The Connecticut Agricultural Experiment Station, New Haven

High Tunnels Extend Tomato and Pepper Production

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SUMMARY

In early spring unheated high tunnels covered with clear polyethylene film extended the production season of tomato by accelerating growth and ripening. Earliest yields were from tomato transplanted on April 3 into a high tunnel ventilated at 86F. Fruit ripened in early June. Tomato in cooler tunnels with more ventilation ripened later. The optimum duration of ventilation of a high tunnel on sunny days was 3 hours in early April, increasing to 5 hours in early May and 7 hours in early June. Tomato planted later ripened later, but yield and fruit size were bigger. A mid-April planting was the best compromise between earliness and yield and quality. In fall, tomato in high tunnels continued ripening into late November, but slowly. In fall, tunnels ventilated at 58F had the greatest yield and fruit size. The less frequent ventilation of warmer tunnels reduced fruit size and quality and increased disease. Each two week delay in planting after July 15 delayed ripening by one month and reduced yield.

In spring, ripening of sweet pepper in high tunnels was advanced less than that of tomato. In fall, pepper also continued ripening until late November, but in contrast to tomato, yield and fruit quality were improved in a warm tunnel with little ventilation.

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In early summer, Connecticut consumers are eager to buy native, vine ripened tomatoes and peppers. However, when grown conventionally, tomatoes do not ripen until late July and peppers do not ripen until August. Planting in plastic shelters can prevent frost damage, and speed growth and development by warming plants during the daytime. This leads to earlier ripening and extends the harvest and availability of local produce. Using plastic shelters for earlier production should benefit farmers, because out-of-season vegetables command high prices. The farmer would get a good return for vegetables grown under shelter, despite the increased production cost.

Shelters accelerate crop production because spring-time temperatures in Connecticut are too cool for rapid growth in the field. In general, Connecticut soils have adequate moisture and fertility. In spring, the solar radiation that energizes photosynthesis is intense. However, tomato grows best at or above 75F (Austin and Ries 1968, Wolf et al 1986), while the daily average temperature in Connecticut exceeds 70F only between June 20 and Sept 6 (Brumbach 1965). Actual temperatures vary dramatically about the long term average, from day to day and from season to season (Bingham 1963). Thus field grown plants are often far from their optimum temperature for growth.

Plants can be sheltered in several ways. Opaque blankets laid over plants at night protect from frost, but they do not warm plants during the day. Row covers or low tunnels that cover plants for a month or two after transplant may protect from slight frosts, but primarily they warm plants during the day and accelerate growth (Wells and Loy 1985). Overheating on sunny days is a disadvantage of row covers (Wolfe et al 1989, Gent 1990). Cold frames are more effective for frost protection but the construction limits their use to small areas. High tunnels, or houses built of metal hoops covered with clear plastic are large enough to cover plants through fruit production and they can be built cheaply to cover large areas. In Connecticut such structures are already widely used to protect container-grown ornamentals in the nursery industry. They provide frost protection, and warm plants during the day. The principle modification used here was to increase ventilation and to control it more accurately. Ventilation is necessary to moderate air temperature on sunny days since plastic shelters will heat above 100F by conservation of heat from solar radiation. This damages the plants inside (Waggoner 1958). In the present investigation, an automatic system was devised to give precise control of ventilation, so that warm day-time temperatures could be achieved without damaging the plants.

High tunnels may fail to improve production for several reasons. One is cool nights, which are common in early spring. At night, the air in high tunnels is only a degree or two warmer than that outside. For some plants that are not acclimated to cold, temperatures below 50F can cause chilling injury (Drozdov et al 1984). In addition, the air temperature in high tunnels may vary by 50F from day to night. Although tomato responds only to the average temperature when the variation is less than 20F day to night (Hurd and Graves 1984, Gent 1988), the plants may fail to cope with a larger variation. In the present study, the warm days required to compensate for cool nights were only slightly less than that causing high temperature injury.

Cold soil may also cause problems. Cold soil retards growth and fruit production of tomato (Gosselin and Trudel 1983; Papadopoulos and Tiessen 1983). Planting in pots may accelerate production of tomato in high tunnels, since soil in pots is warmer than that in level ground during the day. However, soil in pots cools more at night.

This study explores the use of unheated high tunnels to extend the season for vegetable production in Connecticut by examining the optimum and limiting temperatures and planting dates for tomato and pepper production.

METHODS AND MATERIALS

Cultivars

The tomato (*Lycopersicon esculentum* Mill) cultivars used were EARLY CASCADE (Peto Seed Co, Saticoy CA), EARLY GIRL (Park Seed Co, Greenwood SC), FIRST LADY (Hart Seed Co, Wethersfield CT) and TROPIC (Burpee Seed Co, Warminster, PA). EARLY GIRL and FIRST LADY were indeterminate cultivars with medium size fruit that

ripens early. TROPIC, was an indeterminate cultivar with larger fruit that ripens later than EARLY GIRL. EARLY CASCADE had the smallest fruit and ripened earliest when grown outside. The sweet pepper (*Capsicum annuum* L.) cultivars were CANAPE and GOLDEN BELL (Harris Moran Seed Co, Rochester, NY) and LINCOLN BELL (Stokes Seeds, Inc., Buffalo, NY). CANAPE was a small blocky green pepper that turned red when ripe. LINCOLN BELL was a larger pepper that also turned red when ripe. GOLDEN BELL was a large, blocky, green pepper that turned yellow when ripe. Seeds were germinated and grown in Promix BX in 24-count flats. Seedlings were grown in a heated greenhouse at about 70F for 5 to 8 weeks before transplanting into the high tunnels or outside. When transplanting, tomatoes were set to the depth of the first true leaf and peppers were set to the level in the seedling flat.

Experiments in 1988

All experiments were conducted at Lockwood Farm in Hamden, CT. In a preliminary experiment in 1988 plants were either grown in a high tunnel, under row cover, or outside. The high tunnel, 48 x 14 x 9 foot high, was constructed of hoops of one-half inch steel pipe placed at 4-foot intervals. The long axis of the high tunnel was oriented north to south. Compared to similar structures used in the nursery industry, the principal modifications were 2 foot higher side walls and larger end doors to increase natural ventilation. At both ends, rectangular doors, 7 x 6.5 foot high, were opened and closed by rolling up a sheet of plastic attached to a wooden strip. The tunnel and the doors were covered with a single layer of 4 mil clear polyethylene film (Visqueen 1504, Ethyl Corp, Richmond VA).

The soil was Cheshire fine sandy loam at pH 6.3 amended with N:P:K 10:10:10 at 880 lbs/acre for tomato and 440 lbs/acre for pepper. Before planting, the soil was tilled and covered with 4 foot x 1 mil black polytheylene mulch, except for 1 foot aisles between rows. The rows were oriented north to south.

In 1988, the tomato cultivars grown were EARLY GIRL and TROPIC and the pepper cultivar was CANAPE. Tomatoes and peppers were transplanted in the high tunnel on May 1 and June 1 and remained in the shelter throughout the season. Tomato and peppers were transplanted outside on April 20 and May 23. Half the tomato plants outside were covered with row cover for the first month after transplant. Half the peppers were covered with row cover that was removed on June 24 and July 13, for the early and late plantings, respectively. A row cover of white spun-bonded polypropylene (Kimberly Farm floating row cover, Kimberly Clark Co, Roswell GA) was placed over plants directly after transplanting outside, and held in place by burying the edges in soil. For tomato, each replicate block was four plants set in a 3-foot-square spacing. Plants were pruned to three or four stems after row cover removal and supported by stakes. For pepper, each replicate block consisted of nine plants in an 18-inch-square spacing. Peppers were neither pruned nor supported.

Experiments in 1989

In 1989, two tunnels were compared with different ventilation regimes. The doors of one tunnel opened whenever the temperature inside was warmer than 60F, the doors of the other opened when the air inside was warmer than 95F. The doors were also opened if the temperature averaged since 6 a.m. exceeded 76F inside the high tunnel. These two new tunnels, 56 x 14 x 9 foot high, were constructed from hoops of 1-inch steel pipe set at 4-foot intervals (Growell Greenhouses, Cheshire CT). Doors and frames were constructed of 2 x 4 lumber and set on a sill attached to either side of the end of the tunnel. The tunnels and doors were covered with a single

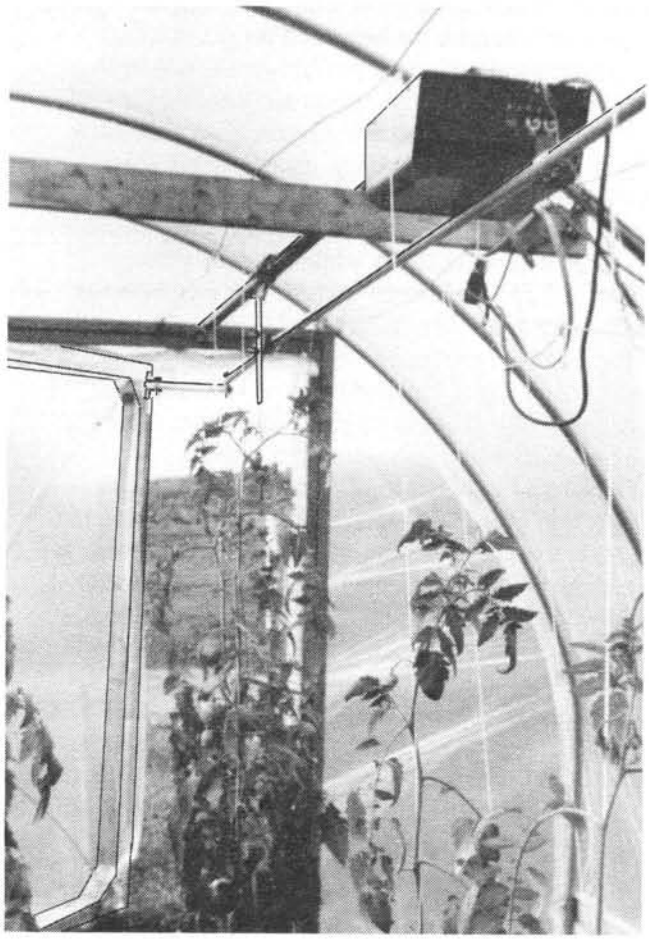

Figure 1. An interior view of the door of a high tunnel showing the method for automatic control of ventilation.

layer of 4 mil clear polyethylene film (Tufflite T34144, Armin Plastics, City of Industry CA). Cracks around the door were sealed with film doubled and stapled inside the frame. The long axis of the tunnels was oriented east to west. The principal modification over 1988 was precise, computer control of the opening and closing of the doors at both ends. Rectangular doors, 7 x 6.5 foot high, were opened by rotation through 60 degrees about a center pivot. They were operated by a garage door opener (Sears Model 13953110 Chicago IL) attached to a rigid tube running the length of the tunnel (Figure 1).

Temperatures were measured and the doors were controlled by a computer (Campbell Scientific model CR10, Logan UT). Air temperatures in each tunnel were measured at heights of 1.5 and 5 foot with shielded copper-constantan thermocouples. Soil temperatures were measured at a depth of 4 inches next to a plant. The computer opened the doors when the air inside the tunnel was warmer than the ventilation limit. At night, plants were sprinkled to protect from frost whenever temperatures inside the high tunnels fell below 35F. The computer activated mist nozzles arranged at 8-foot intervals along the center line of the tunnel at a 7 foot height. During the summer, the doors were removed so each tunnel had continuous ventilation.

In 1989, EARLY GIRL tomato and GOLDEN BELL and LINCOLN BELL peppers were grown. There were two replicate blocks of each planting and treatment. For tomato, each replicate block consisted of nine plants set on 3-foot centers in a square arrangement. For pepper, each replicate block consisted of 10 plants spaced 18 inches apart in a double row. Before planting, the soil was tilled and covered with 1 mil black polyethylene mulch, except for 1 foot wide aisles running the length of the tunnel. Half the plants were transplanted through the mulch and half the plants were grown in black polyethylene 3-gallon pots placed on top of the mulch and filled with soil from the same plot. On May 1, two replicate blocks were planted outside as a control, in level ground covered with black plastic mulch. Tomato plants in the control plot were staked but were not pruned. Tomato plants in the tunnels were supported by string and reduced to a single stem as they developed. All plants were watered to excess via 0.060 inch diameter drip tubes when soil moisture tension rose above 0.20 bar in any treatment. Plants were watered with a complete fertilizer (Peters 20-10-20, W.R. Grace Co., Cambridge MA) supplied at 100 ppm N.

Experiments in 1990

In 1990, two more tunnels were built near those constructed in 1989, for a total of four high tunnels, that were identical except for the temperature at which the doors were opened. Ventilation was governed by a computer, as described previously. In 1990, the doors were opened for ventilation when the air inside was warmer than 58F, 72F, 86F or 100F, respectively, for the four tunnels. Tomatoes were planted in the tunnels on three dates in the spring, and another series of three sequential plantings were made in the summer for fall production. The cultivars EARLY GIRL, EARLY CASCADE and FIRST LADY were germinated on February 13, March 6 and March 27 for planting on April 3, April 17 and May 1, 1991. The same cultivars were germinated on June 26, July 12 and July 26 for planting on July 26, August 9 and August 23, 1991. All plants were grown in level ground in 1990. All other horticultural aspects were the same as in 1989. No peppers were grown in 1990.

In each year, ripe fruits were harvested every 5 days, separated into marketable and unmarketable (blemished, cracked or weighing less than 2 ounces) categories, counted and weighed. In 1990 the defects were enumerated into categories of vertical cracks, circular cracks, rough skin, green shoulder, small, misshapen, blossom end rot, or insect damage.

RESULTS

Tomato production in a high tunnel compared to row cover in 1988

Over 3 years, the date tomatoes ripened depended most on the date of transplant into the high tunnels (Table 1). After transplanting on May 1, 1988, tomatoes of the cultivar EARLY GIRL began ripening on June 28, about 3 weeks earlier than when grown outside. When transplanting was delayed until June 1, production in the tunnel began at the same time as that outside (Table 2). TROPIC, a cultivar that produced larger fruit, also ripened earlier when transplanted in the high tunnel on May l, compared to plants transplanted outside on April 20.

Yields from the tunnel were greater than that from plants grown under row cover or grown outside (Table 2). The yield of tomato from the tunnels was very high, in part because they were picked for over 3 months, and there were two flushes of fruit production in the tunnel compared to only one outside. The fruits produced by May 1 transplants in the high tunnel was smaller than those produced outside. The quality of fruit from EARLY GIRL grown in the tunnel was remarkably good, more than 80% marketable over the season. Thus, high tunnels seemed promising compared to using floating row covers for early production of tomato.

Temperature of air and soil in warm and cool tunnels in 1989

In 1989, hourly records of air temperature in the high tunnels showed the air warmed swiftly on sunny days. Even in April, the air in one tunnel warmed to the

Table 1. Summary over three years for EARLY GIRL tomato grown in unheated high tunnels or outside.

Year	Transplant date	First ripe fruit	Weeks picked	Total yield	Fruit size	Quality	Green shoulder
1988 [a]	May 1	Jun 28	14	Very high	Med small	Good	None
	Jun 1	Jul 14	12	High	Med	Good	None
	Outside [b]	Jul 21	11	Med	Med	Poor	None
1989	Apr 3	Jun 5	5	Very low	Small	Good	Severe
	Jul 14	Sep 1	11	Med	Large	Poor	Mild
	Outside	Jul 7	14	Med	Med	Fair	Mild
1990 [c]	Apr 3	Jun 7	7	Low	Med small	Good	Moderate
	Apr 17	Jun 20	7	Med	Med	Good	Moderate
	May 1	Jul 4	7	Med	Med	Fair	Moderate
	Jul 27	Sep 20	10	Low	Very large	Fair	Mild
	Aug 9	Oct 11	7	Very low	Very large	Fair	Mild
	Aug 23	Nov 14	2	Insignificant			
	Outside	Jul 21	11	Med low	Small	Poor	Very mild

[a] TROPIC ripened two weeks later than EARLY GIRL in 1988, but the fruit were twice as large.
[b] Tomatoes were transplanted outside on May 1 in each year.
[c] EARLY CASCADE ripened a week earlier and FIRST LADY ripened a week later than EARLY GIRL after transplant on May 1, 1990.

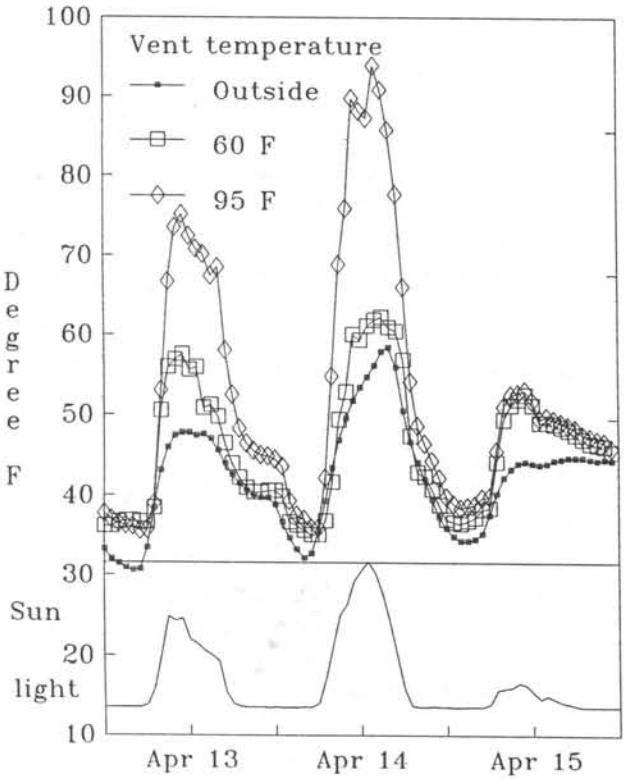

Figure 2. Air temperatures on April 13th through 15th 1989 in unheated high tunnels ventilated at 60F and 95 F compared to that outside.

ventilation limit of 95F before noon (Figure 2). The tunnel whose doors opened at 60F was cooler, but even with ventilation, the air in the tunnel was warmer than that outside. On cloudy days, when the doors remained closed, temperatures in the two tunnels were similar, a few degrees warmer than outside.

The tunnel ventilated at 95F (warm tunnel) achieved an average daytime temperature of 73 to 77F on 12 days in April and on 21 days in May. This is the optimum temperature for rapid ripening of tomato (Wolf et al 1986). Thus, this tunnel achieved an optimum daytime temperature during more than half the days in spring. By the second half of May, the tunnel ventilated at 60F (cool tunnel) regularly achieved this optimum daytime temperature. In contrast, the air outside was as warm on only one day before June 1. An examination of daily temperature records in April and May indicated daytime temperatures were related to the number of hours during each day that the house was vented. A rule of thumb is given below for the number of hours of ventilation needed to give optimum growth of tomato.

At night in spring, air in the tunnels cooled to within a degree or two of that outside. There was little residual warmth from the heat trapped in the tunnels during the day. During mid-April, when the first flower clusters were setting fruit, minimum night temperatures averaged 40F and on three nights in April the minimum temperature in the tunnels was 35F. Plants were often sprinkled during

the night for frost protection. Thus, a high tunnel that remained closed until it warmed to 95F achieved the optimum day temperature for tomato growth. However, the day-to-night variation in temperature was much greater than that normally experienced by plants grown outside.

During the day, the average temperature of soil in pots reached or exceeded 77F on 13 days in April and 19 days in May. In contrast, soil in level ground was about 52F in early April rising to 73F by June 1. Potted soil in the warm tunnel was considerably warmer than that in the cool tunnel with maximum temperature often exceeding 86F. At night, temperature of the soil in pots gradually cooled to that of the air. Thus, day to night variation of soil in pots was about 40F. This was similar to the variation in temperature of air in the tunnel ventilated at 95F, but greater than that in the tunnel ventilated at 60F. Temperature of soil in pots lagged behind that of the air by several hours. Again, planting in pots achieved an optimum soil temperature for tomato growth but at the expense of a great day-to-night temperature variation.

In the fall, the tunnel whose doors opened when the air warmed to 95F, maintained average daytime temperatures above 68F until late October, but at the expense of adequate ventilation. The doors of the tunnel ventilated at 60F were open most days during the fall, and daytime temperatures were 7F less than in the warm tunnel. At night the temperature in the tunnels was up to 5F warmer than outside, because of the warm soil and the large plant biomass. In conjunction with overhead sprinkling, both tunnels protected plants from frost when temperatures outside fell to 20F.

Tomato production in warm and cool tunnels in spring 1989

In 1989, tomatoes from April 3 transplants in the warm tunnel began ripening around June 5. Production in the cool tunnel began around June 21. Production outside did not begin until July 7. Thus, an unheated tunnel ventilated at 95F produced tomatoes 35 days earlier than was possible outside (Table 1). Plants in pots yielded no earlier than those in level ground. Plants in level ground had faster production than those in pots and by July 14 they yielded 30% more ripe fruit (Table 3). Plants in level ground produced larger fruit, as well as a greater number of fruit than plants in pots. Plants in the cool tunnel produced fewer but larger fruit than plants grown in the warm tunnel. Plants grown outside produced larger fruit than any treatment within the tunnels.

Tomato production in warm and cool tunnels in fall 1989

A fall tomato crop was produced in 1989 from July 14 transplants in the two tunnels. During the fall, tomatoes planted in level ground in the tunnel ventilated at 60F had the greatest yield, largest fruit, and highest percentage of marketable fruit (Table 3). Ventilation at 95F reduced yield, size and quality of fruit from plants grown in level ground. Plants grown in pots had lower yield than those grown in level ground in each tunnel, and size and quality were reduced in the cool tunnel.

High tunnels extended tomato production by more than a month at the beginning and at the end of the normal growing season in 1989. Ventilation had a large effect on yield, earliness and fruit size. The warmth from less ventilation was beneficial in spring, but nearly continuous ventilation was best for fall production of tomato.

Plants in level ground always yielded more than those in pots. This was attributed to the hot soil in pots during the day. This could have been alleviated by using larger pots, white or reflective pots, or shading the pots. Some growers may need to plant in pots to prevent soil-borne diseases that can not be controlled other than by fumigation or moving the high tunnel.

Effect of planting date on tomato production in spring 1990.

In 1990, planting date was the most critical factor for production of tomato in unheated high tunnels (Table 1). The earliest transplants ripened earliest. Tomatoes from the April 3 transplants of EARLY GIRL in a tunnel ventilated at 86F, began ripening on June 7. This was a full 6 weeks earlier than that of May 1 transplants outside (Tables 4, 5 and 6). Later planting resulted in later production. Tomatoes from April 17 and May 1 transplants grown in the tunnel ventilated at 86F, began ripening on June 20 and July 4, respectively (Figure 3). Production began 64 days after transplanting in each case. However, the seedlings were different ages at transplanting, 7, 6 and 5 weeks, respectively.

There were problems associated with planting as early as April 3. In each tunnel, the tomato plants had spindly stems and smaller leaves than those planted later. Despite watering with a complete fertilizer solution, the plants lacked nutrients, especially nitrogen, within 2 weeks of transplanting. Reduced yield and fruit size were obvious disadvantages of early planting (Table 1). The April 3 transplants yielded less than 6 pounds per plant after 7 weeks of picking, whereas the April 17 and May 1 transplants yielded 9 or more pounds (Tables 4, 5 and 6). The average weight per tomato picked from April 3 transplants of EARLY GIRL was 3.5 oz., less than that of 4.3 oz. for the April 17 and May 1 transplants. A mid-April planting date may be the best compromise between early ripening and high yield.

In several respects the three tomato cultivars grown in this trial responded similarly to the environment in the high tunnels in spring. For each cultivar, tomatoes in the tunnel ventilated at 86F ripened first and the April 3

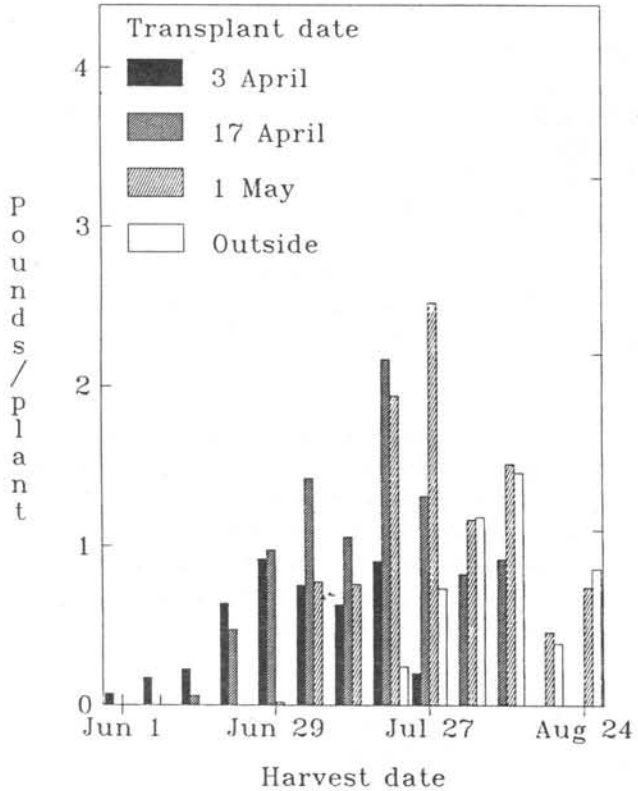

Figure 3. The yield per week in spring 1990 of ripe tomatoes from EARLY GIRL in a high tunnel ventilated at 86F when transplanted on April 3 and 17 and May 1, compared to plants transplanted on May 1 outside.

planting yielded far less than later plantings. The cultivars did differ in yield characteristics. EARLY CASCADE produced the smallest fruit (Table 5), and fruit size did not increase with later plantings, as it did for EARLY GIRL and FIRST LADY. Although the first fruit ripened on similar dates for the three cultivars, for April 3 transplants, the date of initial ripening varied by 2 weeks after transplanting on May 1. EARLY CASCADE ripened first and FIRST LADY ripened last, when transplanted on May 1 (Tables 5 and 6).

Ventilation of high tunnels to achieve optimum temperatures in spring

In each planting, the earliest and greatest yield came from a tunnel ventilated at 86F. More ventilation retarded ripening (Figure 4). April 3 transplants grown in the tunnel ventilated at 58F ripened a month later than those in the tunnel ventilated at 86F. Ventilation at 100F was most detrimental later in spring. Ripening of May 1 transplants of FIRST LADY was delayed by a week in a tunnel ventilated at 100F compared to 86F. Ventilation had no consistent effect on fruit size or quality.

A simple rule was derived to determine how many hours a day a high tunnel should be ventilated to achieve the optimum ventilation temperature of 86F, based on hourly observations of air temperatures inside the high tunnels. Ventilation was necessary on sunny days when the temperature outside was warmer than 50F. The duration of ventilation increased as spring progressed: about 3 hours of ventilation was necessary in early April, from 11 a.m. to 2 p.m., increasing to 5 hours in early May, from 10 a.m. to 3 p.m., and to 7 hours in early June, from 9 a.m. to 4 p.m. By mid-June high tunnels should have the end doors removed to maximize ventilation. On warm days, or days without wind, tunnels should be ventilated a few more hours. On partly cloudy days they should be ventilated less. In the fall, continuous ventilation throughout the day was preferred, except on days that were cooler than 50F or windy.

Effect of planting date on tomato production in fall 1990.

Planting date was also the most critical factor for fall production of tomato in 1990. Each 2-week delay in transplanting delayed ripening by 3 to 4 weeks (Figure 5). In fact, tomatoes from the August 23 transplants grown in

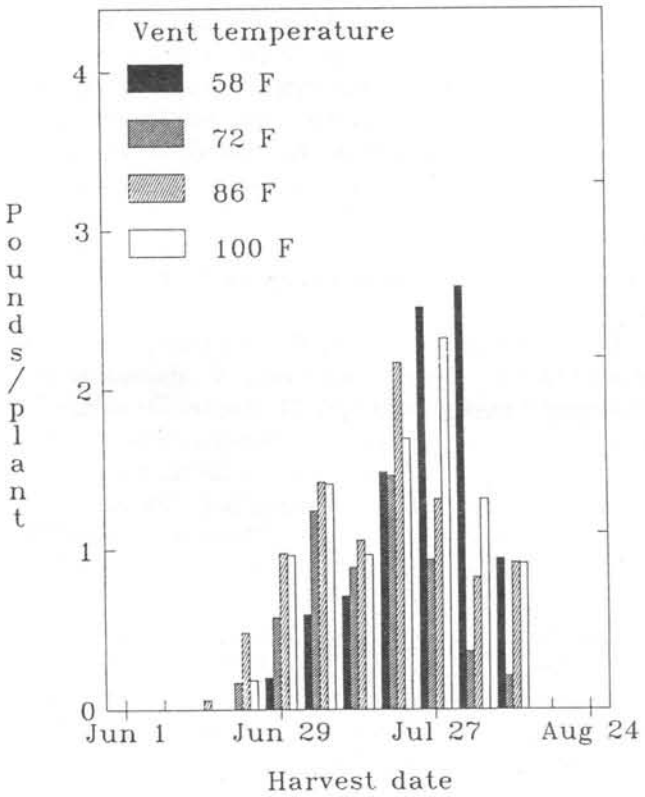

Figure 4. The yield per week in spring 1990 of ripe tomatoes from EARLY GIRL transplanted on April 17 into high tunnels ventilated at 58, 72, 86, or 100F.

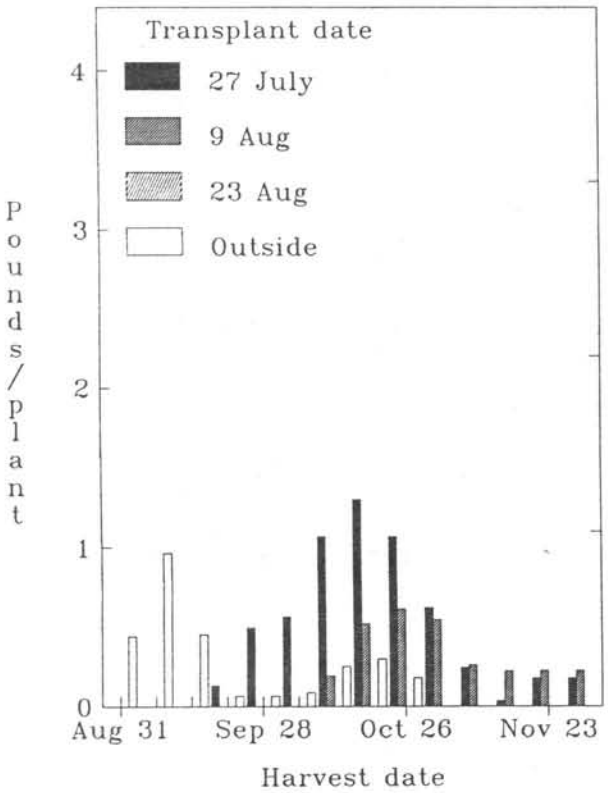

Figure 5. The yield per week in fall 1990 of ripe tomatoes from EARLY GIRL in a high tunnel ventilated at 58F when transplanted on July 27 and August 9 and 23, compared to plants transplanted outside on May 1.

the tunnel ventilated at 58F never ripened. Each planting had an initial burst of production for several weeks. A much slower rate of picking followed that was probably limited by low sunlight and cool temperature late in the fall. Total yields were reduced dramatically when planting was delayed (Tables 4, 5 and 6), suggesting a greater benefit from earlier planting. However, planting on July 15, 1989 resulted in the bulk of production in September, in direct competition with field production. A late July planting in unheated high tunnels may be the best compromise between high yield and timing production to follow that of field grown plants.

In the fall, the quality of fruit produced in tunnels was better than that produced outside, but it was worse than the quality produced in the spring. However, tomatoes produced in the fall were much larger than in the spring. In all plantings for fall production, reducing ventilation to achieve warm days reduced marketable percentage and fruit size (Tables 3, 4 and 5). Fruit also ripened later in the tunnel ventilated at 100F than in tunnels ventilated at 72 or 86F. When transplanted on July 27, plants in the tunnel ventilated at 58F yielded the most, and the fruit size and quality were significantly better than in the warmer tunnels. Thus, nearly continuous ventilation was optimum for fall production of tomato in 1990, as in 1989. FIRST LADY gave the best yields and largest fruit when planted on July 27. In later plantings, all cultivars had similar yields. EARLY CASCADE had the best fruit quality but FIRST LADY showed fewest green shoulder symptoms.

Summary of the effect of planting date over three years

Table 1 summarizes the production of EARLY GIRL, a tomato cultivar grown in high tunnels and outside over 3 years. In general, transplanting into high tunnels in spring resulted in much earlier ripening and higher yields with better quality than when grown outside. However, transplanting as early as April 3 in 1989 and 1990 resulted in poor yields and small fruit. Transplanting in summer for fall production resulted in lower yields and worse quality than in spring, but the tomatoes were bigger.

Disease, insect and physiological problems

Green shoulder or uneven ripening was the most common defect of tomatoes in unheated tunnels. In Tables 4, 5 and 6, the fraction of marketable fruit includes those with green shoulder, as reported in earlier trials, and the green shoulder percentage corresponds to otherwise marketable fruit with more than 5% of the skin surface exhibiting green shoulder. In more severe cases this green area had a clear demarcation line and covered 25 to 50% of the fruit surface. In less severe cases, the green area corresponded to one or more oval areas on the shoulder with no clear demarcation. In 1990, the severity of green shoulder was less than for the earliest fruit picked in 1989. When grown in high tunnels in 1990, green shoulder was not related to planting date, ventilation temperature, or cultivar. When planted outside on May 1, only 5 to 8% of the fruit had this symptom. Uneven ripening may be related to a large day-to-night variation in temperature of the fruit and to a lack of shading of the fruit from solar radiation (Lipton, 1970). Because the amount of ventilation had no effect on the occurrence of green shoulder, the temperature at night, and not during the day, may have caused this disorder. Tomatoes did not ripen unevenly after transplanting on May 1, 1988 in an unheated tunnel. These plants were not exposed to nights as cold as in April 1989 or April and May 1990. A means to prevent green shoulder would improve the quality of tomato grown in unheated shelters.

Except for this defect, quality of tomatoes produced in the tunnels generally exceeded that produced outside. No fungicides or insecticides were applied in 1990. In spring, insects were not a problem and plants showed few signs of disease. An exception was the tunnel ventilated at 72F in the spring of 1990, where some blocks of plants were infected with verticillium wilt. Several plants died by the

Table 2. Yield summary statistics for tomato grown in 1988.

Cultivar/ Transplant Date	Treatment	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight
EARLY GIRL					
May 1	High tunnel	Jun 28	29.4	3.2	80%
Apr 20	Row Cover	Jul 17	16.6	3.6	71%
Apr 20	Outside	Jul 21	11.4	3.9	65%
Jun 1	High tunnel	Jul 14	14.2	3.8	83%
May 23	Row Cover	Jul 25	13.4	3.5	76%
May 23	Outside	Jul 16	13.4	3.6	81%
TROPIC					
May 1	High tunnel	Jul 18	21.6	6.4	68%
Apr 20	Row Cover	Aug 2	13.9	7.6	51%
Apr 20	Outside	Aug 4	12.1	6.8	69%
Jun 1	High tunnel	Aug 2	13.9	7.6	51%
May 23	Row Cover	Aug 16	12.8	6.3	57%
May 23	Outside	Aug 2	11.2	6.9	58%
L.S.D. [a]		2.0 days	3.2	0.6	7%

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a Least significant difference at 5% probability level

Table 3. Yield summary statistics for EARLY GIRL tomato grown in unheated high tunnels 1989.

Transplant date	Ventilation Temp. °F	Root zone	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight
Apr 3	60	Ground	Jun 22	2.7	3.2	86%
	60	Pot	Jun 19	2.1	2.9	90%
	95	Ground	Jun 5	3.3	2.7	88%
	95	Pot	Jun 5	2.5	2.5	86%
May 1	Outside	Ground	Jul 7	14.2	3.7	87%
Jul 14	60	Ground	Sep 1	9.6	4.5	63%
	60	Pot	Aug 31	5.8	3.8	52%
	95	Ground	Sep 1	7.2	4.1	46%
	95	Pot	Aug 31	5.1	3.1	47%
L.S.D.			5.0 days	2.0	0.7	10%

Table 4. Yield summary statistics for EARLY GIRL tomato grown in unheated high tunnels in 1990.

Transplant date	Ventilation temp. °F	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight	Green shoulder by weight
Apr 3	58	Jul 3	4.1	3.2	64%	17%
	72	Jun 25	4.7	3.6	92%	48%
	86	Jun 7	5.7	3.5	93%	53%
	100	Jun 8	5.8	3.2	75%	28%
Apr 17	58	Jul 2	9.2	4.4	79%	38%
	72	Jun 26	7.2	3.4	75%	29%
	86	Jun 20	11.3	4.3	79%	35%
	100	Jun 21	9.8	3.7	75%	41%
May 1	58	Jul 19	9.7	4.0	71%	29%
	72	Jul 18	9.0	4.7	80%	45%
	86	Jul 4	12.2	4.3	74%	23%
	100	Jul 4	9.3	4.3	79%	41%
May 1	Outside	Jul 21	7.8	2.6	52%	8%
Jul 27	58	Sep 24	5.9	5.3	73%	18%
	72	Sep 20	3.3	3.9	70%	43%
	86	Sep 20	3.7	4.1	54%	38%
	100	Sep 22	4.4	4.4	52%	33%
Aug 9	58	Oct 15	2.8	5.6	76%	16%
	72	Oct 11	2.4	4.1	88%	50%
	86	Oct 11	3.4	4.9	74%	49%
	100	Oct 11	2.9	4.5	62%	24%
Aug 23	58					
	72	Nov 8	0.8	4.6	80%	5%
	86	Nov 14	1.1	4.9	65%	9%
	100	Nov 20	0.5	5.3	29%	14%
L.S.D.		4.8 days	2.4	1.1	25%	35%

Table 5. Yield summary statistics for EARLY CASCADE tomato grown in unheated high tunnels in 1990.

Transplant date	Ventilation temp. °F	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight	Green shoulder by weight
Apr 3	58	Jul 1	3.9	2.6	72%	17%
	72	Jun 25	4.2	2.7	86%	41%
	86	Jun 10	7.4	2.9	87%	26%
	100	Jun 10	5.9	2.1	70%	31%
Apr 17	58	Jun 30	9.8	2.7	75%	72%
	72	Jun 23	6.5	2.4	78%	39%
	86	Jun 22	12.2	3.2	87%	43%
	100	Jun 22	8.5	2.2	65%	23%
May 1	58	Jul 11	11.9	3.1	81%	28%
	72	Jul 1	3.7	1.8	65%	20%
	86	Jun 30	10.9	2.9	92%	40%
	100	Jul 3	7.9	2.7	74%	24%
May 1	Outside	Jul 19	4.7	2.0	68%	5%
Jul 27	58	Sep 23	5.4	3.7	92%	28%
	72	Sep 19	3.5	3.0	80%	32%
	86	Sep 22	4.6	4.6	53%	33%
	100	Sep 21	5.1	3.4	79%	35%
Aug 9	58	Oct 15	3.1	4.6	92%	15%
	72	Oct 9	3.4	3.3	69%	21%
	86	Oct 9	3.6	3.6	80%	42%
	100	Oct 11	3.5	3.3	75%	13%
Aug 23	58					
	72	Nov 5	1.0	2.7	93%	2%
	86	Nov 2	1.4	3.6	88%	6%
	100	Nov 17	0.5	4.1	87%	4%
L.S.D.		4.8 days	1.9	0.8	22%	35%

Table 6. Yield summary statistics for FIRST LADY tomato grown in unheated high tunnels in 1990.

Transplant date	Ventilation temp. °F	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight	Green shoulder by weight
Apr 3	58	Jul 1	2.5	2.9	70%	6%
	72	Jun 24	4.1	2.9	80%	48%
	86	Jun 18	7.2	3.9	87%	35%
	100	Jun 16	6.3	3.1	76%	25%
Apr 17	58	Jul 1	7.7	3.6	70%	25%
	72	Jun 27	5.0	2.8	73%	47%
	86	Jun 20	12.0	3.8	85%	34%
	100	Jun 22	11.1	3.0	76%	37%
May 1	58	Jul 19	10.5	4.2	77%	25%
	72	Jul 9	8.8	4.0	83%	26%
	86	Jul 10	9.8	3.8	85%	35%
	100	Jul 17	8.3	3.6	81%	39%
May 1	Outside	Jul 23	8.7	2.9	55%	7%
Jul 27	58	Sep 26	6.7	5.5	75%	11%
	72	Sep 22	4.3	4.3	82%	54%
	86	Sep 25	6.3	4.9	51%	36%
	100	Sep 27	5.9	4.6	57%	20%
Aug 9	58	Oct 20	2.3	6.4	75%	9%
	72	Oct 13	3.4	5.1	84%	27%
	86	Oct 15	3.3	5.0	60%	27%
	100	Oct 14	2.9	4.4	38%	7%
Aug 23	58					
	72	Nov 20	0.6	5.6	38%	0%
	86	Nov 18	0.6	4.6	54%	8%
	100	Nov 24	0.4	6.0	23%	0%
L.S.D.		5.6 days	1.6	1.0	31%	41%

Table 7. Yield summary statistics for CANAPE sweet pepper grown in 1988.

Transplant date	Treatment	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight
May 1	High tunnel	Jul 24	4.3	2.8	91%
Apr 20	Row Cover	Jul 25	2.9	2.5	84%
Apr 20	Outside	Aug 6	2.7	3.2	93%
Jun 1	High tunnel	Aug 11	3.1	2.5	75%
May 23	Row Cover	Aug 15	2.9	2.5	76%
May 23	Outside	Aug 5	2.3	3.1	90%
L.S.D.		7 days	1.1	1.0	21%

Table 8. Yield summary statistics for sweet pepper grown in unheated high tunnels in 1989.

Cultivar/ Transplant date	Ventilation Temp. °F	Root zone	First ripe fruit	Yield lb/plant	Size oz/fruit	Marketable by weight
GOLDEN BELL						
Apr 3	60	Ground	Jul 6	1.0	2.7	17%
	95	Ground	Jul 4	1.2	2.7	20%
May 1	Outside	Ground	Aug 9	1.7	5.2	88%
Jul 14	60	Ground	Sep 11	2.0	4.1	48%
	60	Pot	Sep 11	1.7	3.3	69%
	95	Ground	Sep 9	2.5	4.2	63%
	95	Pot	Sep 9	1.6	3.7	73%
LINCOLN BELL						
Apr 3	60	Ground	Jul 12	0.9	3.1	0%
	95	Ground	Jul 10	1.6	3.8	4%
May 1	Outside	Ground	Aug 2	2.3	5.6	81%
Jul 14	60	Ground	Sep 15	2.1	4.9	41%
	60	Pot	Sep 13	2.0	3.7	64%
	95	Ground	Sep 17	2.3	5.0	44%
	95	Pot	Sep 16	2.2	4.2	67%
L.S.D.			5 days	0.7	0.8	23%

end of picking. This reduced the yield and fruit size from this tunnel, as seen in Tables 4, 5 and 6. The plantings for fall production were affected less, but they grew slowly and produced small fruit. Late in the fall of 1989 and 1990, early blight developed in all the tunnels. Symptoms were most severe in November in tunnels with little ventilation. White fly populations were heavy early in the fall but not later. In the fall, some tomatoes were eaten by fall armyworm, tomato fruitworm, and tomato hornworm, which decreased the percentage marketable. Tomatoes from the July 27 transplants that set fruit in mid-summer had more cracks than did those of other plantings.

Pepper production in a high tunnel compared to row cover in 1988.

In 1988, May 1 transplants of cultivar CANAPE in the high tunnel ripened at the same time as April 21 transplants grown outside for 2 months under row cover (Table 7). Peppers ripened about 2 weeks earlier than when grown outside without row cover. Yields were greatest for plants grown in the tunnel. Peppers from plants grown outside were larger, but the total yield was less.

Compared to use of row covers, tunnels were not as promising for early sweet pepper production as they were for tomato. Planting under row cover advanced early production of pepper by up to 2 weeks (Gent 1989), so there was little difference in earliness of production in a tunnel compared to using row cover.

Pepper production in warm and cool tunnels in spring 1989

In 1989, the two sweet pepper cultivars, GOLDEN BELL and LINCOLN BELL, transplanted on April 3 into the tunnel ventilated at 95F began production on July 5 and 11, respectively (Table 8). The two cultivars ripened on similar dates in the tunnels ventilated at 60F. This was 4 and 3 weeks earlier than production of May 1 transplants outside. Compared to plants grown outside, high tunnels accelerated ripening of pepper less than tomato, and warm days resulting from less ventilation had little effect on ripening. In spring, peppers produced in the tunnels weighed less than those produced outside. In particular, the first peppers to ripen were parthenocarpic, small and lacking seeds. Unmarketable peppers were damaged by corn borer or were too small.

Pepper production in warm and cool tunnels in fall 1989

When transplanted on July 14, 1989 for fall production, GOLDEN BELL began to ripen about September 10 and LINCOLN BELL began to ripen on September 16. Production continued until late November. In contrast to the results with tomato, peppers yielded more when grown in a tunnel ventilated at 95F than at 60F. The weight per fruit in the fall was larger than that in the spring and fruit quality was improved (Table 8). A greater percentage of peppers were marketable when grown in pots, but greater yields and larger fruit were produced by plants in level ground. In the fall, most of the unmarketable peppers were damaged by corn borer. Otherwise, the plants were healthy and produced peppers of good quality. Thus, unheated high tunnels had more utility for prolonging pepper production in the fall than they did for accelerating earliness in spring.

ECONOMIC ANALYSIS

The extra costs associated with producing tomatoes in an unheated tunnel were about $450 for hoops, $50 for lumber, $120 for the plastic cover, and 50-man hours to set up a 15 x 50 foot tunnel. Only the plastic, which is rated for a 3-year life, would have to be replaced at regular intervals. The extra income from this cultural practice would derive from the high retail price of native tomatoes sold in June and July. A 15 x 50 foot tunnel containing 120 plants should produce 6 pounds of fruit per plant between mid-June and mid-July. During this period wholesale prices are about $1.50/pound (Figure 6), or $1.00/pound more than the price later in the season.

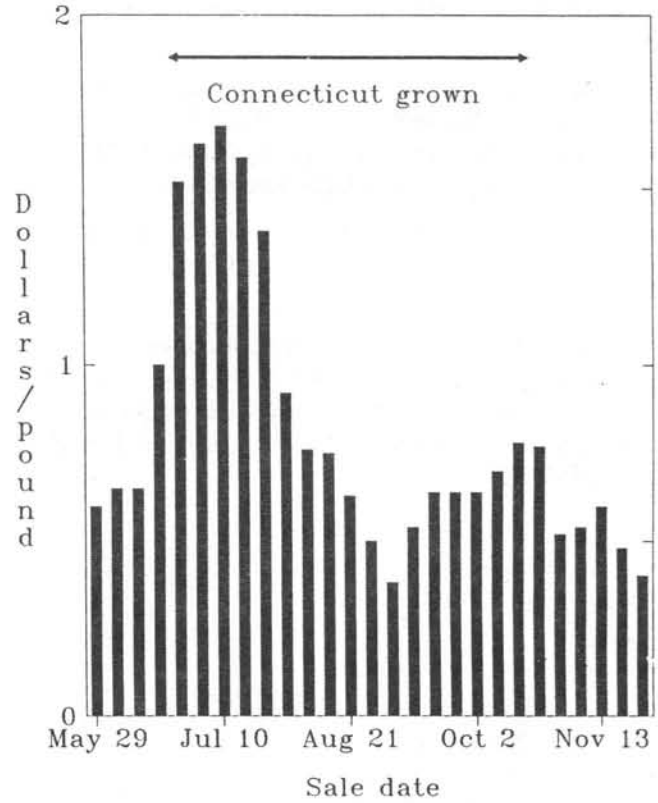

Figure 6. The wholesale price of tomatoes at the Hartford market by week in 1990 as reported in the Connecticut Market Bulletin.

Consequently the extra income from production in a high tunnel would be $720. Thus, an unheated high tunnel should pay for itself in a year or two, based on these wholesale prices. In fact most growers interested in early production sell produce at their own retail stands. It may be of greater benefit to them that native produce is available earlier and the retail stand can be opened for a longer period in the summer. Although the retail prices of red and yellow peppers are higher than for tomato ($2 to $3/pound), the yield is substantially less, about 2 pounds/plant in July and early August. Thus, the economic benefit of production of ripe peppers in a high tunnel would be less than that for tomato.

A heated greenhouse would provide more control of temperature than unheated high tunnels. This would allow earlier and higher quality production than can be achieved in high tunnels. However, the cost of construction and operation of a heated greenhouse and the ramifications in terms of zoning regulations may make unheated high tunnels the preferred alternative for early production of tomato and pepper in Connecticut.

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