Growing Sweet Cherries under Plastic Covers and Tunnels: Physiological Aspects and Practical Considerations

G.A. Lang
Department of Horticulture
Michigan State University
East Lansing, MI 48824
USA

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Abstract

Other than growing sweet cherries in environments with minimal rainfall during ripening, the next best method to avoid rain-induced fruit cracking is to exclude rainfall from contact with the fruit by protecting trees with plastic covers. Numerous covering systems have been engineered over the years, from pole-and-wire "tents" to steel hoophouses or "high tunnels". Although rain exclusion is the common trait, often there are additional unique benefits and limitations to each system, including not only practical management issues but also significant impacts on cropping physiology and insect/disease management. Five years of research on cherry production in high tunnels has highlighted how the seemingly simple modification of the orchard environment by plastic covers can reduce wind speed, increase air temperatures and consequently growing degree units, and reduce the incidence of some diseases while increasing the potential for others. The reduction in transmitted light can impact not only photosynthesis, but depending on specific spectral variations, can influence the activity of pollinators and other insects, tree architectural development, and fruit color and bioactive compound biosynthesis. Furthermore, simply excluding direct contact of rainfall with fruit does not necessarily guarantee an absence of cracked fruit! Overall, yields and fruit quality in high tunnel production have been outstanding, though each season has brought new challenges to resolve. We are nearing the optimization of high tunnel cherry production systems that incorporate and synthesize multiple technologies, including dwarfing rootstocks, fruiting wall architectures, reflective orchard floor materials, high frequency/low volume fertigation, and overhead canopy spray delivery systems. The scheduling of sequential covering dates, to broaden the periods for bloom and ripening, is best optimized by tracking growing degree unit accumulations rather than by using calendar dates. The various potential impacts of intensive high tunnel production systems are discussed relative to less extensive covering systems, such as pole-and-wire tents.

INTRODUCTION

Orchard covering strategies to protect high value sweet cherry (*Prunus avium* L.) crops from rain-induced fruit cracking, fruit damage from birds, and/or tree and fruit damage from hail, have been used in various regions of the world as necessary to produce consistent yields. Just as increasing sweet cherry market values have driven tremendous expansion of worldwide cherry acreage over the past 10 to 15 years, it has also stimulated new covering strategies and technologies. Generally, the least expensive covering strategies have been pole-and-wire support systems to create temporary bird-net enclosures (e.g., in Australia and New Zealand) or tent-like structures for polyethylene rain exclusion covers over tree rows during ripening. The latter are prevalent in Norway (Børve and Meland, 1998a, 1998b; Børve et al., 2008; Meland and Skjervheim, 1998) and appear in other countries, such as Belgium, Germany (Balmer, 1998; Balmer et al., 2005; Balmer and Blanke, 2008), Italy, Netherlands (Balkhoven-Baart and Groot, 2005), Switzerland, the United Kingdom (U.K.), and the United States (U.S.). Costs of these systems vary with the use of steel posts instead of wood, steel cables instead of high-

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tensile wire, thickness and durability of polyethylene, and/or self-venting covers (e.g., multi-panel netting plus solid covers, e.g., VOEN) instead of solid polyethylene sheeting.

Since the 1990s, protected environment cherry production systems also have included high tunnels in the United Kingdom (e.g., Haygrove, Ltd.) and to a small extent, several other European countries, the U.S. (Lang, 2008, 2009), and China. Even greenhouses have been planted with sweet cherries in Belgium, China, New Zealand, Spain, and other regions for specialized high value markets (G. Lang, pers. observation). Multi-bay, three-season plastic-covered high tunnels are about twice as expensive as pole-and-wire covering structures, but they have reversed declining production of U.K. strawberries and cherries due to significantly improved control of diseases and rain-cracking in the challenging U.K. environment.

The higher cost of high tunnels for protection from rain-induced fruit cracking necessitates that additional value must be derived from the technology to achieve a favorable return on investment. In addition to reduced fruit-cracking potential, the potential for protecting sweet cherries from spring frost events, rain-disseminated diseases, and possibly certain insect pests would be advantageous. Tunnel covers reduce wind, and consequently wind-based fruit bruising, better than do pole-and-wire covers. Furthermore, tunnels may provide a tool to manipulate fruit ripening time to extend or target the particularly valuable market windows. Therefore, we have been studying the optimization of sweet cherry production in high tunnels since 2005, and report herein the benefits, challenges, and other considerations for their use.

MATERIALS AND METHODS

Research on high tunnel sweet cherry production systems at Michigan State University (MSU) in 2005 with the construction of multi-bay, three-season tunnels (Haygrove, Inc.) covered with 6-mil Luminance THB polyethylene (light diffusing and reduced infrared and ultraviolet [UV] spectra transmittance) at two MSU research and extension centers (Clarksville and Benton Harbor, Michigan), details of which are provided in Table 1.

The tunnels at the Clarksville Research Center (CRC) were constructed over the middle of a bearing 6-year-old orchard, providing immediate fruiting results for a direct covered vs. uncovered orchard comparison. The tunnels at the Southwest Michigan Research and Extension Center (SWMREC) near Benton Harbor were constructed first, and then a new orchard was planted under them, concomitant with an identical, adjacent comparison no-tunnel orchard, to provide a direct comparison of covered vs. uncovered orchard development. In 2008, additional trees were planted in the SWMREC high tunnels to increase space utilization with high density training systems (noted below). Automatic climatic dataloggers (mobile temperature/light sensors and fixed recording weather stations with anemometers and sensors for relative humidity, leaf wetness, photosynthetically-active radiation, and air and soil temperatures) were installed at each site.

Overall, nearly 50 sweet cherry varieties or advanced selections from breeding programs have been tested under the tunnels, entirely on precocious Gisela™ (Gi5, Gi6, or Gi12) rootstocks. A variety of tree canopy architectures and training systems have been imposed, including high density single leaders (e.g., Tall Spindle Axe/TSA), very high density single leader fruiting walls (e.g., Super Slender Axe/SSA), and high density oblique leader fruiting walls (e.g., Upright Fruiting Offshoots/UFO). Since 2006, pollination has been facilitated by introducing one bumblebee (*Bombus* spp.) hive per 30 m of tunnel length at the beginning of bloom; additional native pollinators also have been observed working in the tunnels. Growth and fruiting data have varied from year-to-year. Measurements of growth generally included trunk diameter for cross-sectional area (TCSA) calculations and, for development data on young trees, samples for shoot length, terminal growth, and leaf size. For fruiting data, trees were usually identified for one-time harvest to obtain complete tree yields, and 100-fruit samples were taken randomly from each tree for fruit quality measurements. Most varieties were harvested at two maturity dates (whole tree harvests for each date) 3 to 4 days apart. The 100-fruit samples were used to obtain average fruit weight and number of defects, and 25-fruit subsamples were used to obtain average fruit diameters (mm), soluble solids contents (°Brix), and fruit firmness (measured as depression force in g/mm^2 using a FirmTech II, Bioworks, Inc., Manhattan, Kansas). The experimental designs and number of replications varied by tunnel plot, with randomized four-tree replications at CRC and six-tree replications at SWMREC, and at least six replications for most tunnel comparison objectives (genotype evaluations were not randomized and usually have only 2 or 3 replications).

RESULTS AND DISCUSSION

Cover Impacts on Orchard Design

Sweet cherries protected by pole-and-wire tent-like plastic covers are typically planted in standard rows, with one cover per row. As high tunnels have been adapted to cherries, several schemes for covering have been used. Most typical is the retrofitting of a tunnel bay over two rows of trees separated by a tractor alley, as with the CRC research tunnels. When the fruiting volume (i.e., not the entire tree, but just the portion of the canopy that bears fruit, often starting 1.0 m above the ground) per tunnel area was estimated, the tunnel fruiting space efficiency of the modified central leader trees at CRC was 0.9 m^3 m^{-2} (Table 1). When trees were planted at a higher density in the SWMREC tunnels and trained to spindle-type canopies, the tunnel fruiting space efficiency increased about 10%, to 1.0 m^3 m^{-2}. Other attempts to improve tunnel fruiting space efficiency have included 1) the covering of two adjacent rows (a two-row bed system) lacking a significant alley between them, but with a tractor alley between the bed and one side of the tunnel, and 2) a similar concept with three adjacent rows (a three-row bed system) and an offset tractor alley in each tunnel bay (Graham Moore, Haygrove, pers. communication). These multi-row bed and offset alley systems facilitate tractor-spraying into one side of the bed from within the same tunnel, and into the other side of the bed from the adjacent tunnel. At least with the two-row bed, spray distribution can be improved compared to a center tractor alley which facilitates spraying of each row from only one side; however, due to the tractor alley, fruiting space efficiency is not significantly greater than the standard two-row orchard design.

In 2008, the research tunnels at SWMREC were modified with the planting of a center row of trees in the previous tractor alley, which were trained to narrow fruiting wall architectures like the Super Spindle Axe (SSA) from Bologna, Italy, and the Upright Fruiting Offshoots (UFO) from Washington, U.S.A. Concomitantly, a multi-year renovation of the original two rows of spindle trees was begun to narrow their canopies, to ultimately result in three narrow rows of fruiting wall tree architectures with two narrow alleys for access by pickers, ultra-narrow tractors as in vineyards, or elimination of the tractor altogether. In this latter case, the application of protective pesticide or nutrient/ growth regulator sprays has been accomplished by an overhead spray technology, termed a Solid-Set Canopy Delivery (SSCD) spray system, comprised of micro-emitters affixed directly to the tunnel hoop structure and/or dropped partially into the canopy via drop-tubing (Fig. 1). This technology, using microsprinkler and microfogger emitters, is under development and testing at MSU to provide adequate coverage within the narrow tree canopies. With such an integrated production system, the tunnel fruiting space efficiency was increased an additional 25%, to 1.25 m^3 m^{-2} (Table 1).

Cover Impacts on Environmental Modifications

The high tunnel covers alone (with open sides and ends) increased Growing Degree Day (GDD) accumulation by about 10%, reduced wind speed in the orchard by 5 to 20 km h^{-1} (higher reductions at higher wind speeds), and reduced daily direct light integral by 15 to 25%, although scattering (diffusion) of transmitted light was likely increased by the properties of the Luminance THB plastic. Cherry tree canopy architectures that facilitate good light distribution and uniformity, such as narrow fruiting wall canopies that reduce the proportion of the canopy subject to significant shade, are recommended since fully-exposed leaves still receive an amount of light greater than that needed for maximum photosynthesis. It is the shaded portions of the canopy that would be most greatly impacted by the reduced transmission of light by the plastic cover. Reduced wind speed in the high tunnel orchard helped reduce evapotranspiration and maintain more consistent plant water relations.

In the spring, when heat retention is most valuable for promotion of early growth and development during periods of cool outside air temperatures, enclosing the tunnel side walls and ends created air temperature differentials between inside and outside of as much as 30°C or more. This can be a valuable tool for advancing bloom and early fruit growth, but it must be managed wisely to prevent supra-optimal day temperatures that lead to abnormal final flower meristem differentiation while still in the bud or premature ovule degeneration during pollination, pollen tube growth, and fertilization. With only covers (no enclosed walls or ends), the inside-outside heat differential was about 10 to 15°C. This can be advantageous between Stage II and early Stage III of fruit development, but as ripening begins, excessive heat must be avoided to preclude negative effects on fruit quality, such as premature flesh softening. This is generally accomplished by venting of the tunnel, i.e., raising of the plastic along the lower sides of the hoops (above the tunnel legs) to create gaps between the tunnel bays that allow greater air and heat movement, yet still prevent rain exposure.

During the early years of tree development, the tunnels significantly improved the environment for growth (warmer air temperatures and reduced evapotranspiration, while maintaining good light interception). More rapid, and greater overall, shoot extension growth provided more rapid filling of allotted space and thus greater early yield potential during the period of canopy establishment. In a study conducted during the 2007 season that incorporated the use of reflective (Extenday) and weed barrier (as well as water conserving, DeWitt Pro-V) orchard floor fabrics, canopy growth (TCSA) averaged across four cultivar/rootstock combinations was increased by 29 to 40% with tunnels, by 24 to 34% with the fabrics, and by an incredible 73% when trees grown in tunnels with the fabrics were compared to standard non-tunnel trees grown without fabrics (Table 2). The favorable tunnel growth environment alone also increased tree height up to 24% and leaf size was about 20% larger.

Consequently, when debating whether to first construct tunnels and plant under them, or to delay tunnel construction until a new orchard comes into production, the investment in tunnels from the outset of establishing a new protected orchard is clearly merited due to the significantly improved growth, more rapid filling of expensive tunnel space, and higher initial fruiting potential to be gained. Furthermore, the use of water-serving, weed-preventing, and/or light reflective orchard floor fabrics further is worth the investment. Whiting et al. (2008) have also reported that reflective orchard floor fabrics positively affected sweet cherry fruit yield and quality in standard orchards; this is the first known report of synergistic effects when combined with tunnels and weed barrier fabrics. Additional positive effects of reflective fabrics on fruit quality in tunnels will be discussed below.

Although heat can accumulate quickly during the day in an enclosed tunnel, it also dissipates rapidly at night. Thus, like pole-and-wire orchard covers, only slight frost protection (about 1°C) can be gained with the use of the tunnel cover alone (with no tunnel sides or ends enclosed). Sometimes before dawn, air temperatures inside a tunnel bay can actually become lower than outside because of lower dew points due to the drier air and soil under the tunnel. The supplemental heat provided by sources such as portable propane heaters is more effective inside a tunnel than in an open or pole-and-wire-covered orchard; that is, while the supplemental heat is still eventually lost through the single layer of plastic, more is retained (especially in windy conditions) to protect buds, flowers, or young fruits. Thus, tunnels only provide better frost protection than pole-and-wire covers if they are used with supplemental heat sources and have enclosed ends and sides. When covers are removed in late summer or early fall, cherry tree cold acclimation progresses normally and winter cold hardiness is generally as good, or better, than standard orchard trees due to generally better tree health acquired during the protected growing season. When a severe spring freeze occurred at the SWMREC plot, before the tunnels were covered (hence trees inside and outside were exposed to identical temperatures), the trees that had been grown the previous season under the tunnel suffered far less cold damage (and subsequent bacterial canker, *Pseudomonas syringae*, infection) than the outside trees.

Cover Impacts on Fruit Yield, Quality, and Consistency

The first year of research at CRC, yields in the tunnel were half those of the trees outside (on average, 10-11 t ha^{-1} vs. 20-22 t ha^{-1}, respectively); this was attributed to the use of European honeybees (*Apis mellifera*), since the plastic covers affected the light spectral quality that honeybees use for effective navigation. In subsequent years, hives of bumblebees (*Bombus* spp.) were placed in each tunnel to achieve adequate pollination for yields equal to comparable open orchards, e.g., 20 to 25 t ha^{-1} for mature ‘Rainier’ on Gi5 and Gi6, with average fruit weights of 10.4 to 11.2 g $fruit^{-1}$ and some fruit diameters up to 36 mm. Fruit size in the tunnels has been equal or better than outside, even at equal or higher crop loads. Average fruit size ranged from large (10 g) to very large (12 g and larger) for more than two dozen genotypes on five-year-old trees in the tunnels at SWMREC (Table 3).

The penultimate use of any covering system for sweet cherries is to protect the ripening fruit rain, and the cracking that can occur from prolonged contact of the fruit skin with rainwater that allows absorption into the fruit flesh, resulting in localized swelling. This direct, prolonged exposure of the fruit to water, particularly in the “bowl” around the pedicel or where rain drips from the stylar end of the fruit, strains the elasticity of the skin to the point of rupture, resulting in unmarketable fruit (Knoche and Peschel, 2006). Covering systems that exclude rainwater contact with the fruit eliminate this type of cracking. However, excessive rainwater in the root zone can be taken up by the tree and increase internal turgor within the tree conductive system, extending to the fruit and thereby causing additional fruit swelling and cracking. In 2008, fruit cracking due to rootzone water reached 60% in the tunnel vs. 89% outside for ‘Rainier’, and 32% in the tunnel vs. 91% outside for ‘Lapins’. Therefore, neither high tunnels nor pole-and-wire covers can prevent this type of cracking unless some sort of gutter system is utilized to remove run-off rainwater before it can enter the root zone.

Unfortunately, the need for venting of cherry tunnels to manage excessive heat during fruit ripening precludes the use of available gutters that could be installed to capture rainwater run-off. Solutions for this situation depend on orchard topography (flat, sloped, or variably sloped high and low points). If the tunnel orchard has a continuous slope, an impermeable plastic strip (a ground gutter) can be installed along each tunnel leg row as wide as the drip line of the fully vented tunnel, capturing run-off and allowing it to flow naturally away from the tree rows. If the tunnel orchard is flat or has variable slope, subsurface drain tiles can be installed along the leg rows at a sloping grade, with gravel backfilled to the surface, to drain away most of the run-off rainwater as it falls to the soil.

The alteration of light spectra by polyethylene orchard covers not only influence photosynthesis and honeybee navigation, but also anthocyanin biosynthesis within the fruit epidermis. Therefore, yellow-fleshed varieties like ‘Rainier’ and ‘Early Robin’ develop less red blush (Mulabagal et al., 2009) on shaded fruit due to reduced ultraviolet (UV) light transmission. Therefore, venting during ripening to allow not only better escape of heat, but also greater incident light distributed throughout the canopy, is important for improving blush on ‘Rainier’-type cherries. The use of reflective fabrics on the orchard floor to increase light capture and re-distribution into the canopy also improves blush formation.

In some locations, the manipulation of ripening time to advance or extend harvest can be critical for increasing economic returns derived from more profitable marketing windows. In 2009, differential covering of the four SWMREC tunnels about 1 week apart

(17 and 24 March, 2 and 8 April) advanced the accumulation of GDD, and 'Rainier' bloomed 11, 7, 3, and 0 days, respectively, earlier than the non-tunnel trees (Table 4). When mid-season measurements were taken 25 days after bloom of the non-tunnel trees, shoot growth was nearly 88% greater for both of the tunnels covered in early April, and 115% and 137% greater for the tunnels covered on 24 and 17 March, respectively. Fruit diameters were similar for the last covered tunnel and the non-tunnel trees, but fruits from trees covered on 2 Apr, 24 Mar, and 17 Mar were 14%, 17%, and 21% larger, respectively. At harvest one month later, the non-tunnel and sequentially-covered tunnels maintained a tunnel-by-tunnel sequence of ripening and maturity, in terms of fruit diameter (ranging from 25 to 34 mm), weight (7.0 to 15.5 g), and SSC (14.3 to 18.8°Brix). For sequential covering strategies to alter bloom and ripening, a logical production plan would be to cover not on a calendar basis, but rather on a specified GDD accumulation basis since GDD accumulation in early spring can be quite variable, with equal calendar intervals generally not resulting in equal GDD accumulation intervals for optimized market-oriented ripening periods.

Cover Impacts on Pest Management

Thus far, season-long high tunnel covers have eliminated cherry leaf spot (*Blumeriella jaapi*) infections, a major savings of fungicide applications in the Michigan complex of pests, and greatly reduced the incidence of Japanese beetle (*Popilla japonica*) damage. While trees in tunnels are still susceptible to bacterial canker infection, and are uncovered during the prime infection times from leaf drop through the end of winter, the incidence of infections is usually less due to reduced dispersion of the bacteria from rain in the spring, healthier trees (as noted above), and potentially increased protection from spring frosts.

Pest issues that were increased in the tunnels included powdery mildew (*Podosphaera clandestina*), two-spotted spider (*Tetranychus urticae*) or European red (*Panonychus ulmi*) mites, and San Jose scale (*Quadraspidiotus perniciosus*). No differential effects, between tunnel and non-tunnel trees, have been detected with regards to black cherry aphid (*Myzus cerasi*) or its natural predators; cherry fruit fly (*Rhagoletis cingulate*); oblique-banded (*Choristoneura rosaceana*) and red-banded (*Argyrotaenia velutinana*) leafrollers; spotted wing drosophila (*Drosophila suzukii*); plum curculio (*Conotrachelaus nenuphar*); or brown rot (*Monolinia fructicola* and *Monilia laxa*).

CONCLUSIONS

Growing sweet cherries under some type of plastic covering system can be essential to guarantee consistent marketable crops in production regions at significant annual risk of rain-induced fruit cracking. High tunnels are more expensive than pole-and-wire tent-like plastic covers, so additional production values must be realized for adequate economic returns on investment. Both pole-and-wire and high tunnel protective structures can also provide a support structure for netting to protect the crop from birds, which is particularly important for small orchards where bird damage can be proportionally much higher than in large orchards. Both types of structures, if used to cover trees from bloom throughout the growing season, can reduce some key diseases (cherry leaf spot and bacterial canker), and it may be feasible to increase certain pesticide spray intervals due to less loss of protective residues to rain or UV light breakdown.

High tunnels also reduce wind damage to fruit during ripening and better facilitate both harvest picking and other orchard tasks, like pruning, in any weather, compared to pole-and-wire covers, which is particularly important for pick-your-own orchards. By fully enclosing high tunnels at the beginning of the season, the use of supplemental orchard heaters to protect trees from spring frosts can be more effective, and growers can even advance bloom and/or stagger the bloom sequence across multiple tunnel bays to target earlier ripening market windows or spread out the ripening window for higher-value cultivars, like 'Rainier'. Management of heat during ripening is more of a challenge in high tunnels than under pole-and-wire covers, requiring adequate venting.

To most effectively achieve adequate returns on investment, high tunnel sweet cherry production systems should begin commercial yields at least by Year 3, with essentially full yields by Year 5. This objective is achieved more readily when new high tunnel orchards are covered from the moment of planting, and when space efficient, high-density intensive canopy training systems that utilize trees on precocious, vigor-controlling rootstocks are used. Systems that create narrow fruiting wall architectures, such as the UFO or SSA, also optimize light interception and distribution throughout the canopy, which is important since the plastic cover generally reduces available light by 15 to 25%. Such narrow canopies also allow better penetration and distribution of protective sprays throughout the canopy, reducing the need for tractor-based airblast sprayers and facilitating the development of fixed spray systems mounted on the tunnel structure itself, such as the SSCD concept (Fig. 1) under development at Michigan State University. Such an integration of advanced technologies (high quality cultivars, precocious and vigor-controlling rootstocks, climate-modifying high tunnels, space- and light-efficient training systems, and space-efficient spray systems) creates opportunities for growing high quality sweet cherries in regions where production has been inconsistent due to increasingly variable climates.

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Tables

Table 1. Sweet cherry high tunnel research sites established in 2005 at Michigan State University research centers near Clarksville and Benton Harbor, Michigan (each plot of trees was duplicated under tunnels and in an identical adjacent open orchard).

Site	Clarksville	Benton Harbor	
Soil type	Clay loam	Loamy sand	
Number of tunnel bays	3	4	
Dimensions per bay (m)	8.6 x 49.0 x 5.0	7.4 x 62.0 x 4.2	
Year trees planted	2000	2005	2008
Tree rows/tunnel	Two (2.0 m from tunnel legs and 4.6 m between tree rows)	Two (1.5 m from tunnel legs and 4.4 m between tree rows)	Three (1.5 m from tunnel legs and 2.5 m between tree rows)
Tree x row spacing (m)	2.0 x 4.6	2.0 x 3.7	1.5 x 2.5
Trees/ha	1,085	1,350	2,500
Canopy fruiting volume (m^3)	1.85 m x 2.15 m (spread) x 2.15 m (height)	1.85 m x 1.85 m (spread) x 2.1 m (height)	1.5 m x 1.7 m (spread) x 2.0 m (height)
Canopy fruiting volume per tunnel area ($m^3\ m^{-2}$)	0.9	1.0	1.25
Research plot cultivars	On Gi5: Lapins, Rainier On Gi6: Rainier, Sweetheart	On Gi5: Rainier, Skeena, NY 119 On Gi12: Early Robin	On Gi5: Skeena On Gi12: BlackPearl
Cultivar evaluation plot genotypes	None	On Gi5: Benton, BlackGold, BlushingGold, Cristalina, Lapins, Regina, Sandra Rose, Sonnet, Summit, Tieton, Ulster On Gi6: Glacier	On Gi5: BurgundyPearl, EbonyPearl, Kristin, Selah On Gi6: Kordia (Attika)
Breeding selection evaluation plot genotypes	None	8 from Cornell, 12 from Washington State University	4 from Cornell University
Sour cherry cultivars	None	Danube, Jubileum	None

Table 2. Effect of reflective (and water conserving) orchard floor fabrics (Extenday + DeWitt Pro-V weed barrier) on sweet cherry tree growth (3rd leaf) in a high tunnel orchard and an adjacent standard orchard.

	2007 TCSA^z (cm^2) Increase			
	Tunnel		No tunnel	
Cultivar/Rootstock	Fabric	No fabric	Fabric	No fabric
Early Robin / Gi12	33.3	20.0	16.8	11.5
Skeena / Gi5	25.2	18.2	18.0	18.1
Rainier / Gi5	19.7	19.7	15.0	12.2
NY 119 / Gi5	17.2	13.4	18.4	13.4
Mean	23.9	17.8	17.2	13.8

Comparison	% Increase in growth by treatment factor
Tunnel vs. No tunnel	40% with fabric, 29% without fabric
Fabric vs. No fabric	34% with tunnel, 24% without tunnel
Tunnel + Fabric vs. No Tunnel + No fabric	73%

Table 3. Twenty-eight sweet cherry variety/rootstock combinations with average fruit sizes of 10 g or larger, from five-year-old trees grown under high tunnels at Benton Harbor, Michigan (2009).

Mean fruit size	Cultivar/rootstock combination
10 g	BlackGold/Gi5, Lapins/Gi5
11 g	BlackPearl/Gi12, Cristalina/Gi5 Three breeding selections (1 Cornell, 2 Washington State University)
12 g	BlushingGold/Gi5, Regina/Gi5, SandraRose/Gi5 Four breeding selections (2 Cornell, 2 Washington State University)
13 g	Benton/Gi5, Early Robin/Gi12, Summit/Gi5 Four breeding selections (1 Cornell, 3 Washington State University)
≥14 g	Rainier/Gi5 Six breeding selections (2 Cornell, 4 Washington State University)

Table 4. The effect of sequential covering of high tunnels, compared to an adjacent uncovered orchard, on 2009 Growing Degree Days (GDD) and five-year-old 'Rainier'/Gi5 sweet cherry shoot and fruit growth on 22 May (~Stage II) and 22 June (Stage III ripening) near Benton Harbor, Michigan.

Tunnel covering and enclosure dates[z]	No tunnel	8 Apr	27 Mar-2 Apr	20-24 Mar	13-17 Mar
Added Growing Degree Days ($GDD_{10^\circ C}$)	0	38	48	78	81
Bloom (date)	28 Apr	28 Apr	25 Apr	21 Apr	17 Apr
Bloom advancement (days)	-	0	3	7	11
May 22 Data					
Shoot growth (cm)	13.9	26.1	26.1	29.9	33.0
Fruit diameter (mm)	13.2	13.3	15.0	15.5	16.0
June 22 Data					
Fruit diameter (mm)	25	28	31	32	34
Fruit wt (g)	7.0	9.1	11.8	13.2	15.5
SSC[y] (°Brix)	14.3	15.8	17.7	17.4	18.8

[z] Date of covering and enclosure = tunnel hoops covered with plastic on first date, ends and sides of tunnel bays enclosed in plastic on second date.

Uncovered orchard, on 2009 Growing Degree Days (GDD) and five-year-old 'Rainier'/Gi5 sweet cherry shoot and fruit growth on 22 May (~Stage II) and 22 June (Stage III ripening) near Benton Harbor, Michigan.

Figures

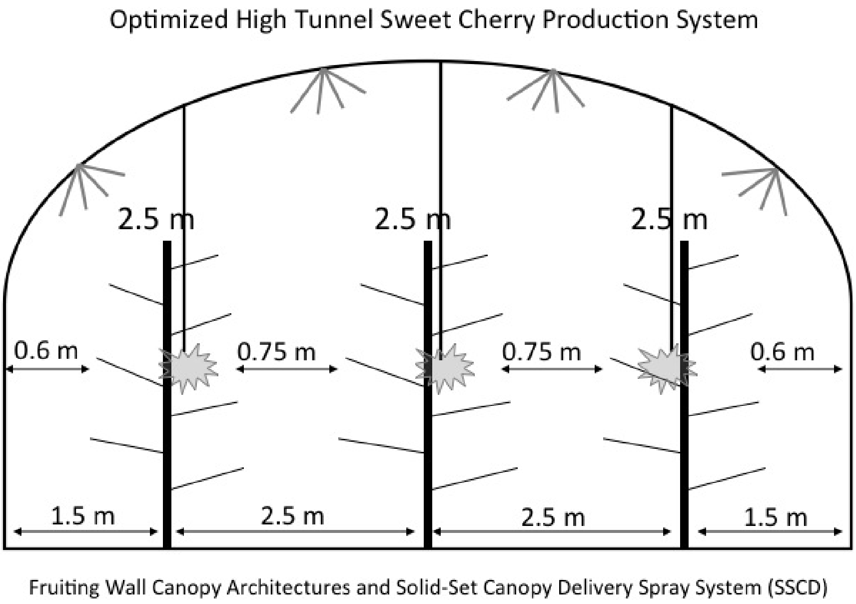

Fig. 1. Optimization of high tunnel sweet cherry production capacity utilizing fruiting all canopy architectures, such as Upright Fruiting Offshoots (UFO) or Super Slender Axe (SSA) training systems, and a solid-set canopy spray delivery (SSCD) system to eliminate the tractor alley.