Research Reports

Evaluation of a Manual Energy Curtain for Tomato Production in High Tunnels

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ADDITIONAL INDEX WORDS. **air and soil temperature, daily light integral, growing degree days, relative humidity**

SUMMARY. **The impact of a manually operated energy curtain on the recorded nighttime inside air and soil temperatures, relative humidity (RH), and daily light integrals during early-season high tunnel tomato (*Lycopersicon esculentum*) production in central and southern New Jersey were examined. Environmental data (air and soil temperatures, RH, and photosynthetically active radiation) were collected from late March through mid-May at two New Jersey locations for the 2004 and 2005 growing seasons. The continued impact of the early use of an energy curtain was further evaluated by collecting light, temperature, and marketable fruit yield data for the remainder of both growing seasons for one of the two experimental sites. Results showed that although the use of the curtain modestly increased early season nighttime inside air and soil temperatures and RH, the curtain reduced accumulated light integral during the first 7 weeks after transplanting and resulted in a marginal early yield increase. The main benefit of the energy curtain occurred on cold nights when an early season crop might otherwise be exposed to potentially damaging low temperatures.**

The high tunnel production system has recently received increased attention from fruit, flower, and vegetable growers who often have limited or no experience with greenhouse production (Lamont, 2004). High tunnel production is a relatively inexpensive method of extending the growing season and providing protection from inadvertent weather conditions. For tomato growers, the possibility of planting tomatoes in high tunnels for earlier harvests is attractive, because prices are usually higher when field production has not yet reached its harvest window. However, the earlier plants are started in high tunnel systems, the greater the chance of frost damage. Different management strategies can be used to prevent potential frost damage, including temporary standby heating systems, water tubes (Storlie et al., 1994), or covering the crop with an additional protective layer (e.g., rowcover material, plastic film, or energy curtain). The objective of this study was to evaluate the effectiveness of a highly transparent, manually operated energy curtain to reduce the chance of frost damage during early season plant growth and to promote plant growth and development through the remainder of the growing season.

Materials and methods

Early season trials with the commercial tomato cultivars 'Sunbrite' and 'Sunshine' were simultaneously conducted in New Brunswick [Horticultural Research Farm 3 (HF3)] and Centerton [Rutgers Agricultural Research and Extension Center (RAREC)], a central and southern New Jersey location, respectively. At both locations, two identical 17-ft-wide by 36-ft-long high tunnels (Ledgewoods Farms, Moultonboro, NH) were used. The tunnels were covered with a 4-year, single-layer, no-drip, infrared-blocking polyethylene greenhouse film [6 mil thick (model GT IR/AC; Green.Tek, Edgerton, WI)]. Additional information about high tunnel construction

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
100	bar	kPa	0.01
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
3.7854	gal	L	0.2642
2.5400	inch(es)	cm	0.3937
25.4000	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

and operation were described in Lamont et al. (2002), Lamont and Orzolek (2003), Jett et al. (2004), and Reiss et al. (2004).

In 2004 and 2005, the tomato seedlings were transplanted into the tunnels on 25 and 26 Mar. and 28 and 29 Mar. for the RAREC and HF3 locations, respectively. In 2004, each of the four beds in each tunnel was covered with differently colored plastic mulch (red, green, black, and clear). In 2005, each of the four beds was covered with black plastic mulch, because the 2004 results showed no benefit of using one of the other colors (data not shown). The average distance between the centers of the beds was 40 inches, whereas the distance between the plants within a bed was 18 inches. This resulted in a plant spacing of 0.2 plants/ft^2 (excluding walkways along the sides and at the ends of the tunnels). Each bed was divided into two identical sections (≈15 ft long), each planted with eight experimental plants with a guard plant at the end of each bed and a guard plant separating each section (for a total of 19 plants per bed). In each of the bed sections, plants of one of the two cultivars were planted according to a randomized block design (Fig. 1). Plants were irrigated based on tensiometer readings [when the soil tension reached 40 kPa (model R; Irrometer Co., Riverside, CA)] by supplying municipal water through drip tape. Fertilizer was applied at the same rate 1 week after transplanting when the first fruit reached a size of 1 inch in diameter and again when the first fruit started to change color. A soluble fertilizer mixture [20N–8.7P–16.6K (Peter's Professional; The Scotts Co., Marysville, OH) at a rate of 826 g per tunnel amended with 10 g Solubor (US Borax, Valencia, CA) and dissolved in a 5-gal bucket filled with water] was injected into the irrigation water. As the plants grew, stakes and strings were used to keep the plants growing in an upright direction and to support the weight of the tomatoes. All plants were scouted weekly for insect infestations or disease development and sprayed according to standard recommendations (Garrison and Orton, 2006) when necessary.

At each location and only during the early stages of crop growth (from transplanting through 16 May), one of the tunnels was outfitted with a manually operated energy curtain (style XLS 10; Ludvig Svensson, Charlotte, NC) that was installed inside the tunnels (Fig. 2) and manually closed at the end of the day in an attempt to reduce the heat loss to the outside environment. The curtain material consisted of 4-mm-wide transparent polyester strips woven together with a polyester filament yarn. This particular curtain material was selected because the manufacturer claimed: 1) it had a high light transmission (85% and 78% for direct and diffuse light, respectively), and 2) it had respectable energy retention properties (47%) compared with the other types of curtain material that typically have varying amounts of

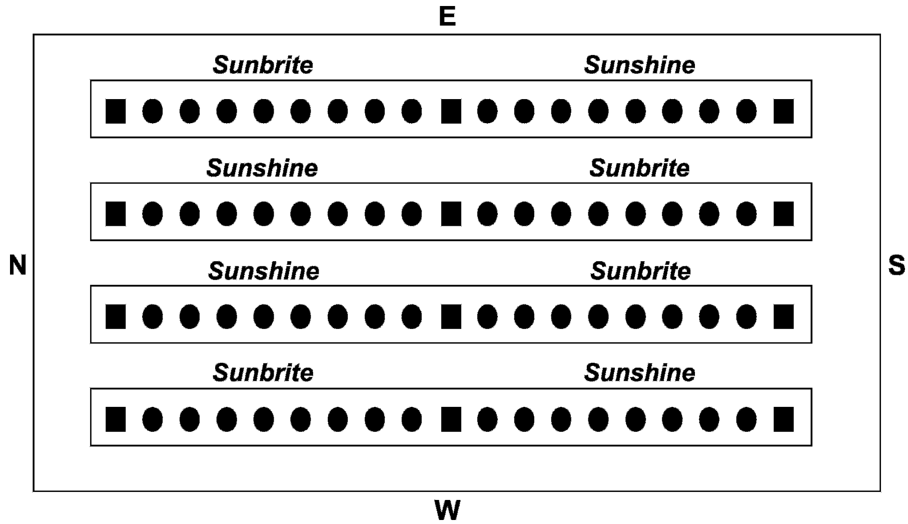

Fig. 1. Sketch of the high tunnel layout showing four beds containing 19 plants each [16 experimental plants (circles) and three guard plants (squares)]. The two tomato cultivars 'Sunbrite' and 'Sunshine' were randomly divided as indicated, each occupying half the length of a bed and separated by a guard plant (N, S, E, W = north, south, east, and west, respectively).

Fig. 2. Picture showing the installation of the (retracted) energy curtain inside the high tunnels. While closed, the curtain material was supported by four horizontal guide wires and enclosed the tomato crop on top and all four sides.

aluminum strips interspersed with the polyester strips. Because the curtains were operated manually, and usually at the start and end of the day (at ≈0800 and 1700 HR), they typically remained closed several hours of the day early in the morning and late afternoon and early evening when sunlight was present, but before or after they were repositioned. Using the selected curtain (XLS 10) material was thought to significantly reduce the negative impact a more typical energy curtain would have on the amount of available sunlight while still realizing significant energy retention. Curtain operation was stopped when minimum nighttime temperatures exceeded 60 °F (around mid-May). The operating strategies followed for the curtains and the rollup sides (for ventilation) are summarized in Table 1. Note that both temperature and relative humidity (RH) measurements were needed to implement these operating strategies. The target inside temperature was dropped at the onset of flowering in an attempt to reduce the RH, because high RH levels can have an adverse effect on pollination.

The environmental conditions inside and outside the tunnels were displayed and recorded with dataloggers (model 21X; Campbell Scientific, Logan, UT). At HF3, data were recorded using 1-min measurement averages, whereas 5-min averages were recorded at RAREC (where additional, nonrelated environmental data were recorded, necessitating the longer recording interval). To evaluate the impact of the energy curtain, only the time intervals between 2000 and 0600 HR during the 29 Mar. through 16 May time period were considered, ensuring the curtain was always closed during those time intervals.

Air temperature measurements were recorded using calibrated thermocouples [accuracy = ±1 °C (model EXPP-T-20; Omega Engineering, Stamford, CT)] placed in aspirated boxes. Soil temperatures were recorded using similar calibrated thermocouples buried 4 inches below the soil surface. The RH was recorded using calibrated RH sensors [accuracy = ±3% over the range 0% to 90% and ±5% over the range 91% to 98% (model Humitter 50U; Vaisala, Woburn, MA)] placed in the same aspirated boxes as the air temperature sensors. Light measurements were recorded with calibrated quantum sensors [accuracy = ±5%, measurement range = photosynthetically active radiation (*PAR*) 400 to 700 nm (model LI-190; LI-COR, Lincoln, NE)].

Inside and outside environmental conditions were continuously recorded through both growing seasons at both locations. The accumulated values for growing degree days (GDD) and light integral were determined starting on the day of transplanting. To calculate the GDD, the following equation was used (McMaster and Wilhelm, 1997):

$$GDD = \sum[(T_{max} + T_{min})/2 - 10] \quad [1]$$

where:

T_{max} = highest temperature recorded during a 24-h day (°C)

T_{min} = lowest temperature recorded during a 24-h day (°C)

Note: Before calculating Eq. 1, T_{max} and T_{min} were set at 10 °C when their measurements were less than 10 °C and at 30 °C when their measurements were more than 30 °C.

Starting late May (2004) or early July (2005), the tomato plants were harvested at least once per week (Fig. 3). Only fruit at the breaker stage or beyond was harvested. Harvested fruit was evaluated for salability (i.e., removal of culls) and saleable fruit was sized (data not shown). Yield data were reported as total yield per cultivar (kilograms) and per treatment (curtain or no curtain), because no individual plant data were recorded. The final harvest occurred in late August in both 2004 and 2005.

Results

Measurements of individual parameters (particularly the nighttime soil and air temperatures, RH, as well as the accumulated light level during the preceding daylight period) were averaged into single data points for each day (or measurement period). The average temperatures, RH, and integrated light levels over the 29 Mar. through 16 May time period are shown in Table 2.

For the 29 Mar. through 16 May time period, the potential correlation between the average (for the 2000 through 0600 HR time period) soil temperature inside the high tunnels and the amount of light (and thus energy) received during the preceding daylight hours was investigated using the following equation:

$$Tsoil = A \times (DLI) + B \quad [2]$$

where:

Tsoil = average nighttime (between 2000 and 0600 HR) soil temperature (°C) inside the tunnels measured at a depth of 4 inches (10.2 cm) below the surface of the beds

Table 1. High tunnel energy curtain and the rollup sides operating strategies implemented from the day of transplanting through 16 May during tomato trials in 2004 and 2005 at two different New Jersey sites.[z]

	Curtain
Night	If predicted minimum temperature less than 60 °F (15.6 °C), then close curtain.
Day	Open curtain when inside temperature greater than 60 °F.
After two cloudy days	Open curtain on third day when relative humidity (RH) greater than 80% and outside RH is lower.
	Rollup sides
Between transplanting and the onset of flowering	Start venting when inside temperature greater than 75 °F (23.9 °C).
	If inside temperature less than 75 °F and RH greater than 80%, then vent for up to 5 min at a time to dehumidify.
During and after flowering	Start venting when inside temperature greater than 65 °F (18.3 °C) in an attempt to keep the temperature in the 65 to 75 °F temperature range.
	If inside RH greater than 80%, then vent for up to 5 min at a time to dehumidify.

[z]These strategies were implemented manually between ≈0800 and 1700 HR (mostly at the start and end of the day, but occasionally adjustments were made during the day).

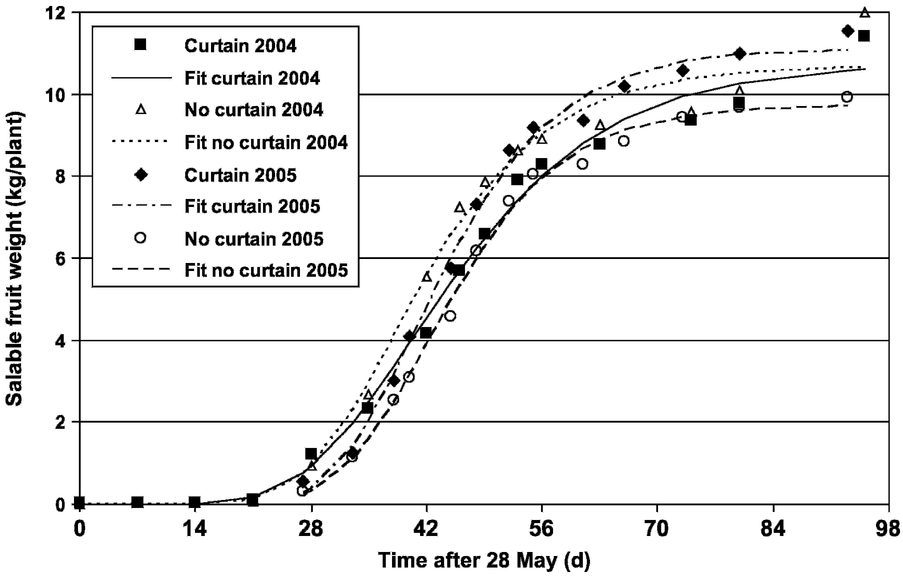

Fig. 3. Comparing Rutgers Agricultural Research and Extension Center, Centerton, NJ, tomato growth data (markers) from the 2004 and 2005 growing seasons based on whether a manually operated energy curtain was used (note that the data from each of the two tested cultivars were combined so that the graph only shows a possible curtain effect). The data were fitted (lines) using the Richards growth equation (Richards, 1959); 1 kg = 2.2046 lb.

DLI = outside daily light integral (mol·m^{-2}) accumulated during the preceding day

A = slope of the linear regression equation (°C·m^2·mol^{-1})

B = intercept and equal to the average minimum nighttime soil temperature during the 29 Mar. through 16 May time period (°C)

The values for the slope, intercept, and correlation coefficient of the correlation equations (Eq. 2) are shown in Table 3. Table 3 shows that the average minimum nighttime soil temperature measured at a depth of 4 inches (10.2 cm) below the surface of the beds was between 13 and 14 °C.

The trials at HF3 encountered significant problems during both growing seasons. In 2004, the crop sustained a severe infestation of white mold [*Sclerotinia sclerotiorum* (first symptoms observed on 2 June)], and in 2005, the crop was severely affected by drift from a chemical application (on 28 June) on a nearby research plot. Hence, fruit harvests from HF3 were not conducted. Tables 4 and 5 show a summary of the environmental and fruit harvest data collected at RAREC during both the 2004 and 2005 growing seasons.

Figure 3 compares harvest data and fitted growth curves for the RAREC data collected during the 2004 and 2005 growing seasons. The growth curves were fitted using the Richards growth equation (Richards, 1959). Harvest data from the two cultivars were combined so that only the effect of the energy curtain could be evaluated.

Discussion and conclusions

Although the data presented in Table 2 summarize the recorded environmental conditions (between 2000 and 0600 HR) in a very condensed form, and thus fail to show the instantaneous effect the energy curtain can have, they allow for some general conclusions for early season (29

Table 2. Average nighttime air temperature [Tair (inside an aspirated box)] and soil temperature {Tsoil [4 inches (10.2 cm) below the surface]}, relative humidity [RH (inside an aspirated box)] calculated for the 2000 to 0600 HR time period (with SD in parentheses), and accumulated light integral for the period 29 Mar. through 16 May during tomato trials in 2004 and 2005 at two different New Jersey sites.[z]

29 Mar.–16 May, 2000–0600 HR	HF3[y] 2004	HF3 2005	RAREC[w] 2004	RAREC 2005	Avg.	Change (%)
Tair, outside (°C)[x]	11.1 (1.5)	9.6 (1.9)	11.6 (1.5)	9.3 (1.8)	10.4 (1.7)	—
Tair, no curtain (°C)	12.4 (1.3)	10.2 (1.7)	12.7 (1.4)	9.8 (1.8)	11.3 (1.6)	+9
Tair, curtain[x] (°C)	13.7 (1.2)	12.0 (1.6)	14.5 (1.4)	10.7 (1.7)	12.7 (1.5)	+22
Tsoil, outside (°C)	11.7 (0.6)	11.2 (0.8)	13.6 (0.7)	12.8 (0.6)	12.3 (0.7)	—
Tsoil, no curtain (°C)	19.1 (1.2)	18.7 (1.3)	19.7 (1.3)	18.5 (1.3)	19.0 (1.3)	+54
Tsoil, curtain (°C)	19.3 (1.0)	19.3 (1.2)	20.4 (1.2)	19.0 (1.3)	19.5 (1.2)	+59
RH, outside (%)	76 (7.0)	71 (10.7)	81 (6.4)	79 (8.5)	77 (8.2)	—
RH, no curtain (%)	93 (2.2)	90 (4.2)	90 (5.4)	83 (4.6)	89 (4.1)	+16
RH, curtain (%)	97 (1.2)	89 (2.8)	90 (2.2)	90 (3.5)	92 (2.4)	+19
Light integral, outside[v] (mol·m^{-2})	1684	1925	1686	2069	1841	—
Light integral, no curtain[v] (mol·m^{-2})	1333	1468	1383	1433	1404	–24
Light integral, curtain[v] (mol·m^{-2})	1213	1296	1319	1401	1307	–29

[z]The terms "curtain" and "no curtain" refer to the tunnels with and without an energy curtain, respectively.
[y]HF3 = Horticultural Research Farm 3, New Brunswick, NJ; RAREC = Rutgers Agricultural Research and Extension Center, Centerton, NJ.
[x](1.8 × °C) + 32 = °F.
[w]Underneath the curtain.
[v]Accumulated during the daylight period immediately preceding the nighttime measurement window (2000 to 0600 HR) and summed over the 29 Mar. through 16 May time period.

Table 3. Values for slope, intercept, and correlation coefficient of the correlation equation (Eq. 2: Tsoil = A × (DLI) + B[z]; A = slope, B = intercept) for the 29 Mar. through 16 May time period during the 2004 and 2005 tomato trials at two different New Jersey sites.[y]

Location, yr [x]	Treatment	Slope ($°C·m^{-2}·mol^{-1}$)	Intercept (°C)[w]	R^2
HF3, 2004	Curtain	0.16	13.7	0.68
	No curtain	0.18	12.9	0.66
HF3, 2005	Curtain	0.16	13.5	0.50
	No curtain	0.15	13.3	0.50
RAREC, 2004	Curtain	0.21	13.5	0.58
	No curtain	0.21	12.6	0.56
RAREC, 2005	Curtain	0.13	14.0	0.52
	No curtain	0.12	13.9	0.45

[z]Tsoil = average nighttime soil temperature (°C) measured inside the tunnels between 2000 and 0600 HR at a depth of 4 inches (10.2 cm) below the surface of the beds; DLI = outside daily light integral ($mol·m^{-2}$) accumulated during the preceding day.
[y]The terms "curtain" and "no curtain" refer to the tunnels with and without an energy curtain, respectively.
[x]HF3 = Horticultural Research Farm 3, New Brunswick, NJ; RAREC = Rutgers Agricultural Research and Extension Center, Centerton, NJ.
[w](1.8 × °C) + 32 = °F.

Mar. through 16 May) tomato production in high tunnels located in central and southern New Jersey:

1. The use of an energy curtain inside a high tunnel increased the inside nighttime air temperature on average by 2.3 °C (or 22%) compared with the outside nighttime air temperature. A tunnel without an energy curtain maintained an inside nighttime air temperature that was 0.9 °C (or 9%) higher compared with the outside nighttime air temperature.

2. The use of an energy curtain inside a high tunnel increased the inside nighttime soil temperature on average by 7.2 °C (or 59%) compared with the outside nighttime soil temperature. A tunnel without an energy curtain maintained an inside nighttime soil temperature that was 6.7 °C (or 54%) higher compared with the outside nighttime soil temperature.

3. The use of an energy curtain inside a high tunnel increased the inside nighttime RH on average by 15% (for an increase of 19%) compared with the outside nighttime RH. A tunnel without an energy curtain maintained an inside nighttime RH that was 12% (for an increase of 16%) higher compared with the nighttime outside RH.

4. The use of an energy curtain inside a high tunnel decreased the inside accumulated light integral on average by 534 $mol·m^{-2}$ (or 29%) compared with the outside accumulated light integral. A tunnel without an energy curtain accumulated an inside light integral that was 437 $mol·m^{-2}$ (or 24%) lower compared with the outside accumulated light integral.

Given these conclusions and the fact that 1) only a modest increase in early tomato yield (because the earlier harvests are relatively small when expressed in kilograms of fruit harvested per plant) was observed when comparing the curtain and no-curtain treatments, 2) pulling the curtain twice a day requires labor, and 3) the use of a curtain further reduces the amount of light available for crop production, it is not clear the benefits of the curtain outweigh the costs. Of course, the curtain will be very useful on clear nights that result in a significant amount of radiation loss from inside the tunnel to the surrounding cold night sky. On such nights, the use of an energy curtain may well prevent serious damage to a crop potentially incited by low temperature exposure. It should be noted that this potential benefit of an energy curtain is dependent on the weather conditions during the preceding day(s); the benefit will be larger on a sunny day followed by a cold night compared with a cloudy day followed by a cold night because more energy will be stored in the (mulched) soil during the sunny day. Figure 4 shows an example from the RAREC location where in the early morning of 5 Apr. 2004, the outside air temperature dropped below freezing, the air temperature in the tunnel without a curtain dropped to 0 °C, and the air temperature in the tunnel with the curtain (underneath the curtain) did not drop below 2.0 °C.

High nighttime RH conditions were recorded during the 29 Mar. through 16 May time periods of both years and for both locations (Table 2). For both years, RAREC recorded the highest outside RH during this period but the lowest inside RH. One reason for this might be the observation that the wind speed at the RAREC location is generally higher than at HF3. However, wind speed measurements were not recorded during these trials. A higher wind

Table 4. Selected growing degree days [GDD (Eq. 1)] and accumulated light integral data since the day of transplanting (25 and 26 Mar. for 2004 and 2005, respectively) for the tomato trials conducted at the Rutgers Agricultural Research and Extension Center, Centerton, NJ.[z]

		GDD (°C)[y]			Light integral ($mol·m^{-2}$)		
Harvest	Date	Outside	Curtain	No curtain	Outside	Curtain	No curtain
Harvest 1	28 May 2004	442	667	626	2246	1743	1811
Harvest 5	25 June 2004	737	978	935	3355	2596	2634
Harvest 7	9 July 2004	917	1164	1122	4063	3136	3154
Harvest 15	31 Aug. 2004	1599	1861	1820	5932	4565	4576
Harvest 1	24 June 2005	574	892	853	3830	2625	2672
Harvest 5	12 July 2005	826	1151	1110	4572	3161	3205
Harvest 13	29 Aug. 2005	1531	1869	1831	6649	4610	4630

[z]The terms "curtain" and "no curtain" refer to the tunnels with and without an energy curtain, respectively.
[y](1.8 × °C) + 32 = °F.

Table 5. Selected accumulated salable fruit harvest weight (kg/plant) for the 2004 and 2005 tomato trials conducted at the Rutgers Agricultural Research and Extension Center, Centerton, NJ.[z]

		Sunbrite (kg/plant)[y]		Sunshine (kg/plant)	
Harvest	Date	Curtain	No curtain	Curtain	No curtain
Harvest 1	28 May 2004	0.0	0.0	0.1	0.0
Harvest 5	25 June 2004	1.2	1.0	1.3	0.9
Harvest 7	9 July 2004	4.1	5.4	4.2	5.7
Harvest 15	31 Aug. 2004	12.3	13.1	10.5	10.9
Harvest 1	24 June 2005	0.2	0.1	0.9	0.5
Harvest 5	12 July 2005	4.3	3.7	7.2	5.5
Harvest 13	29 Aug. 2005	11.0	10.2	12.0	9.6

[z]The terms "curtain" and "no curtain" refer to the tunnels with and without an energy curtain, respectively.
[y]1 kg = 2.2046 lb.

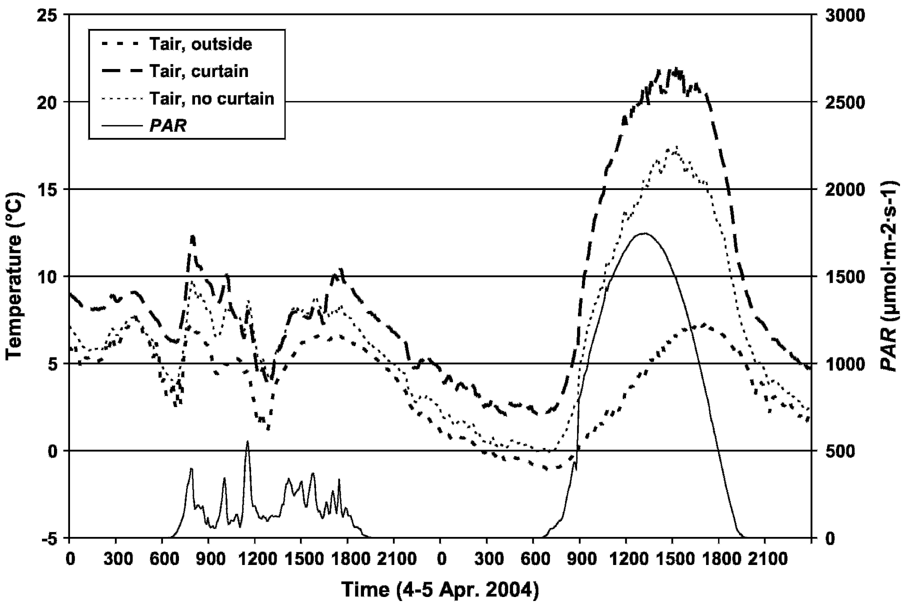

Fig. 4. Air temperatures (Tair) and instantaneous light levels (photosynthetically active radiation, 400 to 700 nm) for 4 to 5 Apr. 2004 for the Rutgers Agricultural Research and Extension Center, Centerton, NJ, location. The air temperatures were measured inside an aspirated box that was located either outside or inside the tunnels. One of the tunnels was outfitted with a manually operated energy curtain and in this tunnel, the nighttime air temperature was measured underneath the closed curtain. On both days, the curtain was opened ≈0800 HR and closed ≈1700 HR (1.8 × °C) + 32 = °F.

speed would result in a higher infiltration rate that could explain the lower RH measurements. Table 2 also shows that the inside nighttime RH at both locations was higher in 2004 compared with 2005. The same trend was observed for the outside RH, but the increase was not as large. Possible explanations for the high inside nighttime RH measurements are that 1) the curtain material was new in 2004 making it somewhat tighter compared with 2005 when it was reused for a second year, or 2) possible small differences in the tunnel operation (e.g., implementation of curtain closing procedure, irrigation scheduling).

The low correlation coefficients found for Eq. 2 (Table 3) indicate that the data varied significantly and that likely other factors contributed to the resulting average nighttime soil temperatures. These factors likely included the management strategy and its implementation for the rollup sides used for ventilation as well as local radiation and wind conditions at night.

The growth curves for 2005 fit the corresponding harvest data better than the curves for 2004 (Fig. 3). In particular, the final three saleable fruit yield measurements for 2004 were less well simulated using the Richards equation. Nevertheless, the simulated growth curves appear to reasonably capture the trends that can be derived from the yield measurements. From the harvest data and the corresponding growth curves, it appears that the use of the curtain did slightly increase the accumulated saleable fruit yield during the earlier part of the harvest window. However, final accumulated fruit yield did not appear to differ much in 2004, whereas in 2005, the use of the curtain did appear to result in an increase in accumulated fruit yield per plant.

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