Yields and Economics of High Tunnels for Production of Warm-Season Vegetable Crops

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Summary. Crop development rates, yields and production economics for muskmelon (*Cucumis melo*), pepper (*Capsicum annuum*) and tomato (*Lycopersicon lycopersicum*) grown in high tunnels [4.3 m wide x 2.5 m high x 29 m long (14 x 8 x 96 ft)] were compared to standard low tunnels over several cropping seasons in a temperate production area. The polyethylene-covered high tunnels protect several rows of crop for the duration of the cropping season. Air temperatures in the high tunnels were controlled by raising the sides of the tunnel. Low tunnels cover only a single row and must be removed soon after the crop is established to prevent overcrowding or overheating. When the low tunnels were in place, rates of accumulation of growing degree days (GDD) and early crop growth were comparable in the two tunnel systems. However, once the low tunnels were removed, the accumulation of GDD in the high tunnels exceeded the standard system. The crops in the high tunnels matured 1 to 2 weeks earlier and produced substantially greater fruit yields prior to frost than in the low tunnel treatments. The high tunnels provided little frost protection and were of limited utility for extension of the growing season. The high tunnels were much more costly to purchase and construct than the low tunnels but were durable enough to be used for multiple cropping seasons. Based on wholesale commodity prices, it would take 2 to 5 years for the enhanced gross returns obtained with the high tunnels to cover their higher capital costs.

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The cool, short growing season characteristic of most of Canada limits commercial production of many vegetable crops. Production of warm-season crops such as melons, peppers and tomatoes is particularly difficult unless means are employed to improve the growing conditions. Plasticulture involves using plastic soil mulches and crop covers to improve the microclimate surrounding the crop, thereby enhancing earliness, improving yields and increasing profitability (Waterer, 1992, 2000; Wells and Loy, 1985; Wittwer and Castilla, 1995). At present, low tunnels represent the standard method for using plastics to enhance the growth of most vegetable crops (Wells and Loy, 1993). A low arch [typically less than 0.75 m (2.5 ft) tall] of perforated clear polyethylene or non-woven fibre is supported above the crop using wire hoops. Typically, a single row of the crop is protected by each cover. By increasing air temperatures, reducing wind damage and by providing a degree of frost protection, the low tunnels accelerate crop development and extend the growing season (Waterer, 1992; Wells and Loy, 1985). However, low tunnels have several limitations. Due to their small size, the low tunnels must be removed soon after installation, otherwise they interfere with crop growth (Waterer, 1992). The small size of the low tunnels also limits the cultural practices which can be accomplished with the tunnels in place; for example weeding or spraying are impractical. Unusually warm spring weather can cause heat stress to the covered crop unless the low tunnels are partially removed. Removal and reinstallation of the tunnels is however labor intensive. The covers also must be removed to allow access to the crop by insect pollinators. Finally, the materials used in low tunnels have a limited lifespan and typically new materials are used every year. Adoption of low tunnel technology represents a substantial additional cost to the growers in both the tunnel materials and the labor required for their installation and removal (Wells, 1996).

High tunnels are similar to low tunnels in design and function, except that; 1) one tunnel covers several rows, 2) the high tunnels are large enough to grow the crop to full maturity under the tunnels, 3) the tunnels are large enough to allow many cultural practices to occur with the tunnels intact and 4) the tunnels remain in one spot for several cropping seasons (Wells, 1996; Wells and Loy, 1993). The high tunnel structure consists of arch ribs driven into the ground covered with a single layer of greenhouse-grade polyethylene. There are no artificial heating or cooling systems. Rolling up the sides or opening the end doors of the high tunnels provides both ventilation and access to the crop by pollinating insects. At the conclusion of the growing season, crop residues are removed and the soil in the high tunnels is tilled in preparation for the next season. The covers are left in place over the winter. The initial cost of purchasing and installing the high tunnels is higher than traditional low tunnels but the economics of production with high tunnels may still be favorable if they increase yields or allow growers to access markets at times when prices are at a premium (Hochmuth et al., 1998; Wells, 1996; Wells and Loy, 1993). If the high tunnels are durable, the costs of materials and installation may be amortized over multiple growing seasons.

High tunnels are used extensively in the Middle East and Europe for the production of melons, tomatoes and other high-value warm-season produce (Wittwer and Castilla, 1995). To date, utilization of high tunnels has been limited in North America, although the potential benefits of this technology have been demonstrated (Lamont et al., 2001; Wells and Loy 1993). Penn State University has recently established the High Tunnel Research and Education Center to research production and management issues for high tunnels (Lamont et al., 2001). Profitable operation of the high tunnels hinges on maximizing productivity within the constrained space available (Lamont et al., 2001; Loncaric et al., 1999), with a corresponding focus on high value crops which command price premiums for off-season production. This project compared yields, crop quality and production economics of the high tunnel system versus traditional low tunnels over three years using warm-season vegetable crops in Saskatchewan, Canada - a region with a cool, short growing season.

Materials and methods

The trials were conducted at two sites in Saskatchewan (Outlook and Saskatoon), Canada during the 1998, 1999, and 2000 cropping seasons. The crops selected for testing (muskmelon, pepper, and tomato) are high-value vegetables, responsive to enhanced growing conditions. There is a significant demand for these crops outside of the window provided by traditional field production. Muskmelon (cv Earligold) was grown at both sites, but tomato (cv. Roadside Red and Spitfire) was only grown in Saskatoon and pepper (cv. Valencia, Ultraset, Whopper and Superset) was only grown in Outlook. The cultivars for each crop were selected based on superior performance in previous field trials (Waterer and Bantle, 1998).

The soil in both the high tunnels and the low tunnel plots was prepared by rotovating and incorporating sufficient fertilizer to raise soil fertility levels to those recommended for irrigated vegetable production [100 $kg \cdot ha^{-1}$ (89.2 lb/acre) nitrogen (N) and 59 $kg \cdot ha^{-1}$ (52.6 lb/acre) phosphorus (P)](Millar, 1988). Plastic mulch [IRT (Ken-Bar Products, Reading, Mass.), 1 m (3.3 ft) wide,] was laid on 1.4 m (4.59 ft) centers in both the high and low tunnel plots. The mulch was applied in advance of planting to encourage soil warming. Drip irrigation tube [0.34 gal/min (1.287 $L \cdot min^{-1}$), T-Tape, San Diego, Calif.] was installed under the mulch. In last week of May, once the risk of spring frost had largely passed, greenhouse-grown seedlings of the test crops were transplanted into both the high and low tunnel treatments. The peppers and tomatoes were 4 weeks old at transplanting, while the muskmelon seedlings were 14 d old. In-row spacings were; tomato 45 cm (17.7 inches), pepper 15 cm (5.9 inches) and melon 30 cm (11.8 inches). The resulting plant populations [15,870/ha (6,423/acre), 47,620/ha (19,271/acre) and 23,800/ha (9,631/acre) respectively] were higher than normally recommended for standard field production (Maynard and Hochmuth 1997) but corresponded with standard practices in more intensive plasticulture production systems (Wells and Loy, 1985).

The low tunnels [1 m wide x 0.75 m tall (3.3 x 2.5 ft)] were constructed by applying the covering material over metal hoops. Clear perforated polyethylene [2 mil (0.051 mm, 0.002 inch), Western Concorde Mfg, Calgary, Alta.] was used to cover the melons, while spunbond polyester [Reemay, Reemay Inc., Old Hickory, Tenn.] was used on the peppers and tomatoes. The specific row covering was selected for each crop based on previous research under Saskatchewan growing conditions (Waterer, 1992, 1993). The low tunnels were installed immediately after transplanting and were left in place until the crops began to flower or they had fully utilized the available growing space within the tunnels. Depending on the year and the crop, the crops in the low tunnels treatments were covered for 4 to 6 weeks.

The high tunnels [Ledgewood Farm Greenhouse, Moultonboro, N.H.] were 4.3 m wide, 2.5 m high and 29 m long. The tunnels were covered with a single layer of 6 mil (0.153 mm, 0.006 inch) polyethylene [Ledgewood Farm Greenhouse, Moultonboro, N.H.]. Endwalls were also constructed of polyethylene.

Air temperatures at 30 cm (0.98 ft) were monitored at two points inside both the high and low tunnels and in the open. In the first year of the trial, the sides of the high tunnel were raised whenever temperatures inside the tunnel exceeded 35 ºC (95.0 ºF). In subsequent years, the high tunnels were kept closed, irrespective of the temperature, until the onset of flowering. From flowering onwards, the high tunnels were managed to maintain temperatures below 40 ºC (104.0 ºF). No attempt was made to regulate the temperature inside the low tunnels.

Honeybee hives were placed in the immediate vicinity of the test plot. In 2000, small colonies were also placed inside the high tunnels. The plots were irrigated whenever soil moisture potentials in the root zone fell below -40 kPa (-0.40 bars). At 6 and 12 weeks after transplanting 20 $kg \cdot ha^{-1}$ (17.8 lb/acre)

N as 46N-0P-0K was applied through the drip irrigation system. The crops were evaluated weekly for insect or disease problems.

The melon and tomato crops were harvested twice weekly once the fruit reached maturity. The muskmelons were harvested at full slip and the tomatoes at the breaker stage. The peppers were once-over harvested just prior to the first killing frost. Fruits were counted, weighed, and graded based on Canadian Food Inspection Agency market standards (Canadian Food Inspection Agency, 2002) for acceptable size, shape, and freedom from defects. Peppers which had begun to mature to red were segregated from the green fruit, as red fruit command a substantial price premium. The crop residues were removed from the high tunnels in the fall and the sides of the tunnels were rolled up to expose the interior to winter conditions. The low tunnels were moved each year, but the high tunnel remained at its original site.

Data analysis. Each crop was analyzed separately. All yield data were converted to yield per unit length of row. Cultivar yields were pooled and averaged in crops where multiple cultivars were tested in a given year. Standard analysis of variance procedures were used, with site-years considered as replicates, followed by t-tests for comparisons of treatment means. In the tomato and melon crops, weekly fruit yields until the first killing frost were used to calculate the time after transplanting required for 50% of the fruit to mature (T-50). Gross returns were based on in-season wholesale prices for the various crops (F.O.B. Saskatoon, Canada in $ 1 U.S = $ 1.66 CDN). Gross returns for the pepper crop factored in the price premium paid for red fruit. The cost per unit production area of the two tunnel systems was calculated by dividing the cost of materials and installation by the corresponding amount of usable cropping space. The relative cost efficiency of the two tunnel systems was calculated by comparing gross returns/unit production area as a function of the cost of the materials and labor required to install and maintain the tunnels.

Results and discussion

High tunnel observations. The high tunnels were easily erected with minimal construction skills or equipment. After three growing seasons, the high tunnels were still structurally sound, but the 6-mil polyethylene covers had to be replaced due to tears and yellowing.

The 1998 growing season was considerably warmer than 1999 or 2000. Cumulative growing degree days (GDD) [base 10 ºC (50.0 ºF)] in the open and inside the two types of tunnel from the time of planting until the low tunnels were removed and from the time of planting until the first fall frost during the three cropping seasons at the Saskatoon site are presented in Table 1. Low tunnels constructed of perforated polyethylene accumulated GDD more rapidly than the more porous nonwoven polyester. The relative rate of accumulation of GDD in the high tunnels varied among years. In 1998, the non-ventilated low tunnels constructed of clear polyethylene accumulated GDD more rapidly than the high tunnels which were ventilated once temperatures exceeded 35 ºC. As early crop growth in the low tunnels was superior to growth in the ventilated high tunnels in 1998, in subsequent years the high tunnels were kept closed early in the season, irrespective of the temperature. In 1999, cumulative GDD in the high tunnels, both early in the season and accumulated over the entire season, were substantially higher than in the low tunnel treatments. Cloudier than normal weather during 2000 kept temperatures in the high tunnels relatively low.

Although temperatures in both types of high tunnels often exceeded the published optima for the test crops (Kinet and Peet, 1997; Maynard and Hochmuth, 1997; Wien, 1997) there were few indications of heat stress. Gent (1992) found that delaying ventilation of high tunnels until temperatures exceeded 38 ºC (100.4 ºF) accelerated vegetative growth of tomatoes and promoted early fruiting relative to ventilation at lower temperatures. However, maintaining the tomato plants under these conditions eventually resulted in nutrient deficiencies and reduced total fruit yields. By contrast, the tomato and muskmelon crops in the high tunnels in this study appeared healthier than the crop in the open field through the warmest days of the summer. Once fruiting began, the pepper plants in the high tunnel were less vigorous than the plants grown in the open field. This loss of vigor may have been related to heat stress, but it may also reflect the metabolic load exerted by the larger and more rapidly developing fruit crop in the high tunnels. When several crops are grown simultaneously in a high tunnel, conditions must be managed to maximize overall productivity. As the optimum temperature for pepper plants is lower than for tomatoes and muskmelons (Maynard and Hochmuth, 1997; Wien, 1997), health of the pepper crop may have been compromised for the sake of the two other crops. Dedicating entire high tunnels to a single crop would simplify temperature management.

The high tunnels provided only about 2 ºC (3.6 ºF) protection from spring or fall frosts (data not shown). This is comparable to the degree of protection provided by standard low tunnels (Waterer, 1992). The frost protection provided by the high tunnels extended the fall harvest period by an average of two weeks but the impact on yield was minimal as low temperatures slowed crop development well in advance of the first killing frost.

Weed populations between the mulch rows were lower inside the high tunnels than outside. The area between the rows in the high tunnel never received rainfall, while in the standard management regime weeds germinated between the rows following each rain event. All weeds were controlled by mechanical tillage and did not compete with the crop. Over the three cropping seasons there were few problems with disease or insect pests in either of the tunnel treatments and no pesticides were required. The short, cool and dry growing season typical of the Canadian prairies appeared to prevent the problems with insects and foliar disease noted when high tunnels are used in warmer and more humid regions (Wells and Loy, 1993).

The cost of materials, installation, and maintenance for the high tunnels over the 3-year test period was $US 1990. This corresponds to a cost of $ 13.25/m ($ 4.04) of usable row space based on three rows spaced 1.4 m (4.59 ft) apart running the length of the high tunnel. The corresponding cost for the standard spun bonded polyester or perforated polyethylene low tunnels was $ 0.46/m ($ 0.14/ft).

Muskmelon. The first fruits matured 2 to 3 weeks earlier in the high tunnel than in the standard low tunnel treatments. Similarly, the T-50 in the high tunnels was two weeks earlier than in the standard regime (Table 2). In the unusually warm 1998 growing season, differences in marketable yields with the two types of tunnel were minimal. By contrast, in the much cooler 2000 growing season, excellent yields were obtained with the high tunnels, while no fruits matured prior to the first fall frost in the low tunnel plots. Averaged over the three test seasons and two sites, total yields of mature fruits were 59% higher with the high tunnel than with the low tunnel treatment (Table 2). A far greater proportion of the fruits set in the high tunnels matured prior to frost than when standard low tunnels were used (Table 2). Total yields (mature and immature fruit) were similar with the two production systems. Fruits grown inside the high tunnel were larger than fruits in the standard management regime (Table 2) while the flavor and sugar contents were not influenced by the tunnel type (data not shown). Hochmuth et al. (1998) noted that producing melons in high tunnels in Florida reduced grade-out due to fruit cracking relative to low tunnel. The cooler temperatures and limited rainfall characteristic of the Canadian prairies minimized problems with fruit cracking in this trial.

Vigor of the muskmelon crops in the high tunnel declined rapidly during August and few fruits were harvested through the last 30 d of the growing season. The decline in crop vigor coincided with the main fruit harvest. The stress placed on the plants by the heavy crop of developing fruit may have weakened the plants. The muskmelon cultivar Earligold was selected for its high yields in field trials conducted under the limited growing season available in Saskatchewan (Waterer and Bantle, 1998). Cultivars adapted to longer growing seasons may have a higher overall yield potential in the high tunnels. Sequential planting would also extend the potential harvest period in the high tunnel. Trampling damage to the vines during harvest within the confined space of the high tunnels may have contributed to the observed decline in crop vigor. Staking could potentially alleviate this problem. Staking may also accelerate fruit maturity but it is labor intensive and the handling required may cause plant and fruit damage.

Tomato. The crop flowered and the first fruits matured 2 to 3 weeks earlier inside the high tunnel than in the low tunnel regime. However, the time required for 50% of the fruit to mature was only about a week different for the two tunnel types (Table 2). Averaged over the three test seasons, total yields of mature marketable tomato fruits were 47% greater with the high tunnel than with the low tunnels (Table 2). A higher proportion of the fruits in the high tunnels matured prior to frost than in the low tunnel plots (Table 2), but a significant portion of the potential crop was still lost to fall frost in the high tunnel. Total yields (mature + immature) were comparable for the two production systems. Average fruit size (Table 2) and taste were also comparable in the two production systems. The semi-determinant cultivars selected for testing thrived in the high tunnel environment. Fruit set in the high tunnels was excellent in spite of the supra-optimal air temperatures (Kinet and Peet, 1997), limited air movement, and the tendency of honeybees to avoid tomato flowers. Fruit quality was excellent in both production systems. The incidence of blossom-end rot was lower inside the high tunnel than outside, but this was balanced by slightly higher grade-out due to bacterial spot (*Xanthamonas campestris* pv. *vesicatoria*) in the high tunnel (data not shown). Higher humidities within the confines of the high tunnels could have contributed to the observed reduction in blossom-end rot (Tartier, 1994) and the increased incidence of bacterial disease (Tartier and Pitblado, 1994).

Pepper. Averaged over the three site-years, yields of mature fruit were 59% greater with the high tunnel than with the standard low tunnels (Table 2). More than 10 times as many fruits in the high tunnels had begun to change color to red than with the standard regime (Table 2). Average fruit size (Table 2) and quality were comparable in the high and standard tunnel treatments. As previously noted, vigor of the pepper crop in the high tunnel declined as season progressed. Whether this loss of vigor could be avoided by more careful maintenance of air temperatures or through greater attention to fertility or other inputs merits further attention.

Economic analysis. Gross returns based on in-season wholesale prices (F.O.B. Saskatoon, Canada, in $US) for the high tunnel and standard low tunnel cropping systems averaged over the 1998-2000 cropping seasons are presented in Table 3. The high tunnels consistently produced a higher gross return/unit row length than did the standard production practices. However, the material costs for the high tunnels ($13.25/m of row) far exceeded the cost of the standard low tunnels ($ 0.46/m of row). Depending on the crop, it would take from 2 to 5 growing seasons before the increase in gross returns provided by the high tunnels exceeded their higher capital costs (Table 3). The most economically attractive cropping option in the high tunnels was peppers, primarily because of the superior yields of mature red fruit which commanded a price premium.

Conclusions

The three years of trials demonstrated that high tunnels have the potential to accelerate growth and improve yields of several warm-season vegetable crops relative to standard low tunnels, although the benefits obtained varied with the crop and the growing season. The high tunnels were most beneficial during cool growing seasons particularly if the tunnels were managed with the objective of maintaining relatively high air temperatures through the vegetative stage of crop development. The crops grown inside the high tunnels were of good quality with no unusual disease or insect problems. Material and construction costs of the high tunnels were substantially higher than standard low tunnel option. Cost/benefit analyses suggests that the high tunnels required a multi-year payback period when used to generate product for sale into wholesale markets.

Some options to improve the cost efficiency of using high tunnels include; 1) reduced capital costs through volume purchases of construction materials and use of more efficient construction methods, 2) increase yields / unit area should be possible through the use of better varieties, closer between- and within-row spacings (Lamont et al., 2001; Loncaric et al., 1999), staking, relay cropping, and use of other agronomic practices tailored to high intensity production, 3) growing higher-value crops. The potential benefits of using the high tunnel vary with both the crop and the market. Growers need to select crops that benefit from the high tunnel environment in terms of accelerated maturity, enhanced yields, or improved quality. Although tomatoes, peppers, and melons are high-value crops, which clearly benefit from the high tunnel environment, greater profits may be available from other crops. Off-season production of small fruits (raspberry and strawberry) as well as cut-flowers have been identified as potentially profitable cropping options in high tunnels (Lamont et al., 2001; Wells and Loy, 1993). Produce available either earlier or later than normal may command a price premium. Although the high tunnels accelerated crop development, they provided little frost protection. This limited yields and reduced access to higher value out-of-season markets. The addition of simple supplemental heating systems such as a propane burners may be warranted. Finally, the earliness and high quality of crops grown in high tunnels may make them better suited to marketing direct to the consumer rather than through the wholesale system.

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Table 1. Cumulative growing degree days [base 10 ºC (50.0 ºF)] for tunnel treatments from planting until removal of the low tunnels or for the entire growing season.

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	Early [z]				Growing Season[y]			
	Open	Low tunnel		High tunnel	Open	Low tunnel		High tunnel
Year		Nonwoven	Clear			Nonwoven	Clear	
1998	425[x]	720	835	810	1250	1545	1675	1925
1999	375	620	700	1000	1100	1355	1500	1900
2000	200	310	325	275	1150	1475	1400	1850
Average	333	550	620	695	1167	1458	1525	1891

[z] From transplanting in late May until removal of the low tunnels in early July.

[y] From transplanting in late May until the first killing frost.

[x] 1 ºC = 1.8 ºF.

Table 2. Yield characteristics averaged over 3 years for muskmelon, tomato, and pepper grown using high or low tunnels.

	T-50 (d)[z]	Marketable yield ($kg\cdot m^{-1}$ of row)[y]	% mature[x]	Fruit wt. (kg)[y]
	Muskmelon			
High tunnel	87 (80-92)[w]	17.8 (8.7-32.0)*	90 (79-98)	1.34 (1.10-1.66)
Low tunnel	101 (97-109)	7.2 (0-24.3)	40 (0-82)	0.97 (0.59-1.48)
Significance	**	**	**	**
	Tomato			
High tunnel	99 (97-101)	12.7 (8.1-16.9)	53 (39-57)	0.14 (0.13-0.16)
Low tunnel	107 (104-108)	6.6 (3.5-11.7)	33 (21-49)	0.14 (0.13-0.15)
Significance	*	**	**	NS
	Pepper			
High tunnel	--	10.9 (9.0-13.2)	70 (40-100)	0.12 (0.11-0.13)
Low tunnel	--	4.5 (2.8-5.9)	7 (0-14)	0.13 (0.12-0.13)
Significance	--	**	**	NS

[z] Time from transplanting until 50% of the fruits ripened.

[y] 1.0 $kg\cdot m^{-1}$ = 0.67 lb/ft, 1.0 kg = 2.20 lb. 1 $kg\cdot m^{-1}$ of row = 7,200 $kg\cdot ha^{-1}$ = 6,422 lb/acre.

[x] (Yield prior to frost of mature fruit/total yield) x 100.

[w] Values in brackets represent the range in means over site years. Melon n=6, tomato n=3, pepper n=3.

[NS, *, **] Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively, for tests of tunnel effects for each crop.

Table 3. Gross returns based on wholesale prices and the number of seasons before returns after material costs for the high tunnels exceed standard low tunnels.

		Price ($/kg)[z]	($/m of row)	Seasons [y]
Melon	High tunnel	0.47	8.37	2.6
	Low tunnel		3.38	
Tomato	High tunnel	0.49	6.22	4.3
	Low tunnel		3.23	
Pepper	High tunnel	Red - 1.15	10.89	1.6
	Low tunnel	Green - 0.65	3.08	

[z]Wholesale prices F.O.B Saskatoon Canada in $US for the fall marketing period averaged for 1998-2000.

$ 1.00/kg = $ 0.45/lb, $ 1.00/m = $ 0.30/ft.

[y] Number of seasons required calculated as: (cost/m of high tunnels-cost/m of low tunnel)/(gross/m high tunnel-gross/m of low tunnel).