for this study: Ashmead's Kernal, Grimes Golden, Macoun, Hudson's Golden Gem, and Golden Russet are less common heirloom varieties which can command a high price because of their flavor and historical interest. However, all are susceptible to scab and other diseases and we therefore do not raise them outdoors. Unfortunately, the scionwood which we obtained for Macoun and Grimes Golden was not true to type. The Macoun trees were actually Calville Blanc d'Hiver. The putative Grimes Golden trees were of an unknown red/green skinned, sweet, soft-fleshed apple, referred to as Mystery hereafter. The other two varieties in our study, Winecrisp and Suncrisp, are high-yielding modern varieties popular with local organic growers. We have raised these varieties outdoors. Winecrisp is scab-immune, but fairly susceptible to cedar-apple rust and Alternaria blotch. Suncrisp is moderately resistant to scab, but not immune. We included these two varieties as a comparison to the five heirloom varieties because they are reliable standards and because they are heat-tolerant and thus may thrive in warm high tunnels.

High Tunnels. Two high tunnels purchased from Nolt's Midwest Produce Supplies were used in this study; both allow trees to reach heights of 10+' and are ventilated via rollup sides and endwall doors:

Tunnel	Width	Length	Number of Tree Rows	Trees Per Row	Total Trees	Border Trees[1]	Experimental Trees[2]	Year Constructed	Initial Construction Cost (Materials Only)
1	34'	102'	3	33	99	8	91	2017	$9,643
2	24'	148'	2	49	98	7	91	2018	$9,955

[1]Border Trees are at the ends of rows; no data was collected from these trees
[2]Experimental Trees are the trees from which data was collected

High Tunnel Coverings. When the trees were planted in April 2019, the tunnels were covered with a single layer of standard greenhouse polyethylene. We removed the plastic prior to winter (on 10/25/2019 from tunnel 1, and on 12/5/2019 from tunnel 2). Based on the experience of farmers and researchers with other tree fruits, it is important to not expose trees to the drastic diurnal temperature fluctuations that occur in winter in high tunnels covered with clear greenhouse polyethylene. On sunny days, temperatures can rise steeply in tunnels covered with clear plastic, but at night the temperatures inside the tunnel are similar to outdoor temperatures. Trees cannot remain cold-hardy and acclimated under these constant temperature swings and are likely to suffer cold damage at night. In spring 2020, we covered both tunnels using a single layer of Klerks SunView Cool polyethylene, which lowers tunnel temperatures by approximately 10 degrees compared to the traditional polyethylene covers (tunnel 1 was covered on 5/2/2020, and tunnel 2 on 5/6/2020). We selected the SunView Cool cover because the trees suffered leaf burn during warm spells in 2019 and because apple fruits are vulnerable to sunburn at air temperatures above 95 degrees. For the winter of 2020-21, we elected not to uncover the tunnels because of the time required, the stress and difficulty of re-covering tunnels during windy early spring weather, and the risk of damaging the cover during removal and reinstallation. Instead, on 11/23/2020 we covered both tunnels with Film-Gard black and white 5 mil silage tarp (available at Farm and Fleet). The tarp was installed white side out, and completely covered the south, east, and west sides of each tunnel, preventing winter sunlight from entering the tunnel. We had heard from other growers who raise stone fruits in high tunnels that the silage tarp keeps the tunnel cool in winter and prevents daytime temperature spikes. The silage tarp was removed on 4/6/2021.



Tunnel 1 covered with silage tarp, fall 2020

For ventilation, rollup sidewalls and endwall doors were regularly left open during the growing season. Before mid July, we attempted to close the tunnels during rain to minimize the chance that windblown rain would wet foliage and lead to disease. Later in summer and in fall we no longer closed the tunnels during the rain.

Tree Planting. The trees planted were one year old grafts raised in our on-farm nursery or purchased from Cummins Nursery, Trumansburg, NY. We planted trees by hand on April 12th and 17th, 2019.

Mulch and Weed Control. We completely covered the soil surface in both tunnels with hardwood bark purchased from local sawmills after planting. Tunnel 1 was mulched in May 2019, but Tunnel 2 was not mulched until November 2019 because of time constraints. Both tunnels were hand weeded as needed during the growing seasons. Compared to outdoor plantings, the mulch in the tunnels degraded slowly (presumably because of lack of rainfall), and it was not necessary to replenish the mulch during the first three years of growth.

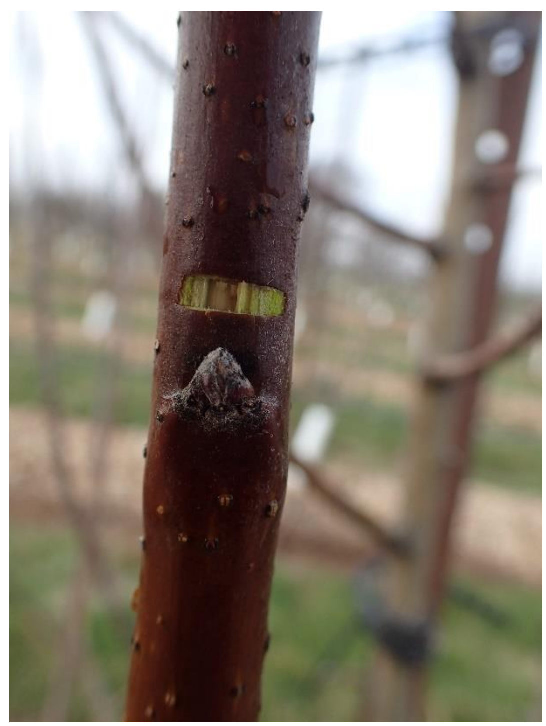
Bark mulch and irrigation line in Tunnel 1, spring 2020

Irrigation. Both tunnels were irrigated using drip tape with a flow rate of 0.34 GPM per 100', with a single tape line by each tree row. Irrigation sessions were generally for 8-12 hours on 4-7 day intervals, depending on weather.

Training. Trees were planted 3’ apart within rows, grafted on dwarfing rootstocks (G. 41 or G.11) and trained using the tall spindle method; these are common practices in outdoor high-density apple orchards.

In the 2019 growing season, we trained trees on a minimal wire trellis suspended from the high tunnel structure. Trees were secured to the wires with tree tie tape, and vigorous branches were tied below horizontal using training wires.

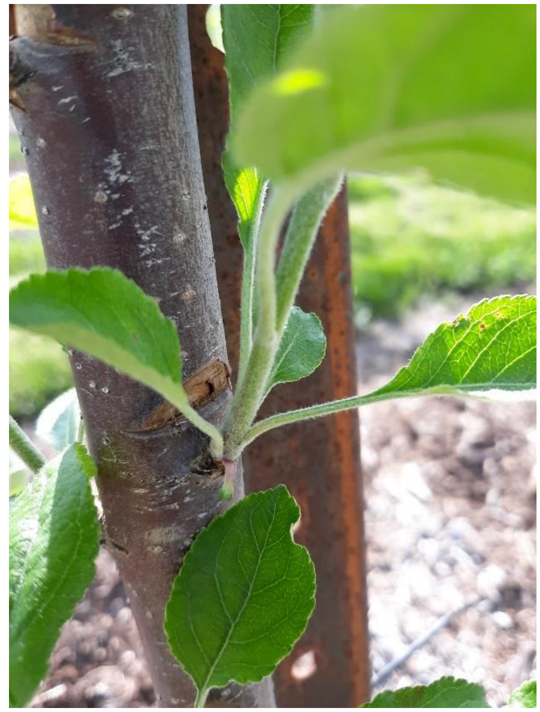
In April, 2020 we installed a permanent support stake next to each tree (Best Angle Tree Stake model PA3120 - 10' high angle iron stake 1-1/4" x 1-1/4"); stakes were pounded 2.5' into the ground, with 7.5' above ground. We secured trees to the stakes with AgLok chain and continued to train vigorous branches below horizontal using training wires. On 4/2/2021, we dormant pruned the trees, removing several larger branches from each tree. In 2021, we continued to train trees to the metal stakes, but did minimal branch training.



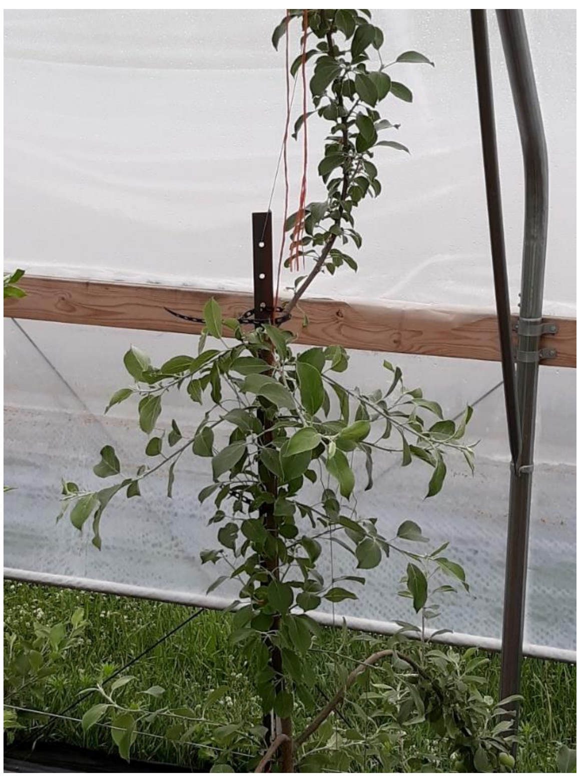
Notch cut above dormant bud in early spring

To encourage branching, we notched the cambium above dormant buds on the leader in all three years (4/22-4/29/2019, around green tip; 5/5-5/8/2020, just before bloom; and 4/16-4/17/2021, at green tip to tight cluster). On one year old wood, we notched by running the saw blade on a Leatherman tool backwards to abrade the cambium just above the bud. On two year old wood, we used a box cutter knife: we pressed the blade straight into the hardwood just above the bud, then made a second cut down at a 45-degree angle to meet the straight cut and we removed the angled notch. Extensive blind wood on leaders is unacceptable in high density apple production; notching is highly effective at promoting branching.

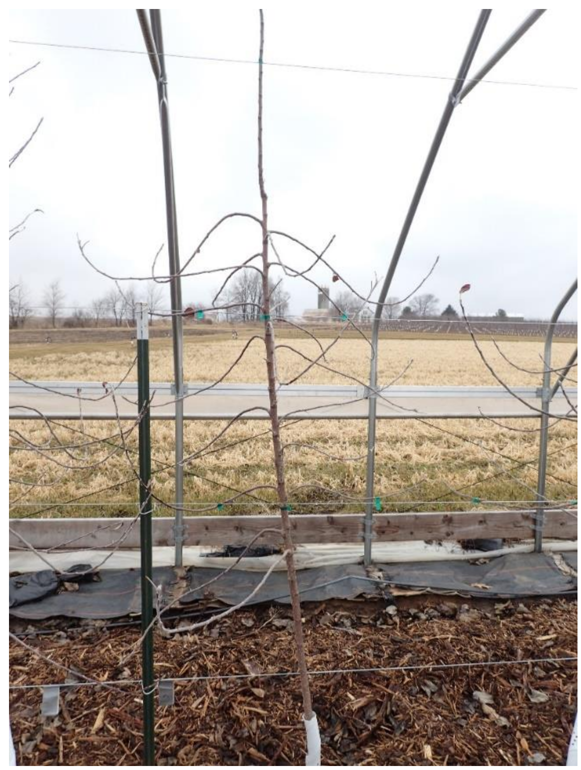
In general, vegetative vigor was high, and we were initially concerned that the trees might outgrow their space over time, but fruiting definitely reduced vigor in the second and third years. Most leaders were close to the roof of the high tunnel by the end of 2020 and were pressing against the roof by the end of 2021. Repeated rounds of branch training were required in both 2019 and 2020. The variety Suncrisp was particularly troublesome because of its propensity to grow strong upright branches.



New branch growing in late May under notch



Young branches held down by training wires



Dormant second year tree in March 2020, showing horizontal and drooping branches developed by training

Insect Pest and Diseases. We scouted each high tunnel weekly for disease and insect pests. In addition we installed delta traps baited with pheromone lures for codling moth, red-banded leafroller, and oblique-banded leafroller in tunnel 1.

Virtually no signs of plant disease were noted in the tunnels. In 2020, a few cedar apple rust lesions occurred on early spur leaves of Golden Russet and Hudson's Golden Gem; it is likely that these infections may have occurred shortly before the tunnels were covered in early May. In 2021, occasional cedar apple rust lesions were noted on many varieties, especially near the edges of the tunnels, and we suspect that infections occurred when the rollup sides were left open during a spring rain event. In both years, the cedar apple rust levels in the tunnels were vastly lower than in our outdoor orchard. Fireblight, scab, Elsinoe leaf spot, alternaria blotch, sooty blotch and flyspeck were all absent or vanishingly rare. All of these diseases occurred in our outdoor orchard during 2020 and 2021. The virtually pristine foliage on tunnel trees, even in mid to late autumn, was remarkable and unprecedented in our experience growing organic apples outdoors. The one notable exception was that in late summer 2021 we observed low levels of powdery mildew in both tunnels on numerous varieties. Powdery mildew is generally common in high tunnels because warm, humid conditions favor its development, and because it does not require wet foliage to infect leaves. This disease is absent or very rare in our outdoor orchards, presumably because the conditions there are less favorable and/or our intensive spray program controls it. We suspect that powdery mildew might continue to develop and spread in our tunnels in future years and that potassium bicarbonate sprays might be needed to control it.

In general, the tunnels did not appear to greatly reduce insect pest damage compared to outdoor orchards. This observation agrees with what growers and researchers have found for other fruit crops grown in high tunnels. The table below details our observations of insect pest damage in the tunnels and sprays used to control insect pests.

Insect	Occurrence in tunnels	Sprays made in tunnels	Qualitative Comparison of Damage in Tunnels to Damage in Nearby Outdoor Orchard
Codling Moth	2 moths caught in tunnel pheromone trap in 2020, none in 2021. 1st and 2nd generation larval feeding damage seen in tunnel 2 in 2021	Granulosis virus sprayed for both 1st and 2nd generations in both years.	Significantly greater level of damage in tunnel 2 in 2021 than outdoors. Outdoors, mating disruption and more extensive granulosis sprays are used to control CM.
Japanese Beetle	Low levels of damage noted in 2021	beetleGONE sprayed in 2020 but not 2021	Lower damage in tunnels than outdoors
Red banded leafrollers	Regularly caught in pheromone traps and some damage noted to terminals	Dipel (Bt) sprayed during larval activity	Similar level of damage
Oblique banded leafrooler	Occasionally caught in pheromone traps and some damage noted to terminals	Dipel (Bt) sprayed during larval activity	Similar level of damage
Plum Curculio	In 2020, damage was seen in tunnel 2 while hand thinning. Approximately 10 damaged fruits were found. This is a low level of damage. Much higher levels of damage were seen in 2021 in both tunnels.	Pyganic sprayed on warm nights during oviposition period	Greater level of damage in tunnels. In outdoor orchard, we spray Surround heavily to deter PC. We opted not to spray Surround in the tunnels out of concern that the residue would not wash off before harvest without rainfall.
Spider mites	In 2020, spider mite damage to foliage was evident in tunnel 1. Lower levels of damage noted in 2021 in both tunnels	JMS Stylet Oil (horticultural oil) sprayed regularly in 2020.	Greater damage in tunnels. Spider mites are not a pest in our outdoor orchard, and they are presumably favored by the dry conditions within the high tunnel.
Rosy apple aphid	Rosy apple aphid infestation occurred in both tunnels in late May and June, 2020	In 2020, infestations were controlled by localized spraying of Safer soap (1 tsp/1 cup water) with a hand spray bottle. In several cases, the aphid	Greater level of damage in tunnels.

Insect	Occurrence in tunnels	Sprays made in tunnels	Qualitative Comparison of Damage in Tunnels to Damage in Nearby Outdoor Orchard
		infestation grew to significant size before we noticed it and multiple time-consuming sprays were needed to eradicate the aphids, showing the importance of timely scouting for this pest.	
Wooly apple aphid	Numerous infestations noted in both tunnels in 2021. Some were very large and covered multiple branches.	Venerate sprayed in summer 2021	Greater level of damage seen in tunnels. Outdoors, infestations are seen but rarely develop to significant size. Tunnel infestations were larger.
Potato leafhopper	Common during summer in all years	Azaguard sprayed in 2020	Similar – this insect is abundant and widespread in our outdoor orchards during the summer and consistently damages foliage.
Brown marmorated stink bug	One adult seen during harvest in fall 2021	None	Similar – this insect is very rare in our outdoor orchards.
Apple Maggot	No damage seen in tunnels	None	Similar – this insect is very rare at our farm.

Spray Schedule. We sprayed insect control products at several times. In general, we made no disease controls sprays. We sprayed micronutrients on the same schedule as used for outdoor apple plantings. Sprays were applied using a Rears Pakblast 50 tractor mounted airblast sprayer, except for safer soap which was spot-sprayed on aphid-infested foliage. All sprays are shown in the table below. The high tunnel plantings were certified organic and all sprays were organically approved. We were unable to spray the outside of the outside rows in both tunnels because the tractor would not fit there. I.e., in Tunnel 1, which had three rows of trees and two drive aisles, the middle row was sprayed from both sides but the outer two rows were sprayed from one side only. In Tunnel 2, which had two tree rows and one drive aisle, both rows were sprayed on one side only.

Rosy apple aphid infestation

Date	Product and rate
05-Apr-20	JMS Organic Stylet Oil 1 Quart per 100 gallons spray per acre
20-Apr-20	Clean Manganese 1 Quart per 50 gallons spray per acre
20-Apr-20	Clean Zinc 1 Quart per 50 gallons spray per acre
20-Apr-20	Clean Iron 2 Cup per 50 gallons spray per acre
20-Apr-20	Clean Symspray 0-0-1 1 Cup per 50 gallons spray per acre
20-Apr-20	Clean Copper 2 Cup per 50 gallons spray per acre
20-Apr-20	Clean Calcium 1 Quart per 50 gallons spray per acre
03-May-20	Dipel 2 Lb per 50 gallons spray per acre
03-May-20	Clean Calcium 2 Quart per 50 gallons spray per acre
03-May-20	Clean Manganese 1 Quart per 50 gallons spray per acre
03-May-20	Clean Symspray 0-0-1 1 Cup per 50 gallons spray per acre
03-May-20	Regalia 4 Cup per 50 gallons spray per acre
07-May-20	Clean Potassium 0-0-6 6 Quart per 50 gallons spray per acre
21-May-20	Regalia 4 Cup per 50 gallons spray per acre
21-May-20	Clean Symspray 0-0-1 2 Cup per 50 gallons spray per acre
21-May-20	Dipel 2 Lb per 50 gallons spray per acre
21-May-20	Lifegard 4 Oz per 50 gallons spray per acre
21-May-20	Clean Calcium 2 Quart per 50 gallons spray per acre
31-May-20	Clean Iron 4 Cup per 50 gallons spray per acre
31-May-20	Clean Manganese 1 Quart per 50 gallons spray per acre
31-May-20	Clean Calcium 2 Quart per 50 gallons spray per acre
31-May-20	Kinetic Nonionic Surfactant and Silicone Surfactant Blend 3 Fl oz per 25 gallons spray per acre
31-May-20	Sil-Matrix 1 Quart per 25 gallons spray per acre

Date	Product and rate
31-May-20	Clean Symspray 0-0-1 1 Cup per 50 gallons spray per acre
03-Jun-20	Citric Acid 12.5 Fl oz per 50 gallons spray per acre
03-Jun-20	Pyganic 15 Cup per 60 gallons spray per acre
06-Jun-20	Citric Acid 4 Fl oz per 100 gallons spray per acre
06-Jun-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
06-Jun-20	Clean Calcium 4 Quart per 100 gallons spray per acre
06-Jun-20	Azaguard 2 Cup per 100 gallons spray per acre
08-Jun-20	Pyganic 15 Cup per 50 gallons spray per acre
08-Jun-20	Citric Acid 15 Fl oz per 50 gallons spray per acre
12-Jun-20	Azaguard 2 Cup per 100 gallons spray per acre
12-Jun-20	Citric Acid 4 Fl oz per 100 gallons spray per acre
12-Jun-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
14-Jun-20	Clean Calcium 4 Quart per 100 gallons spray per acre
17-Jun-20	Molasses 3.33333333333333 Cup per 50 gallons spray per acre
17-Jun-20	Madex 1.25 Fl oz per 50 gallons spray per acre
21-Jun-20	Clean Calcium 4 Quart per 100 gallons spray per acre
21-Jun-20	Clean Manganese 1 Quart per 100 gallons spray per acre
21-Jun-20	Clean Zinc 1 Quart per 100 gallons spray per acre
23-Jun-20	Dipel 2 Lb per 100 gallons spray per acre
23-Jun-20	Madex 1.5 Fl oz per 100 gallons spray per acre
23-Jun-20	Molasses 4 Cup per 100 gallons spray per acre
23-Jun-20	Surround 50 Lb per 100 gallons spray per acre
25-Jun-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
25-Jun-20	Azaguard 2 Cup per 100 gallons spray per acre
25-Jun-20	Citric Acid 4 Fl oz per 100 gallons spray per acre
28-Jun-20	Clean Calcium 4 Quart per 100 gallons spray per acre
29-Jun-20	Sil-Matrix 4 Quart per 100 gallons spray per acre
29-Jun-20	Madex 1.5 Fl oz per 100 gallons spray per acre
29-Jun-20	Dipel 2 Lb per 100 gallons spray per acre
29-Jun-20	Kinetic Nonionic Surfactant and Silicone Surfactant Blend 8 Fl oz per 100 gallons spray per acre
02-Jul-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
02-Jul-20	Azaguard 2 Cup per 100 gallons spray per acre
02-Jul-20	Citric Acid 2 Fl oz per 100 gallons spray per acre
05-Jul-20	Clean Calcium 4 Quart per 100 gallons spray per acre
05-Jul-20	Dipel 2 Lb per 100 gallons spray per acre
08-Jul-20	Madex 1.40625 Fl oz per 50 gallons spray per acre
08-Jul-20	Molasses 3.75 Cup per 50 gallons spray per acre
12-Jul-20	Citric Acid 3 Fl oz per 100 gallons spray per acre
12-Jul-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
12-Jul-20	Azaguard 2 Cup per 100 gallons spray per acre
17-Jul-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
17-Jul-20	Citric Acid 3 Fl oz per 100 gallons spray per acre
17-Jul-20	Azaguard 2 Cup per 100 gallons spray per acre
20-Jul-20	BeetleGone 2.5 Lb per 100 gallons spray per acre
20-Jul-20	Clean Calcium 4 Quart per 100 gallons spray per acre

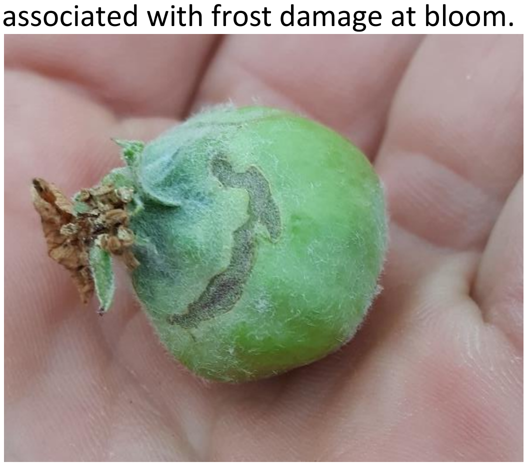
Date	Product and rate
20-Jul-20	Dipel 2 Lb per 100 gallons spray per acre
20-Jul-20	Clean Manganese 2 Quart per 100 gallons spray per acre
29-Jul-20	Dipel 2 Lb per 100 gallons spray per acre
29-Jul-20	Azaguard 2 Cup per 100 gallons spray per acre
29-Jul-20	JMS Organic Stylet Oil 4 Quart per 100 gallons spray per acre
29-Jul-20	Citric Acid 3 Fl oz per 100 gallons spray per acre
30-Jul-20	Clean Manganese 2 Quart per 100 gallons spray per acre
30-Jul-20	BeetleGone 2.5 Lb per 100 gallons spray per acre
30-Jul-20	Venerate XC 2 Quart per 100 gallons spray per acre
30-Jul-20	Dipel 2 Lb per 100 gallons spray per acre
30-Jul-20	Clean Calcium 4 Quart per 100 gallons spray per acre
07-Aug-20	Kinetic Nonionic Surfactant and Silicone Surfactant Blend 8 Fl oz per 100 gallons spray per acre
07-Aug-20	Sil-Matrix 4 Quart per 100 gallons spray per acre
09-Aug-20	Clean Calcium 4 Quart per 100 gallons spray per acre
09-Aug-20	Madex 1 Fl oz per 100 gallons spray per acre
09-Aug-20	Venerate XC 2 Quart per 100 gallons spray per acre
09-Aug-20	Dipel 1 Lb per 100 gallons spray per acre
09-Aug-20	BeetleGone 0.9375 Lb per 100 gallons spray per acre
09-Aug-20	Molasses 4 Cup per 100 gallons spray per acre
21-Aug-20	Clean Calcium 4 Quart per 100 gallons spray per acre
21-Aug-20	Venerate XC 2 Quart per 100 gallons spray per acre
21-Aug-20	Madex 1 Fl oz per 100 gallons spray per acre
21-Aug-20	Molasses 4 Cup per 100 gallons spray per acre
30-Aug-20	Madex 1 Fl oz per 100 gallons spray per acre
30-Aug-20	Molasses 4 Cup per 100 gallons spray per acre
30-Aug-20	Venerate XC 2 Quart per 100 gallons spray per acre
30-Aug-20	Clean Calcium 4 Quart per 100 gallons spray per acre
30-Aug-20	Dipel 1 Lb per 100 gallons spray per acre
07-Apr-21	JMS Organic Stylet Oil 8 Quart per 100 gallons spray per acre
18-Apr-21	Clean Manganese 0.5 Quart per 50 gallons spray per acre
18-Apr-21	Clean Copper 2 Cup per 50 gallons spray per acre
18-Apr-21	Clean Iron 2 Cup per 50 gallons spray per acre
18-Apr-21	Clean Zinc 0.5 Quart per 50 gallons spray per acre
25-Apr-21	Clean Zinc 0.5 Quart per 50 gallons spray per acre
25-Apr-21	Clean Manganese 0.5 Quart per 50 gallons spray per acre
25-Apr-21	Dipel 2 Lb per 50 gallons spray per acre
12-May-21	Clean Calcium 4 Quart per 100 gallons spray per acre
12-May-21	Dipel 2 Lb per 100 gallons spray per acre
12-May-21	Clean Iron 4 Cup per 100 gallons spray per acre
12-May-21	Clean Zinc 0.5 Quart per 100 gallons spray per acre
12-May-21	Clean Manganese 1 Quart per 100 gallons spray per acre
21-May-21	Citric Acid 2.2 Fl oz per 100 gallons spray per acre
21-May-21	Pyganic 26.6666666666667 Cup per 100 gallons spray per acre
21-May-21	Clean Calcium 4.16666666666667 Quart per 100 gallons spray per acre
01-Jun-21	Pyganic 26.6666666666667 Cup per 100 gallons spray per acre

Date	Product and rate
01-Jun-21	Citric Acid 2.2 Fl oz per 100 gallons spray per acre
06-Jun-21	Madex 1 Fl oz per 100 gallons spray per acre
06-Jun-21	Clean Calcium 4 Quart per 100 gallons spray per acre
14-Jun-21	Clean Calcium 4 Quart per 100 gallons spray per acre
14-Jun-21	Madex 1 Fl oz per 100 gallons spray per acre
30-Jun-21	Clean Calcium 4 Quart per 100 gallons spray per acre
30-Jun-21	Dipel 4 Lb per 100 gallons spray per acre
30-Jun-21	Nu-Film P 12 Fl oz per 100 gallons spray per acre
13-Jul-21	Madex 1.28 Fl oz per 100 gallons spray per acre
13-Jul-21	Venerate XC 2 Quart per 100 gallons spray per acre
13-Jul-21	Clean Calcium 4 Quart per 100 gallons spray per acre
13-Jul-21	Nu-Film P 12 Fl oz per 100 gallons spray per acre
30-Jul-21	Dipel 4 Lb per 100 gallons spray per acre
30-Jul-21	Clean Calcium 4 Quart per 100 gallons spray per acre
30-Jul-21	Nu-Film P 12 Fl oz per 100 gallons spray per acre
30-Jul-21	Madex 1.28 Fl oz per 100 gallons spray per acre
17-Aug-21	Clean Calcium 4 Quart per 100 gallons spray per acre
17-Aug-21	Dipel 4 Lb per 100 gallons spray per acre
17-Aug-21	Lifegard 6 Oz per 100 gallons spray per acre
17-Aug-21	Carb-o-nator 5 Lb per 100 gallons spray per acre
17-Aug-21	Nu-Film P 16 Fl oz per 100 gallons spray per acre
17-Aug-21	Venerate XC 3 Quart per 100 gallons spray per acre
17-Aug-21	Madex 2 Fl oz per 100 gallons spray per acre
28-Aug-21	Lifegard 3 Oz per 50 gallons spray per acre
28-Aug-21	Venerate XC 1.5 Quart per 50 gallons spray per acre
28-Aug-21	Madex 1 Fl oz per 50 gallons spray per acre
28-Aug-21	Nu-Film P 6 Fl oz per 50 gallons spray per acre
28-Aug-21	Carb-o-nator 2.5 Lb per 50 gallons spray per acre

Pollination. A Koppert Natupol Excel Startup bumblee colony was placed in each tunnel near the beginning of bloom in each year (on 5/7/2020 and on 4/27/2021) to ensure adequate pollination. We noticed that bumblebee workers from the introduced colonies regularly foraged outside the tunnel, and appeared to actually prefer foraging in the nearby outdoor field orchard. However, bee activity was high inside the tunnels on rainy days. Overall, initial fruitset was high and pollination appears to have been adequate.

Spring bloom and frost damage. In 2020, high tunnel trees bloomed synchronously with field-grown trees, with first flowers opening on 5/12-5/13. (Note, however, that the tunnels were uncovered before 5/2-5/6). Nighttime temperatures in our outdoor orchard reached 28 degrees F on the morning of 5/9 under clear skies with a calm wind, shortly before bloom and when flower buds were very susceptible to cold damage. On this cold night, we kept endwall doors and rollup sides on the tunnels completely closed in an attempt to retain warmth. We found no damage to flowers in the field orchard from this cold event. However, king blooms on most high tunnel varieties were killed (pistils were blackened). In addition most Calville Blanc d'Hiver fruits in the high tunnel which did develop showed blossom end russeting which is commonly associated with frost damage at bloom. We did not have a thermometer in the tunnels but we suspect that the temperatures were actually colder in the tunnel than outside. Other high tunnel growers in our region have noted that nighttime temperatures can be lower in tunnels than outdoors during radiation frost events. Tunnel 2 also occupies a slightly lower position on our hillside than our outdoor orchards, which may also have contributed to the frost damage in that tunnel.

Frost-damaged flower

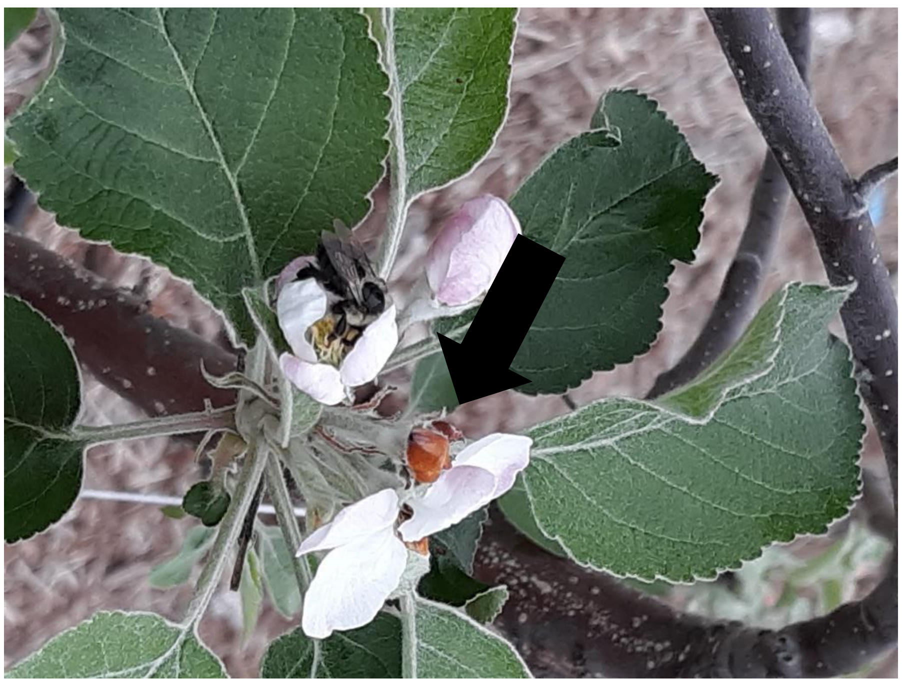


Calville Blanc d'Hiver fruitlet in 2020 showing frost damage

In 2021, high tunnel trees bloomed synchronously with field-grown trees, with first flowers opening on 4/27. (When we removed the silage tarps from tunnels on 4/6/2021, we noted that trees in the tunnels were behind outdoor trees in their stage of development. Thereafter tunnel trees gradually caught up with outdoor trees in their developmental stage.) When both outdoor and tunnel trees were in tight cluster stage, on April 21, outdoor temperatures reached a low of 25 degrees under clear skies with a calm wind. During this cold night, we kept endwall doors and rollup sides in the tunnels completely open. After this frost event, we observed very low levels of frost damage to blooms in the outdoor orchard, and no damage in the tunnels. We have heard speculation that on calm nights, temperatures in tightly closed tunnels can be lower than outdoor temperatures and it is best to leave tunnels open on calm cold nights, and our experiences appear to bear that out.

Summary of Spring Phenology and Bloom in 2020 and 2021

Year	Winter Status of Tunnels	Date Tunnels Covered/Uncovered	Date of First Bloom in Tunnels	First Bloom Date in Outdoor Orchard	Frost Damage in Tunnels During Bloom
2020	Uncovered	Covered with clear poly on 5/2-5/6	5/12	5/12	5/9: outdoor temperatures reached 28 degrees F, at pink stage of bloom development. Tunnels were closed at this time and king blooms suffered serious damage. No damage in nearby outdoor orchard
2021	Covered with clear poly and a white/black silage tarp	Silage tarp removed on 4/6	4/27	4/27	4/21: outdoor temperatures reached 25 degrees F at tight cluster stage. Endwalls doors and rollup sides in tunnels were left open. No damage seen in tunnels; slight damage observed in outdoor outchard

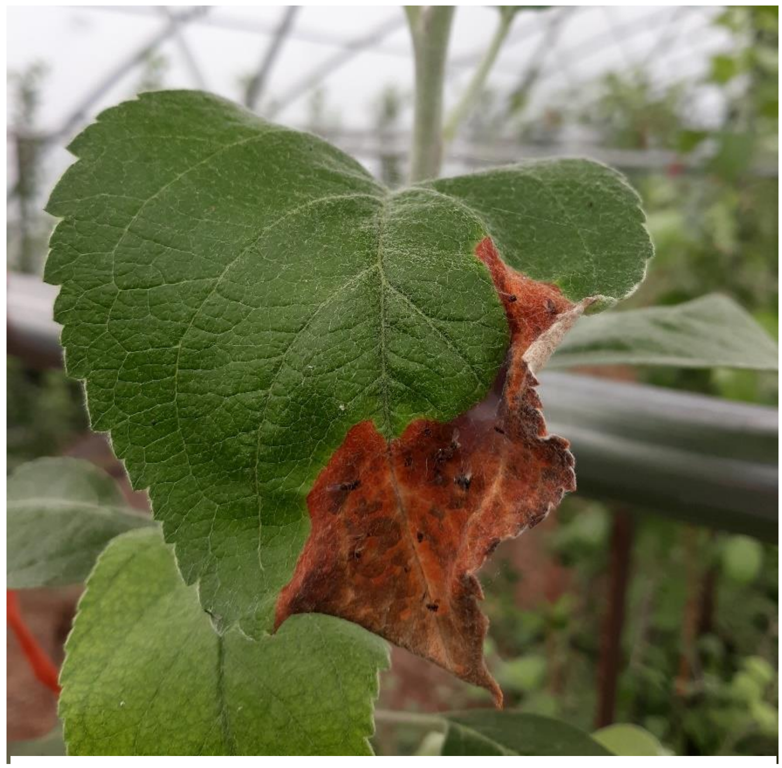


Bumblebee foraging on blossoms in high tunnel, 2020. Note frost damaged king bloom with brown petals in center of cluster. It has failed to open.

<u>Thinning</u>. In 2019, we removed any developing fruit after bloom. In 2020, we hand-thinned fruits, aiming for 1-3 (occasionally 4) fruits per branch, depending on branch length, and 1-4 additional fruits on the leader. Thinning was performed on 6/1 and 6/9, about 1-2 weeks after petal fall. In 2021, we hand-thinned on 5/20-5/29, about 2-3 weeks after petal fall, with an additional follow-up, corrective thinning on 6/11 and 6/15; we aimed for approximately 4-6 inches between fruits.

In both years, we noted a very heavy natural June drop of fruitlets in the weeks after bloom. Qualitatively, the drop appeared to be higher than what we typically see in outdoor orchards. In general, warm temperatures and low light levels favor fruit drop, and we speculate that compared to outdoors the tunnels tend to impose conditions favoring drop: the plastic covering reduces light levels and tunnel temperatures are higher than outdoor temperatures.

Heat stress damage on foliage. There was occasional heat stress damage seen on foliage which was at a young developing stage during extremely hot weather. The Mystery variety was particularly susceptible to foliar damage. This damage was much more common in tunnel 1. Fruit sunburn symptoms, discussed below, were also more pronounced in tunnel 1. We often that note that tunnel 1 feels warmer than tunnel 2, and we presume that temperatures are higher in tunnel 1 for some or all of the following reasons:



Heat stress damage on leaf of Mystery variety

(i) Tunnel 1's larger width (34' vs 24') makes ventilation less effective
(ii) Tunnel 1 is oriented east-west, in line with prevailing winds, whereas tunnel 2 is oriented north-south, which is perpendicular to prevailing winds and improves the effectiveness of ventilation through the rollup sides.
(iii) Tunnel 1 it is located about 12' north from another tunnel (not used in this study) which reduces natural ventilation through the rollup sides.

Harvest and Yield. The table below shows total yields from both tunnels in 2020 and 2021. The table on subsequent pages shows yield divided by variety, tunnel, and year.

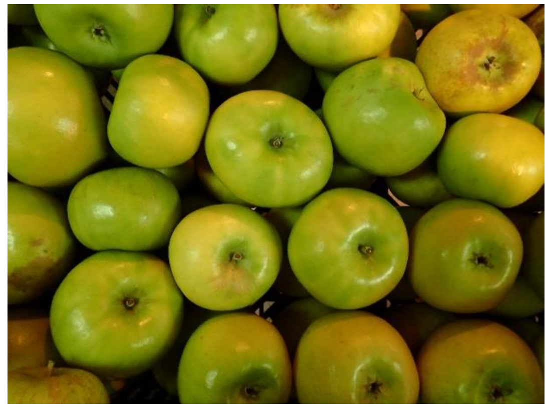
	2020		2021	
Grade	Yield of Saleable Fruit from High Tunnels (Lbs)	Value of High Tunnel Fruit[1]	Yield of Saleable Fruit from High Tunnels (Lbs)	Value of High Tunnel Fruit[1]
#1	788	$2001	3142	$7981
#2	451	$492	1344	$1465
Total, both grades	1239	$2493	4487	$9446
Total, both grades, per tree	6.81	$13.70	24.6	$51.90

[1]Based on average prices that our farm received in 2020: $2.54/lb for #1 grade fruit, and $1.09 for #2 grade fruit.

Some general trends were noted on fruit of many varieties:

- Most fruit were sweeter than would be expected on same varieties grown in field. In some cases, this was accompanied by an aldehyde-type flavor which some eaters found unpleasant. This off-flavor diminished in storage to some extent.
- Watercore was common on some varieties
- Some varieties showed symptoms of sunburn on fruit. Sunburn necrosis was common in Ashmead's Kernal, sunburn browning occurred in most varieties to some degree, and most varieties showed extremely accelerated ripening and softening on the sun-exposed sides of fruit
- Maturity in tunnels was hastened compared to outdoor grown apples
- In general, red skin color was significantly less than would be expected in field-grown apples.
- Hudson's Golden Gem and Suncrisp stood out among the varieties trialed for their excellent flavor and general resistance to the sunburn, watercore, and softening which were common in other varieties.
- Yields were higher in tunnel 2, possibly because of reduced heat stress in tunnel 2.
- Fruit sunburn, watercore, and soft flesh were more common tunnel 1 than tunnel 2.
- No sooty blotch or flyspeck was seen despite lack of fungicide sprays. In outdoor grown apples, we spray potassium bicarbonate (Carb-o-nator) and *Bacillus mycoides* isolate J. (Lifegard) regularly to control these diseases and we still find mild symptoms at harvest.
- The overall percentage of #1 grade fruit was 64% in 2020 and 70% in 2021. By comparison, we typically have about 75% #1 grade fruit in outdoor plantings. We define #1 grade fruit as fruit saleable to our CSA and grocery store accounts. We do accept significant variation in fruit size, russeting, slight deformities in fruit shape, and 1 or 2 plum curculio oviposition scars in #1 apples, but we do not accept feeding damage from adult plum curculio or other insects, watercore, bitterpit, or obviously overripe or underripe fruit.

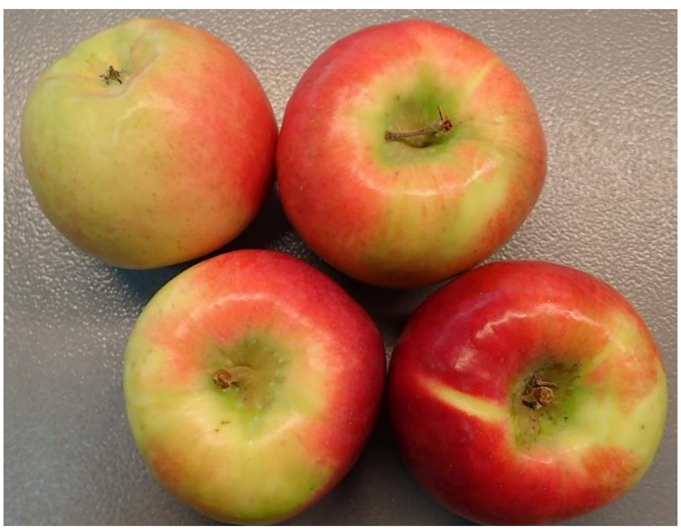
Suncrisp fruit. It was possible to ripen these fruit fully without softening



Golden Russet Fruit. Note lack of russeting, watercore evident on some fruit, and that fruit had to be picked at green stage to avoid softening.

Hudson's Golden Gem fruit were extremely high quality.

Ashmead's Kernal showing sunburn damage and significant russeting.



Mystery Apple.

	2020				2021				
Variety	Harvest Dates	Yield Per Tree High Tunnel 1 (Lbs)	Yield Per Tree High Tunnel 2 (Lbs)	Percent of fruits which were #1 grade	Harvest Dates	Yield Per Tree High Tunnel 1 (Lbs)	Yield Per Tree High Tunnel 2 (Lbs)	Percent of fruits which were #1 grade	Notes
Ashmead's Kernal	9/22	0.3	1	n/a	9/10-9/13	1.2	1.9	50%	Heavy russeting. Bitter pit developed in storage. Sun-exposed fruits sometimes had black necrotic areas on exposed side of fruit (presumably sunburn necrosis). Somewhat soft flesh. Exceptional flavor, high sugar, moderate acid.
Golden Russet	9/22	6.1	9.2	93%	9/10-9/21	19.1	26.1	60%	Generally lacked characteristic russeting. Sunburn and underlying soft flesh common on sun-exposed fruits – difficult to ripen fruit fully without developing soft flesh and sunburn, and therefore quality was generally fair. Watercore common. High sugar, moderate acid.
Mystery	10/9	5.5	15.2	66%	8/26-8/27	18.6	26.3	68%	Large size, excellent appearance. Sunburn and underlying soft flesh common on sun-exposed fruits. Generally soft flesh. High sugar, low acid. Unpopular with consumers because of soft flesh.
Hudson's Golden Gem	10/7-10/8	0	3.2	n/a	9/10-9/18	17.5	31.6	73%	Extremely high June drop noted. Moderate russeting. Some watercore, but otherwise quality and flavor exceptional. No soft flesh. High sugar, low acid.
Calville Blanc d'Hiver	10/7-10/8	1.6	7.2	0%	8/26-8/27	6.3	11.1	0%	Tart flavor and soft texture unsaleable as #1 grade in our markets. Blossom end russeting (“frost rings”) from frost damage before bloom in 2020.
Suncrisp	10/7-10/8	18.6	17.5	61%	9/17-9/20	35.7	80.4	81%	Large size, excellent appearance. Slight watercore and sunburn, but generally excellent quality and flavor. Strong tropical or banana flavor. High sugar, moderate acid. Popular with consumers and grocery store buyers.
Winecrisp	10/7-10/8	3.3	6.6	74%	9/18-9/21	26.9	42.4	77%	Large size. Red skin color did not develop well. High sugar in 2020; but less so in 2021. Some sunburn browning and watercore.

Labor Needs and Materials Costs. The following tables shows labor time spent on the tunnel trees and costs of materials. The total time was almost one hour per tree per year. The most time-consuming tasks in the first two years were trellising and training and planting. The time to construct the trellis and perform regular branch training was significant. In the third year, fruit thinning, harvest, and washing became the most time-consuming tasks.

Labor time (hours) per year for various work tasks for the 182 experimental trees, not including any time related to marketing the fruit

Work Task	2019	2020	2021
Plant fruits	43.9	0.0	0
Irrigation (apply and set up)	5.4	6.1	6.8
Mulch with hardwood bark	10.4	0.0	0
Seasonal covering/uncovering	11.6	19.0	6
Install rodent guards	2.2	0.0	4
Spray pesticide	7.4	16.0	7.4
Trellis and train trees	60.3	90.2	38.7
Weed	23.1	10.9	15.8
Thin fruits	0.0	14.4	44.4
Pick up fruit drops	0.0	3.4	6.33
Harvest	0.0	7.3	26.9
Wash fruit	0.0	4.0	16.8
Monitor temperatures and ventilate	4.0	6.3	2.4
Total hours of labor	168.1	177.7	175.6
Hours of labor per tree	0.92	0.98	0.96

Materials Costs per Tree, 2019-2021

Item	2019	2020	2021	Notes
Mulch	$4.81			$13.13 per yard
Trellis stakes		$7.16		$7.16 each
Trellis and training supplies	$0.77	$0.77		Close estimate of materials used: $0.32 for AgLok chain, $0.93 for 24" wire ties, $0.29 for 12.5 ga high tensile wire for trellis)
Trees	$19.84			Average price per tree of trees purchased from commercial nursery in 2019
Sprays		$2.05	$1.20	
Bumblebee colonies		$1.61	$1.73	Individual colonies cost $158 in 2020 and $170 in 2021
Klerks koolite plastic		$6.56		Plastic should last for three-four growing seasons
Silage tarp		$3.76		We expect that tarp will last for several growing seasons
Total cost per tree	$25.42	$21.91	$2.93	

Based on the actual costs and labor time above, we estimated startup and annual operating costs for a hoophouse operation, as shown below:

Estimated Startup and Annual Operating Labor Needs, Minutes Per Tree. (As described below, we have adjusted some of the figures from the actual times in our experiment.)

Work Task	Year 1	Year 2	Years 3+	Comments
Plant fruits	12			based on time per tree to hand-plant trees outdoors on our farm. The actual time in our high tunnel study was slightly higher, presumably because of extra time laying out trees in our randomized planting arrangement
Irrigation (apply and set up)	2	2	2	
Mulch with hardwood bark	0.85	0.85	0.85	every 4 years, 3.4 minutes per tree
Seasonal covering/uncovering	9	9	9	Covering with silage tarp every fall starting in year 1 (6 minutes per tree), removing silage tarp every spring (2 minutes/tree), except that every 4th year, remove clear poly in fall (2 minutes/tree) and replace in spring (10 minutes per tree)
Install rodent guards	1	0.6	0.6	Based on times in our outdoor orchard for initial installation and annual maintainence
Spray pesticide	2.5	4	4	Based on times measured in our study
Trellis and train trees	20	30	12	Based on times measured in our study
Weed	5.5	5.5	5.5	Based on times measured in our study
Thin fruits	0	5	15	Based on times measured in our study to hand-thin. Spray thinning would reduce this considerably
Pick up fruit drops	0	1	2	Based on times measured in our study
Harvest	0	2.4	8.9	Based on times measured in our study
Wash fruit	0	1.3	5.5	Based on times measured in our study
Monitor temperatures and ventilate	1.5	1.5	1.5	Based on times measured in our study
Total	54.35	63.15	66.85	

Estimated Startup and Annual Costs Per Tree for Materials

Item	Annual operating cost	Incurred when?	Notes
Trellis stakes	$7.16	once, in Year 1	
Trellis and training supplies	$1.54	once, in Year 1	
Trees	$19.84	once, in Year 1	
Mulch	$1.20	annually, starting in Year 1	Assuming mulch is replenished every 4 years
Sprays	$1.62	annually, starting in Year 2	
Bumblebee colonies	$1.73	annually, starting in Year 2	
Klerks koolite plastic	$1.64	annually, starting in Year 1	Assuming 4 year lifespan
Silage tarp	$3.76	annually, starting in Year 1	Assuming 3-year lifespan
Total cost per tree, Year 1	$35.14		
Total cost per tree, Years 2+	$9.95		

Profitability. The profitability of high tunnel apple cultivation depends on the specific details of a farm's production and marketing practices. Overall we do not feel that tunnel cultivation of apples is justifiable on our farm. We have presented as much relevant data as possible to help other growers evaluate this question. In our opinion, here are some of the most important considerations:

Comparison of outdoor vs high tunnel production. For many farms, high tunnel production may represent a possible alternative or adjunct to outdoor, unprotected apple production. In our outdoor orchard, we use a different planting density and training regimen than we used in this high tunnel study: our outdoor trees are planted at six feet apart within the row and twelve feet apart between rows. Here are some major differences which we noted in the economics of outdoor and tunnel production:

- In our outdoor orchard, we mulch an 8' wide strip between rows, whereas in the high tunnels we mulched the entire area within the tunnel (to avoid the difficulty of mowing sod in the tight confines of the tunnel, particularly between the tree rows and the outside walls of the tunnel). Although a greater portion of the ground was mulched in the tunnels, the mulch degraded more slowly in the tunnel and outside: we expect we would need to replenish the mulch in the tunnels every four years, whereas outdoors we replenish the mulch annually. The overall cost of mulch per foot of row would be similar in both systems: outdoors, we spend about $2.50 per year per tree for mulch for trees spaced 6' apart, and in the tunnels the cost for mulch every four years would be $1.20 per year per tree for tree spaced 3' apart.
- Outdoors we annually spend about $2.50 per tree for year for spray materials (about $0.42 per row-foot). In the tunnels we spent about $1.62 per tree for year (about $0.54 per row foot), although we actually sprayed less – the reason for the higher cost in the tunnels was largely that we needed to mix small volumes of water to spray the tunnels and consequently waste was a much higher portion of the total cost.
- Outdoors, mature trees at 6' spacing require almost two hours of labor per year (ignoring marketing time and overhead tasks such as accounting, equipment maintenance, etc). The third year high tunnel trees, at 3' spacing, required slightly more than one hour per tree at 3' spacing, so the overall labor requirement per row foot was similar.
- Cost of silage tarp and clear polyethylene, both of which need to be replaced every few years, add a substantial operating cost for the lifetime of the planting - $5.40 per tree for year.
- It is somewhat difficult to compare yields between the high tunnel plantings and our outdoor orchards. The tunnels were planted at a higher density (3' spacing in the tunnels vs 6' spacing outdoors) and we fruited the tunnels in the second year, whereas we usually wait until the third year to fruit outdoor plantings. In addition, most of the varieties grown in the tunnels are not in our outdoor orchards. The third-year yield in the tunnels averaged almost 25 lbs per tree. For an equal yield per row-foot, outdoor orchards would need to produce 50 lbs per tree. We rarely obtain a 50 lbs/tree yield in 3rd year trees outdoors, but it is common in 4th or 5th year trees. Overall, we would say that the tunnel plantings produced more in the early years than is normal in our outdoor orchards, likely because of the higher planting density. However there is no particular evidence that the yield of mature plantings would be higher in the tunnel.

*<u>Cost of the high tunnel structure and materials</u>***.** The two tunnels used in our study each cost about $10,000 in materials for construction, plus about 180 hours in labor time. On our farm, the materials cost of the two tunnels was covered by funding from the USDA-EQIP program. In addition both tunnels were originally constructed for use in growing vegetables. When we transitioned our farm from vegetable to fruit production we were looking for a new use for the tunnels. Growers who are considering constructing tunnels specifically for fruit production would need to justify the cost of the tunnels. A rough analysis suggests that this would be very difficult – the figures in the table below suggest it would take over 10 years to repay the cost of the tunnel, even with a better mix of varieties than we grew for this study. However, these figures are highly dependent on yields and costs, which depend on variety selection, insect control, labor efficiency and myriad other factors specific to individual farms.

Hypothetical annual costs and returns from high tunnel apple planting, including costs of tunnel construction

Year	Cost of Materials[1]	Labour Hours[2]	Cost of Labor ($18/hour)	Overhead / Marketing Costs[3]	Sales[4]	Total Net Return[5]
0[6]	$10,000	180	$3,240	$0	$0	($13,240)
1	$3,514	91	$1,631	$1,286	$0	($19,671)
2	$995	105	$1,895	$722	$2,613	($20,670)
3	$995	111	$2,006	$750	$6,533	($17,888)
4	$995	111	$2,006	$750	$6,533	($15,106)
5	$995	111	$2,006	$750	$6,533	($12,324)
6	$995	111	$2,006	$750	$6,533	($9,542)
7	$995	111	$2,006	$750	$6,533	($6,760)
8	$995	111	$2,006	$750	$6,533	($3,978)
9	$995	111	$2,006	$750	$6,533	($1,196)
10	$995	111	$2,006	$750	$6,533	$1,586
11	$995	111	$2,006	$750	$6,533	$4,367
12	$995	111	$2,006	$750	$6,533	$7,149
13	$995	111	$2,006	$750	$6,533	$9,931
14	$995	111	$2,006	$750	$6,533	$12,713

[1]Based on a $10,000 cost for the high tunnel materials, plus startup costs of $35.14 per tree and annual operating costs of $9.95 per tree. All figures assume 100 trees per tunnel (our tunnels held 99 and 98 trees each)

[2]180 hours for tunnel construction, 54.25 minutes per tree in year 1, 63.15 in year 2, and 66.85 in years 3+

[3]All of the costs and labor times presented previously in this publication ignore overhead and marketing costs, such as cost of purchasing and maintaining tractors, sprayers, and delivery vehicles, fuel, tax preparation, accounting and tax preparation, and farm planning. In reality, these costs are very substantial. In the table above, we have somewhat arbitrarily set them at 25% of the other costs. Farms should substitute figures relevant to their own operation – but don't ignore these very large and important costs.

[4]Sales based on a yield of 12 lbs per tree in year 2, and 30 lbs per tree in subsequent years, and 75% #1 grade apples. These figures are higher than what we observed in our study but we feel they are reasonably attainable with good variety selection. Sales were calculated using the average prices which we received on our farm in 2020: $2.54/lb for #1 grade apples and $1.09 for #2 grade apples.

[5]Total net return ignores inflation, loan interest, and the opportunity cost incurred by not investing this money in other ways.

[6]Year 0 represents the cost of high tunnel construction.

Labor utilization. We found that the high tunnels provided a place to work and utilize available labor during rainy weather in spring and summer, when it was difficult or impossible to work outside.

Scale. Using large field tunnels such as those manufactured by Haygrove might reduce the costs per square foot of constructing and maintaining the tunnel structures and improve the profitability of tunnel apple cultivation.

Disease and pest pressure. As expected, diseases other than powdery mildew were very rare in the tunnels. In general, insect pest levels were not much reduced in the tunnels compared to outdoor orchards. The reduced disease levels might allow organic cultivation of disease-susceptible varieties which are difficult or impossible to grow organically outdoors, although a full regimen of insect sprays would likely still be required inside the tunnels. Growers need to consider whether those varieties command a market price which would justify the costs of tunnel culture. Also consider whether the reduced disease pressure in tunnels will actually result in reduced spray costs. On our farm, the tunnels represent a small area of land relative to our outdoor orchards. It would be most convenient to spray the tunnels with the same spray mixtures as used outdoors, but this would eliminate any possible savings in spray material costs. Also note that sulfur sprays, commonly used for control of apple scab and other disease in organic orchards, are destructive to greenhouse polyethylene.

Environmental impacts. High tunnel production may be environmentally beneficial if it reduces the amount of pesticide inputs and/or increases local organic apple production and reduces the volume of organic apples which are imported into the north central region from Washington state. However, high tunnel production has clear negative impacts in its reliance on greenhouse plastic and silage tarps, which are energetically costly to produce and can be difficult to recycle.

High tunnel environment. Although we did not measure environmental conditions inside our tunnels, there are clearly important differences in the environment between tunnels and outdoors. In the tunnels, rainfall is absent, daytime temperatures are higher, light levels are lower, humidity is higher, and wind is less. Although the lack of rainfall reduces most diseases, it's important to consider other factors:

- Higher temperatures can damage leaves and fruit.
- Higher temperatures and lower light levels in June may increase self-thinning of fruitlets.
- The different light regime inside tunnels appears to reduce red coloring in fruit.
- The tunnel environment appeared to promote watercore, fruit flesh softening, and early fruit maturation.
- Tunnels may provide little or no protection from freezing temperatures before and during spring bloom. A backup heat source might be a wise investment.

Variety selection. We observed enormous differences between varieties in our study in their yield and susceptibility to sunburn and other fruit defects. Selection of heat-tolerant, high-yielding varieties would be essential to profitable high tunnel apple cultivation. In our study, Suncrisp and Winecrisp were the highest yielding varieties, and Suncrisp and Hudson's Golden Gem produced the highest quality fruit with the lowest incidence of watercore, fruit softening, sunburn and other defects.

High tunnel size and orientation. As discussed previously, tunnel 2 had higher yields and fewer heat-related fruit defects compared to tunnel 1. We recommend siting and designing tunnels for maximum ventilation.

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