Summer Production of Lettuce, and Microclimate in High Tunnel and Open Field Plots in Kansas

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ADDITIONAL INDEX WORDS. *Lactuca sativa*, bolting, wind speed, air temperature, soil temperature, leaf temperature, reference crop evapotranspiration

SUMMARY. High tunnels have been shown to be a profitable season-extending production tool for many horticultural crops. Production of cool-season vegetables during the hot summer months represents a challenge to market growers in the midwestern United States. Two experiments were conducted to investigate the microclimate and production of eight leaf lettuce (*Lactuca sativa*) cultivars in high tunnels and open fields, using unshaded and shaded (39% white shadecloth) tunnels in Summer 2002 and 2003, respectively. Wind speed was consistently lower in high tunnels with the sidewalls and endwalls open. An unshaded high tunnel resulted in an increase of daily maximum and minimum air temperatures by ≈ 0.2 and 0.3 °C, respectively, in comparison with the open field. In contrast, daily maximum air temperature in a shaded high tunnel decreased by 0.4 °C, while the daily minimum air temperature was higher than that in the open field by 0.5 °C. Using high tunnels did not cause a marked change in relative humidity compared with the open field. When using shadecloth, the daily maximum soil temperature was lowered by ≈ 3.4 °C and the leaf surface temperature was reduced by 1.5 to 2.5 °C. The performance of lettuce during summer trials varied significantly among cultivars. Unshaded high tunnels generally led to more rapid bolting and increased bitterness of lettuce compared with the open field. Lettuce grown in high tunnels covered by shadecloth had a lower bolting rate, but decreased yield relative to the open field. Based on our results, summer lettuce production would not be recommended in high tunnels or open fields in northeastern Kansas, although the potential of shaded high tunnels deserves further studies. Reference crop evapotranspiration (ET_0) was estimated from meteorological data on a daily basis using the FAO-56 method. The ET_0 was lowest in the shaded high tunnel and was the highest in the open field. Relatively lower ET_0 in high tunnels indicated a likely lower water requirement and therefore improved water use efficiency compared with the open field.

High tunnels are greenhouse-like structures that provide a protected environment (e.g., rain shelter, temperature moderation, and wind protection) for crop production throughout the year. Management of high tunnels differs considerably from that of greenhouses. High tunnels are typically covered by a single layer of plastic, with no permanent electrical service

or automated ventilation or heating system. Ventilation of the high tunnel is usually accomplished by manually rolling up the plastic sides. Drip irrigation is typically used to apply water and nutrients to crops grown in the ground in high tunnels (Wells, 1996; Wells and Loy, 1993).

In addition to their considerable potential for season extension, high tunnels can significantly improve crop yields and quality relative to the open field during the normal growing

season by providing favorable growing conditions (Wells, 2000; Wells and Loy, 1993). High tunnels have become a significant feature of intensive horticultural production systems in a number of places around the world (Jensen, 2000). As high tunnel research and education programs were developed in the northeastern United States (Both et al., 2007; Lamont et al., 2001, 2002, 2003), market farmers in the central Great Plains have been increasingly interested in profitable year-round vegetable production using high tunnels. The superior performance of high tunnels in the midwestern United States, where continental climates prevail, has been demonstrated in production of cut flowers (Upson, 1998), tomato (*Solanum lycopersicum*) (Jett, 2004), and strawberry (*Fragaria × ananassa*) (Kadir et al., 2006).

Early spring, late fall, and even winter production of cool-season leafy vegetables can be successfully achieved in high tunnels in temperate climates (Gent, 2002), but the potential for extended season production of cool season crops into the hot summer months is less recognized. During the hot summer months, cool-season vegetables can be grown under shaded conditions (Araki et al., 1999; Gao et al., 1996). Cool-season leafy vegetables show abnormal growth under high air and root temperatures. The optimum average daily temperature for field-grown lettuce is 18.5 °C, and the summer heat often results in bolting, tipburn, and unpleasant bitterness (Waycott and Ryder, 1993). Although heat-tolerant and slow bolt cultivars have been identified (Simonne et al., 2002), growing lettuce outdoors in the midwestern United States summer is always a challenge.

Practical systems for the warm season production of lettuce and

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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
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.0254	mil	mm	39.3701
0.4470	mph	m·s ⁻¹	2.2369
28.3495	oz	g	0.0353
6.8948	psi	kPa	0.1450
10.7639	W/ft ²	W·m ⁻²	0.0929
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

other leafy green vegetables would be of interest to market farmers because there is year-round demand for fresh salad greens. The objectives of this study were to compare the microclimate conditions between high tunnel and open field during hot summer seasons and to evaluate the potential of using high tunnels for warm-season lettuce production.

Materials and methods

HIGH TUNNELS AND EXPERIMENTAL SETUP. Six east-west oriented 32 × 20-ft high tunnels with 5-ft sidewalls (Stuppy, North Kansas City, MO) and six adjacent 32 × 20-ft field plots were established at the Kansas State University Horticulture Research and Extension Center (Olathe, KS). The tunnels were covered with a single layer of 6-mil K50 clear polyethylene film with ultraviolet protection (Klerks Plastic Product Manufacturing, Richburg, SC). The endwalls were open and the sidewalls were rolled up throughout the summer trials. At establishment in 2002, the six high tunnels were divided into three groups (blocks), and the two high tunnels in each block were randomly assigned for long-term organic or conventional management treatments. A similar setup was used in the field plots. Microclimate data were collected in 2002 when shade-cloth was not applied and drip irrigation was used for water and nutrient supply, and in 2003 when high tunnels were covered with 39% white woven shade-cloth (Pak Unlimited, Norcross, GA) and sprinkler irrigation was used.

MICROCLIMATE MEASUREMENTS. Sensors were installed in the central area of field and high tunnel plots. One field plot and the adjacent high tunnel were selected for the study of microclimate environment. Probes for wind speed, air temperature, and relative humidity (RH) were set at a height of 18 inches above the soil surface. Wind speed was measured with an RM Young wind sentry anemometer (Campbell Scientific, Logan, UT). The temperature and RH probes (CS500-L Vaisala 50Y, Campbell Scientific) were housed in RM Young six-plate gill solar radiation shields. Two thermocouples (Type T copper-constantan thermocouple wires; Omega Engineering, Stamford, CT) in each plot measuring

soil temperature were placed in the soil of central growing beds at 4 inches below the soil surface. Data were recorded using a datalogger (CR10X; Campbell Scientific) programmed to scan every 30 s and determine maxima, minima, and averages hourly. Thermocouples were connected to the datalogger via a 25-channel solid state multiplexer (AM25T; Campbell Scientific). Photosynthetically active radiation was measured using LI-190 Quantum Sensors (LI-COR Environmental, Lincoln, NE). Leaf surface temperature was measured using IR thermometers (model 100.3ZL; Everest InterScience, Tucson, AZ). These two measurements were taken on several days during the trials and representative data were used.

Reference crop evapotranspiration (ET_0) was estimated on a daily basis using the FAO-56 method, a form of the Penman-Montieth equation (Food and Agriculture Organization of the United Nations, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273.15} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)},$$

where R_n is net radiation ($W \cdot m^{-2}$), G is soil heat flux ($W \cdot m^{-2}$) (G is zero for 24-h calculations), Δ is slope of saturation vapor pressure curve at air temperature ($kPa \cdot K^{-1}$), γ is psychrometer constant ($kPa \cdot K^{-1}$), T is daily average air temperature ($^{\circ}C$), u_2 is wind speed at 2 m, e_s is saturation vapor pressure (kPa), and e_a is vapor pressure of air (kPa). Air temperature and RH at 18 inches above the soil surface were used in the calculations, while wind speed at 2 m was estimated based on the wind speed measured at 18 inches using the equation proposed by Campbell and Norman (1998). Data for solar radiation were collected from the weather station at Ottawa, KS (≈ 35 miles from Olathe, KS) because it was unavailable at the Olathe experiment station. For the irradiance inside the tunnels, a transmittance of 0.52 was used for shaded tunnels, and 0.91 was used for unshaded tunnels (estimated value provided by Klerk's Plastic Product Manufacturing).

LETTUCE CULTIVARS AND PLANTING. Lettuce cultivars Buttercrunch, Ermosa, Green Forest, Hus-sarde, Kalura, Salad Bowl, Simpson Elite, and Red Sails were grown during Summer 2002 and 2003. Seeds were provided by Johnny's Selected Seeds (Winslow, ME). All of the transplants were produced in the greenhouse using 200-cell Speedling flats (Speedling, Sun City, FL) with Premier promix (Premier Horticulture, Quakertown, PA). In 2002, lettuce cultivars were seeded on 3 July, transplanted on 29 and 30 July, and harvested on 27 and 28 Aug. Five plants of each cultivar were grown in one-row plots in beds that contained two rows at a spacing of 12 inches apart between rows and 8 inches apart within rows. During Summer 2003, seeds were sown on 29 May, and lettuce was transplanted on 8 July and harvested on 5 and 6 Aug. Plots consisted of 10 plants at the same spacing as in 2002. Based on soil tests before trials, preplant fertilization and

fertigation were applied and adjusted throughout the experiments (Zhao et al., 2007).

RATING OF BOLTING AND BITTERNESS. At harvest, plots were rated for bolting. Bolting was rated using a scale of 1 to 5, where 1 = no bolting, 2 = initial elongation, 3 = bud appearance, 4 = flower stalk development, 5 = full flowering. Bitterness was rated using a scale of 1 to 5, where 1 = no bitterness, 2 = slightly bitter, 3 = moderately bitter, 4 = bitter, 5 = very bitter. Bitterness was rated by consensus by three people at or immediately following harvest.

STATISTICAL ANALYSIS. Results of yield, bolting, and bitterness were analyzed as a split-split plot design, with the environment (high tunnel vs. open field) as a whole plot factor, fertilization (organic vs. conventional) as a subplot factor, and cultivar as a sub-sub plot factor. Three blocks in each environment served as replications. Treatment and interaction effects reported herein only included

Fig. 1. Wind speed measured at 18 inches (45.7 cm) above the soil surface in high tunnel and open field during Summer 2002 (lettuce transplanted on 29 and 30 July and harvested on 27 and 28 Aug.) and Summer 2003 (lettuce transplanted on 8 July and harvested on 5 and 6 Aug.) at Olathe, KS; 1 m.s⁻¹ = 2.2369 mph.

those that were related to environment and cultivar. Analysis of variance was performed using the MIXED procedure in SAS (version 9.1; SAS Institute, Cary, NC). Multiple comparisons were conducted using Fisher's least significant difference test ($\alpha = 0.05$).

Results and discussion

Wind speed inside the high tunnels was consistently reduced relative to the outside by an average of 34% in 2002 and 41% in 2003 (Fig. 1), probably contributing to a lower transpiration rate in plants grown in high tunnels. Compared with other crops, vegetables are generally sensitive to wind stress (Finch, 1988). Plant growth and development can be directly influenced by wind, while wind may also cause changes in the

crop microclimate (Hodges and Brandle, 1996). With the sides of the tunnels rolled up during the summer, there was often wind in the tunnels, though less than outside. Our high tunnels are oriented east-west, and prevailing winds at this site are typically from the southwest. However, wind velocities would likely be similar in our tunnels if they had been oriented north-south because the endwalls were completely open during the summer season. During the winter, with the sides rolled down, we would expect no wind. Using drop-down sides or skirting at the baseboard rather than roll-up sides could reduce wind speeds in the crop canopy further.

Compared with the open field, daily maximum and minimum air

temperatures were only ≈ 0.2 and 0.3 °C higher on average, respectively, in the unshaded high tunnel during the Summer 2002, a difference that tended to fluctuate from day to day (Fig. 2). Our results were in agreement with the study of Reiss et al. (2004) in which air temperature did not differ greatly between the high tunnel and the outside from July to August in New Jersey, presumably because their tunnels were also well ventilated. In 2003, shade cloth on the high tunnel led to slightly lower daily maximum air temperature relative to the open field, with an average reduction of ≈ 0.4 °C. However, the daily minimum air temperature was increased by 0.5 °C, on average, under shaded high tunnel (Fig. 2). White shade cloth was used in this study on the assumption that it would be cooler than black shade cloth. Overall, RH in the high tunnel did not vary greatly from that in the open field, showing a slight decrease in unshaded high tunnels, and a slight increase in shaded high tunnels (data not shown). The variation of RH in high tunnels may be attributed to combined effects of wind direction and speed, air temperature, and irrigation practices.

Shaded high tunnels had a greater impact on soil temperatures. Although the daily minimum soil temperature was only reduced by 0.2 °C, the daily maximum soil temperature in shaded high tunnel was ≈ 3.4 °C lower than the outside (Fig. 3). Leaf surface temperature was measured on several days between 1330 and 1430 HR in the middle of the Summer 2003 trial, and representative data from 20 July is reported here. In comparison with the open field, high tunnel significantly reduced the leaf surface temperature by 1.5 to 2.5 °C when using shade cloth (Fig. 4). Soil temperature was not measured in unshaded high tunnels in 2002, but according to Reiss et al. (2004), soil temperatures were mostly higher in high tunnels than in the open field from 5 July to 2 Aug. 2003. Regarding the role of shaded high tunnels for summer lettuce production, lower soil temperature most likely contributed to lessen the heat stress on the crop in this study. The impact of root zone temperature on lettuce growth has been demonstrated using aeroponic

Fig. 2. Daily maximum (max) and minimum (min) air temperatures measured at 18 inches (45.7 cm) above the soil surface in high tunnel and open field during Summer 2002 (lettuce transplanted on 29 and 30 July and harvested on 27 and 28 Aug.) and Summer 2003 (lettuce transplanted on 8 July and harvested on 5 and 6 Aug.) at Olathe, KS; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Fig. 3. Daily maximum and minimum soil temperatures at 4 inches (10.2 cm) below the soil surface in open field and shaded high tunnel and during Summer 2003 at Olathe, KS; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

systems. Lettuce with shoots exposed to high ambient temperatures grew successfully at cool root zone temperatures (He and Lee, 1998). Tan et al. (2002) reported that reducing the root zone temperature from the ambient level to 20 °C altered root morphology and nutrient uptake of aeroponically grown lettuce.

Photosynthetically active radiation (*PAR*) in unshaded high tunnels decreased by 16% to 36% during the day (data not shown). In shaded high tunnels, it was reduced by at least 50% relative to the outside where the maximum intensity reached $1800 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$. The light saturation point of head lettuce for photosynthesis during heading stage can reach $800 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ or even higher (Sanchez et al., 1989; Xu et al., 1995). Considering that light is high during the summer season, the lower *PAR* in high tunnels probably did not limit the growth of lettuce during the experiments.

Environment (high tunnel vs. open field) and cultivar showed prominent effects with respect to lettuce growth and quality (yield, bolting, and bitterness) during the summer trials. In 2002, the yield of lettuce varied significantly among cultivars, with the highest head weight from the romaine types 'Kalura' and 'Green Forest'. High tunnels without shade cloth resulted in significantly higher ratings for bolting, accompanied by increased bitterness ratings at a marginally significant level (Table 1). On the other hand, significant environment $\times$ cultivar interaction indicated that not all the cultivars bolted more rapidly or were more bitter in unshaded tunnels. Cultivars Hussarde, Simpson Elite, Ermosa, and Kalura exhibited similarly low bolting and bitterness rates inside and outside. 'Red Sails' in high tunnels bolted earlier than in the open field, but did not differ significantly in bitterness between inside and outside. Among all the cultivars grown during Summer 2002, 'Hussarde', 'Simpson Elite', 'Ermosa', and 'Kalura' showed the best resistance to bolting and the lowest tendency to bitterness.

In 2003, head weight of lettuce grown in shaded high tunnels was marginally significantly lower than that in the open field. However, shade-applied high tunnels led to

Fig. 4. Leaf surface temperatures of lettuce in shaded high tunnel and open field between 1330 HR and 1430 HR on 20 July during Summer 2003 at Olathe, KS; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Table 1. Fresh weight, bolting, and bitterness of lettuce grown in the open field and unshaded high tunnel during Summer 2002 at Olathe, KS.

Type	Cultivar ^z	Head wt (g/plant) ^y		Bolting (1–5 scale) ^x		Bitterness (1–5 scale) ^w	
		Field	Tunnel	Field	Tunnel	Field	Tunnel
Loose leaf	Hussarde	91.4 de	80.3 d	1.4 ab	1.3 de	1.0 c	1.0 c
	Red Sails	104.6 de	119.2 bcd	2.0 a	3.3 a	2.8 a	3.2 a
	Salad Bowl	65.8 e	90.2 cd	1.5 ab	2.5 bc	1.4 bc	2.8 ab
	Simpson Elite	154.4 c	159.3 b	1.2 b	1.8 cd	1.3 bc	1.3 c
Butter-head	Buttercrunch	156.7 c	131.8 bcd	2.0 a	3.2 ab	1.5 bc	2.7 ab
	Ermosa	121.2 cd	90.0 cd	1.0 b	1.2 de	1.3 bc	1.2 c
Romaine	Green Forest	204.4 b	144.3 bc	2.0 a	3.2 ab	1.5 bc	3.2 a
	Kalura	264.6 a	221.7 a	1.0 b	1.0 e	1.8 b	1.8 bc
Effect		Significance					
Environment (E)		NS		**		P = 0.054	
Cultivar (C)		***		**		***	
E × C		NS		**		**	
LSD ^v for field vs. tunnel comparison		60.5		0.6		0.9	

^zNumbers in the same column followed by different letters are significantly different at the 5% level.

^y1 g = 0.0353 oz.

^x1 = no bolting, 2 = initially elongation, 3 = bud appearance, 4 = flower stalk development, 5 = full flowering.

^w1 = no bitterness, 2 = slightly bitter, 3 = mildly bitter, 4 = bitter, 5 = very bitter.

^vLeast significant difference.

NS, **, *** Not significant or significant at $P < 0.05$, 0.01, 0.001, respectively.

significantly less rapid bolting as opposed to the open field (Table 2), resulting in better marketable quality. Consistent with the 2002 trial, ‘Simpson Elite’, ‘Ermosa’, and ‘Kalura’ were very slow to bolt. In a study of lettuce production using high tunnels in Alaska, high tunnels were recommended for the high quality of produce, although the potential for yield increase might be limited (Rader and Karlsson, 2006). Planting in 2003 was 3 weeks earlier than in 2002,

and perhaps as a result, bolting and bitterness were less severe in 2003 trials in general. None of the cultivars grown during Summer 2003 tasted bitter, therefore ratings were not presented (Table 2). It is also noteworthy that the method of irrigation was switched from drip tape to sprinklers from 2002 to 2003 in this study. Spraying water on leaf surface was reported to be a successful strategy for growing lettuce in the greenhouse during hot summer days (Nam

and Yoon, 2002). Except for ‘Salad Bowl’, most lettuce cultivars were slow to bolt during 2003. Sprinkler irrigation might have mitigated heat stress to a certain extent and helped to reduce bolting in summer lettuce.

Reference crop evapotranspiration (ET_0) was determined from meteorological data using the standard method recommended by FAO. As a result of reduced wind speed and light intensity, reference ET_0 decreased in high tunnels, particularly with shade cloth applied (Fig. 5). Furthermore, the calculated ratio of (fresh yield)/ ET_0 was higher in shaded high tunnels (0.89) than in the open field (0.67). Very likely, higher water use efficiency was achieved in high tunnels in comparison with the open field, particularly when using shaded high tunnels for summer lettuce production. It should be noted that rainfall was not considered in the calculation of reference ET_0 , and thus an irrigation trade-off may occur when it rains frequently during the summer. However, in arid regions, efficient water use under high tunnel management would have practical implications. Orgaz et al. (2005) reported that under a Mediterranean climate, the seasonal ET of melon (*Cucumis melo*), green bean (*Phaseolus vulgaris*), sweet pepper (*Capsicum annuum*), and watermelon (*Citrullus lanatus*) grown in unheated plastic greenhouses (high tunnels) was lower than that of irrigated field crops. Future studies could include measurement of irrigation water usage to confirm and quantify this advantage.

Conclusions

High tunnels with open sidewalls and endwalls significantly reduced the wind speed, but did not markedly affect air temperature and RH during the summer. Shaded high tunnels led to lower soil temperature and leaf surface temperature. During the warmest summer months from early July to late August in eastern Kansas, high tunnels with shade cloth and sprinkler irrigation could be employed to grow lettuce with less bolting than in the open. However, the yield of lettuce was reduced under shade. A careful selection of slow-bolt cultivars could also be key to summer lettuce production. To achieve desirable marketable yield, studies to

Table 2. Fresh weight and bolting of lettuce grown in the open field and shaded high tunnel during Summer 2003 at Olathe, KS.

Type	Cultivar ^z	Head wt (g/plant) ^y		Bolting (1–5 scale) ^x	
		Field	Tunnel	Field	Tunnel
Loose leaf	Hussarde	166.4 bc	116.9 b	1.8 bc	1.5 b
	Red Sails	118.4 d	108.4 b	2.2 b	1.2 bc
	Salad Bowl	131.8 cd	104.5 b	4.0 a	3.8 a
	Simpson Elite	129.1 d	106.6 b	1.3 cd	1.0 c
Butterhead	Buttercrunch	150.3 cd	111.4 b	1.8 bc	1.2 bc
	Ermosa	142.3 cd	118.7 b	1.0 d	1.0 c
Romaine	Green Forest	191.2 ab	152.3 a	1.8 bc	1.3 bc
	Kalura	203.3 a	151.7 a	1.0 d	1.0 c
Effect		Significance			
Environment (E)		P = 0.050		*	
Cultivar (C)		***		***	
E × C		NS		NS	
LSD ^w for field vs. tunnel comparison		38.1		0.6	

^zNumbers in the same column followed by different letters are significantly different at the 5% level.

^y1 g = 0.0353 oz.

^x1 = no bolting, 2 = initially elongation, 3 = bud appearance, 4 = flower stalk development, 5 = full flowering.

^wLeast significant difference.

NS, ***, **** Not significant or significant at $P < 0.05$, 0.01, 0.001, respectively.

Fig. 5. Reference crop evapotranspiration (ET_0 ; calculated using the FAO-56 method) in high tunnel and open field during Summer 2002 (lettuce transplanted on 29 and 30 July and harvested on 27 and 28 Aug.) and Summer 2003 (lettuce transplanted on 8 July and harvested on 5 and 6 Aug.) at Olathe, KS; 1 mm = 0.0394 inches.

determine optimal levels of shading for high tunnel production of summer lettuce are warranted. Primarily due to the decrease of wind speed and light intensity, reference crop ET_0 declined in high tunnels, showing a lower water use requirement. In addition to improving crop quality, high tunnels may be useful for improving water use efficiency, especially in the areas where drought conditions present an obstacle to crop production. Future studies should recognize that high tunnel dimensions and degrees of ventilation may vary considerably, perhaps affecting microclimate conditions and influencing crop performance and water use requirements.

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