Active and Passive Zonal Heating Creates Distinct Microclimates and Influences Spring- and Fall-time Lettuce Growth in Ohio

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ADDITIONAL INDEX WORDS. **low tunnel, high tunnel, season extension, root-zone heating, growing degree days**

SUMMARY. **Low and high tunnels and root-zone heating systems are proven tools in horticultural production. However, impacts of their individual and combined application on crop yield, composition, and microclimates are under-reported. We set out to enhance the record of management strategy effects on abiotic environmental conditions and cropping variables in open field and high-tunnel settings. In each setting, raised bed plots were subsurface heated (underlain by electric heating cables), aerial covered (0.8-mil, clear, vented, low tunnels), subsurface heated and aerial covered, or unheated and uncovered (control). The study was repeated four times in spring and fall seasons across 3 years in Wooster, OH. Red-leaved romaine lettuce (*Lactuca sativa* 'Outredgeous' and 'Flagship') was direct seeded in all plots in early October and late March and harvested after ≈4 weeks. Subsurface and aerial temperatures were monitored throughout the experiments. Here, we report primarily on treatment effects on crop microclimate conditions, including temperature and light, and related cropping variables. Subsurface and aerial temperatures varied consistently with plot microenvironment management. Relative to control plots, variability in shoot- and root-zone temperatures generally increased and decreased, respectively, with the addition of low tunnels and electric heating cables, regardless of setting. Still, the relative influence of aerial and soil temperature on crop biomass appeared to differ by setting; aerial temperature correlated most strongly with yield in the high tunnel, while the combination of aerial and root-zone temperature correlated most strongly with yield in the field. Growing degree day accumulation was least in control plots. And, the highest thermal energy to plant biomass conversion efficiency was recorded in the high tunnel. Comparing study-wide and historical climatic data collected in Wooster and other locations in the region suggests that results reported here may hold over a larger area and longer time frame in Wooster, OH.**

Microclimates that surround crops impact their yield and quality. Therefore, microclimates are frequently manipulated (Lamont, 2005; Oebker and Hopen, 1974), but with variable levels of sophistication and success. These manipulations often follow from knowledge gained in tightly controlled studies outlining the role of temperature, light, humidity, and other individual abiotic factors in shaping the productivity and efficiency of horticultural production systems. However, reports from field research tend to emphasize system effects on yield over explanations of the microclimates or mechanisms responsible (Tarara, 2000). Moreover, incomplete descriptions of the microclimates that prevailed during experiments leave open the question—do the results apply elsewhere? And, they constrain the development of a more complete understanding of plant responses to their environment, however tightly controlled. Both limitations must be addressed with regard to root- and shoot-zone temperatures and their effects within low- and high-tunnel systems, particularly those operating during variable weather periods, characteristic of spring and fall in the Great Lakes region.

In contrast to the sophisticated, active temperature control common in modern greenhouse, "plant factory" and similar systems, temperature control in low and high tunnels is passive and a function of solar radiation (heat source), outside temperature, and ventilation. Low and high tunnels are beneficial in the production of many species in multiple climatic regions (Carey et al., 2009; Lamont, 2005; Lamont et al., 2003; Waterer, 2003; Wells and Loy, 1985, 1993; Wien, 2009; Wittwer and Castilla, 1995), but they are not designed to maintain temperatures within narrow ranges typical of actively controlled systems. Though essential in greenhouses, active aerial temperature modification is less effective in tunnels because of their design and is generally implemented only in short-term low-temperature conditions (Lamont et al., 2003). Active root-zone heating, a proven benefit in greenhouse production (Elwell et al., 1985; Shedlosky and White, 1987; Trudel and Gosselin, 1982; Zeroni and Gale, 1987), may also enhance the efficiency of tunnel systems. However, it is incompletely tested in these less controlled environments in temperate climates (Bumgarner et al., 2011, 2012; Hunter et al., 2010; Trudel and Gosselin, 1982). Root-zone

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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
0.0929	ft^2	m^2	10.7639
2.54	inch(es)	cm	0.3937
41.8400	langley(s)	$kJ \cdot m^{-2}$	0.0239
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
305.1517	oz/ft^2	$g \cdot m^{-2}$	0.0033
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

heating can increase subsurface temperatures more directly and with greater control than the use of tunnels and/or mulches. That said, the relative impacts of passive and active aerial and root-zone heating within low and high tunnels operating fall and spring in a temperate climate known for unpredictable solar radiation levels are unclear.

The outcomes of combined active and passive temperature control techniques on microenvironments and vegetable crops are also uncertain given that combined systems are less often studied than ones involving passive modification alone (Diaz-Perez, 2009; Nair and Ngouajio, 2010; Novak and Albright, 1985; Soltani et al., 1995; Wien, 2009; Wolfe et al., 1989). Given economics and crop physiology, incorporating root-zone heating into low- and/or high-tunnel systems may present opportunities to tailor microclimates to meet certain production-quality targets, including for short-cycling crops such as leaf lettuce (Bumgarner et al., 2011, 2012). However, realizing that potential requires a greater understanding of management effects on crop microclimates that, in turn, influence yield and quality.

Here, low and high tunnels undergoing passive and/or active aerial and root-zone heating were employed to meet three objectives: 1) to describe the temperature profiles within eight microclimates established within a field and high-tunnel setting, 2) to calculate thermal energy accumulation and estimate the efficiency with which thermal energy was converted to lettuce biomass in these microclimates, and 3) to compare historical and study-period weather data collected in Wooster and other sites as a first step in estimating the probability that results reported here will hold over larger areas and time frames.

Materials and methods

Site and experimental growing system. This study consisted of root- and shoot-zone microclimate modification treatments tested concurrently in duplicate outdoor and high-tunnel settings in two spring and two fall seasons (2008–10) at the Ohio Agricultural Research and Development Center (OARDC) in Wooster, OH, as reported in Bumgarner et al. (2011). Both experiments employed a split-plot design with four microclimate and two cultivar treatments functioning as main and subplot factors, respectively. Eight wood-framed raised beds (2 ft × 8 ft × 6 inches) contained the four main plot microclimates: 1) unheated and uncovered control, 2) subsurface heated with soil-heating cable, 3) aerial covered with low tunnel, and 4) subsurface heated and aerial covered. Within these main plots were four subplots (2 × 2 ft) containing the two lettuce cultivars. Each of the eight microclimate × cultivar treatments was replicated four times in each experiment for a total of 32 subplots. In Fall 2008, one 13 × 40 × 6-ft single-layer 6-mil plastic tunnel was used, while all subsequent high-tunnel experiments were carried out in one 30 × 80 × 13-ft single-bay, gothic style, single-layer, 6-mil high tunnel. Both tunnels were ventilated manually through doors and/or sidewalls.

The growing medium consisted of (v/v) 35% peat (Premier Horticulture, Quakerstown, PA), 35% dairy manure compost (OARDC), 15% shredded organic red clover (*Trifolium pratense*) hay (OARDC), and 15% silt loam field soil (OARDC). Control plots consisted of unheated and uncovered raised beds. Root zones in treatments 2 and 4 contained a 40-ft automatic electric heating cable (Wrap-On Co., Bedford Park, IL) at ≈3-inch spacing and 4-inch medium depth, which was triggered to function at medium temperatures below 23 °C. Treatment 3 main plots were covered by a single layer of 0.8-mil slitted polyethylene (Hummert International, Earth City, MO) stretched across four wire hoops to create an ≈18 × 30-inch low tunnel. Treatment 4 main plots were polyethylene covered and cable heated as described above.

Biomass data and analysis. About 1000 preweighed primed and pelleted seeds of the two red-leaf romaine lettuce cultivars, Outredgeous (Johnny's Selected Seeds, Winslow, ME) and Flagship (Shamrock Seeds, Salinas, CA), were sown on 9 Oct. 2008, 21 Mar. 2009, 10 Oct. 2009, and 15 Mar. 2010. Biomass yield of a 2-ft^2 section of each plot was taken ≈4 weeks after seeding. Yield data were analyzed separately in field and high-tunnel settings in each experiment as described in Bumgarner et al. (2011). Briefly, a Proc Univariate (SAS version 9.2; SAS Institute, Cary, NC) procedure was carried out to test for normality on all data. Normally distributed data were analyzed using untransformed data, while data with a nonnormal distribution were log transformed. All analysis was then performed using Proc Mixed. Microclimate was analyzed as a fixed effect, and replications within years were analyzed as random effects. Treatment means were separated using a pdiff difference statement at $P \leq 0.05$ when the fixed effects were significant at $P \leq 0.05$. Means were back transformed for inclusion in tables. Yield data reported in this manuscript will focus on microclimate main effects representing both cultivars. Relationships between biomass, solar radiation, average temperature, and growing degree days (GDDs) were analyzed and described using Pearson correlation coefficients from Proc Corr.

Environmental data. Total solar radiation was measured continuously at the OARDC weather station ≈3000 ft from the experimental site. Additionally, photosynthetically active radiation [*PAR* (LI250-A; LI-COR Biosciences, Lincoln, NE)] and ultraviolet (UV) radiation measurements in the UV-A and UV-B regions (IL1350 radiometer/photometer; International Light, Peabody, MA) in individual microclimates were taken periodically at each experimental site. Air and soil temperatures were recorded continuously in each microclimate plot at 30-min (Fall 2008 and Spring 2009) and 15-min (Fall 2009 and Spring 2010) intervals using separate data loggers (Hobo ProV2; Onset Computer Corp., Bourne, MA). Aerial and subsurface temperatures were measured using shielded sensors in each main plot ≈8 inches above and 1 to 1.5 inches below the media surface. Temperatures from each main plot were averaged to obtain daily treatment means in each experiment. GDDs (5 °C base) were then calculated from daily aerial and subsurface temperature treatment means in each experiment.

Results and discussion

Aerial and subsurface temperature effects on key plant processes

Temperature contributes to the rate of biochemical reactions, especially those mediated by enzymes, in

Table 1. Correlations between biomass yield of leaf lettuce in field and high-tunnel settings and average aerial temperature, average subsurface temperature, aerial growing degree days (GDDs) base 5 °C (41.0 °F), subsurface GDDs, total GDDs, and total accumulated solar radiation (ASR) in Wooster, OH, in 2008–10.

		Aerial temp	Aerial GDDs	Subsurface temp	Subsurface GDDs	Total GDDs	Total ASR[z]
Field	Yield	0.60 (0.015)[y]	0.65 (0.0065)	0.72 (0.0016)	0.75 (0.0009)	0.80 (0.0002)	–0.19 (0.49)
High tunnel	Yield	0.60 (0.015)	0.68 (0.034)	0.47 (0.068)	0.53 (0.033)	0.64 (0.008)	0.39 (0.14)

[z]Accumulated solar radiations for specific microclimate treatments were calculated using daily solar radiation measurements taken by the Ohio Agricultural and Development Center weather station (Ohio State University, 2012) and adjusted using average point *PAR* measurements from microclimate treatments.
[y]Number in parentheses represents probability value of Pearson correlation coefficient (r), N = 16.

ways described by the Q10 concept (Campbell, 1977; Krug, 1997) and various researchers (e.g., Burke et al., 1988). Should enzymes in crop species be most efficient within specific temperature ranges, it is reasonable to suggest that crop environments be tailored to maintain these ranges as often as possible. Work outlined here and conducted by many others is consistent with this suggestion.

Aerial and root-zone temperatures impact plant growth; however, the specific modes by which they influence growth in ways that become measurable and discernible at the community or crop level appear to vary. For example, shifts in shoot-zone temperature tend to influence fluxes in the capture and utilization of light, carbon dioxide (CO_2), and water (Hay and Walker, 1989), evident as shifts in photosynthetic productivity in leaves (Oebker and Hopen, 1974). Changes in root-zone temperature can alter nutrient and water uptake, carbon partitioning, and plant hormone synthesis and movement (Bowen, 1991; Cooper, 1973).

This study involved creating and monitoring aerial and root-zone microenvironments and characterizing their effects at the whole plant level. As such, the data represent a summation of processes throughout the root–shoot axis that may have been affected by combinations of the commercially proven active and passive root- and shoot-zone heating methods employed here. Three aspects of these microenvironments are addressed in following sections, namely: 1) aerial and subsurface temperatures: means and variability, 2) thermal energy: its accumulation and conversion to lettuce leaf biomass in low and high tunnels, and 3) study-period specific and georeferenced historical temperature and light data: shaping the scope of inference of project conclusions and management recommendations.

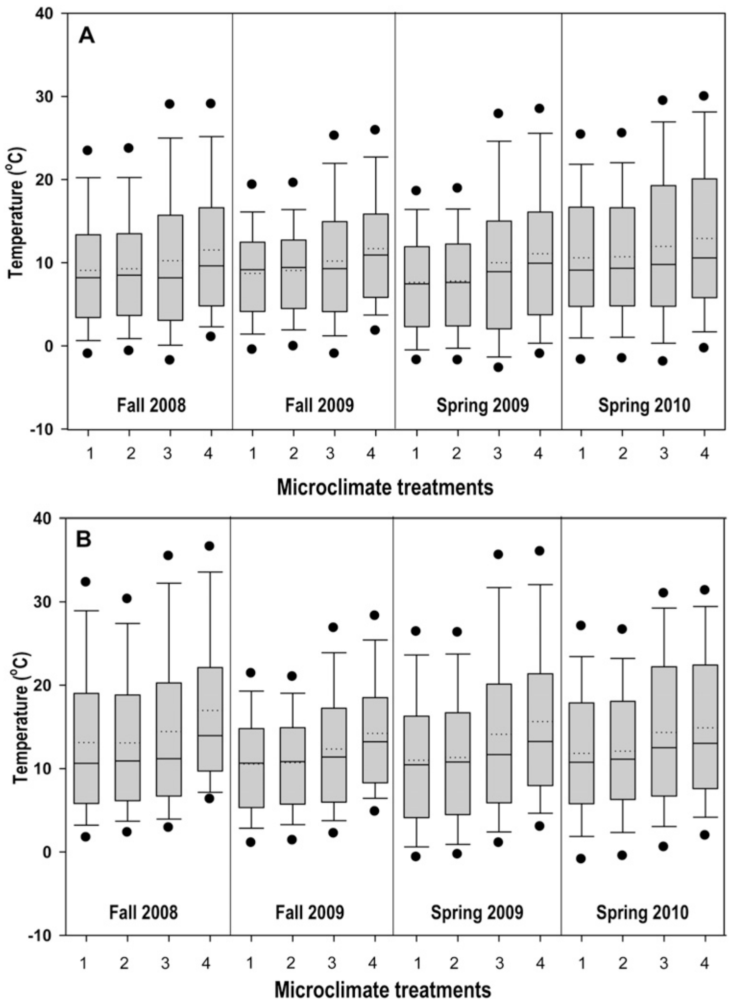

Fig. 1. Aerial temperature profiles from four microclimates in field (A) and high-tunnel (B) settings in four leaf lettuce experiments in Wooster, OH, in 2008–10. Box plots represent fifth and 95th (dots), 10th and 90th (bars), 25th and 75th percentiles (boxes), median (solid line), and mean (dotted line) of all temperature values logged at 30- and 15-min intervals over the entire experimental period. Numbers represent microclimate treatments: 1 = control, 2 = subsurface heated, 3 = aerial covered, 4 = subsurface heated + aerial covered; (1.8 × °C) + 32 = °F.

Aerial and subsurface temperatures: means and variability

Temperature profiles within the four microclimates were distinct and internally consistent (Table 1; Bumgarner et al., 2011). Shoot- and root-zone temperature trends held across experiments although ambient solar radiation and temperature varied with season. Average total daily solar radiation levels were 234, 342, 193, and 361 langleys in Fall 2008, Spring 2009, Fall 2009, and Spring 2010, respectively. Slitted low tunnels, high tunnels, and low tunnels within high tunnels decreased

PAR by ≈14%, 23%, and 33% relative to ambient, respectively. UV light, reported to influence both crop yield and composition (Tsormpatsidis et al., 2008), was reduced under a high tunnel by more than 60% and 90% in the UV-A and UV-B regions, respectively, relative to outdoor uncovered plots.

Aerial temperature profiles. Mean aerial temperatures tended to be higher in covered than in uncovered plots, regardless of setting (Fig. 1). And, soil heating appeared to have little effect on mean shoot-zone temperatures in uncovered plots; perhaps, heat supplied beneath the soil surface dissipated quickly above it. Still, the mean value is only one aspect of the temperature profile and a potentially weak indicator of possible plant responses to prevailing temperatures. Indeed, cumulative-temperature-based plant growth models incorporate temperature variation using daily maximum and minimum values to calculate GDDs (Diaz-Perez, 2009; Wolfe et al., 1989). In the current work, the aerial temperature range was usually wider in passively heated (aerial covered) plots than in bottom heated but uncovered plots or in unheated and uncovered (control) plots (Fig. 1). Also, the fact that mean values often exceeded median values indicates that maximum air temperatures were elevated more by shoot-zone heating strategies than minimum temperatures.

Temperature variability can also be described by calculating the average difference between consecutive logged values in each plot across entire experiments. By averaging the difference between temperature values recorded at 30-min intervals, a single number can be used to represent the variability depicted in Fig. 1. Field aerial temperature differentials (Fig. 2A) are larger and clearly more strongly influenced by aerial covering than by subsurface heating. A similar trend was noted in the high tunnel (Fig. 2B); however, the high-tunnel setting tended to dampen the overall effect of aerial covering on air temperature differentials relative to the outdoor setting.

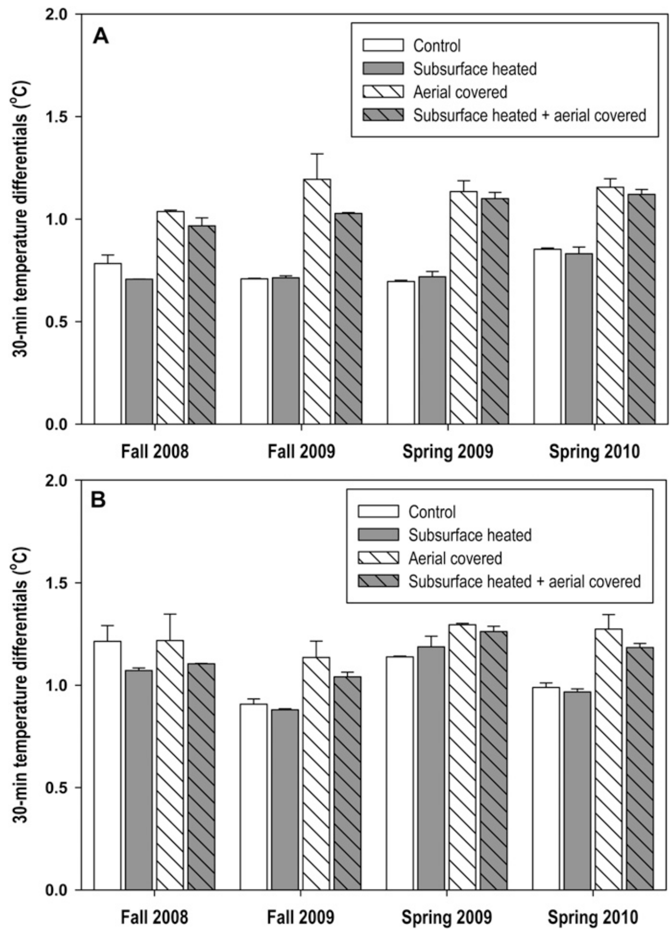

Fig. 2. Aerial temperature differentials from four microclimates in field (A) and high-tunnel (B) settings in four leaf lettuce experiments in Wooster, OH, in 2008–10. Differential represents the mean ± SE of the difference in absolute value between consecutive data logger values representing 30-min intervals in all main plots throughout the experiment. A lower value suggests a more consistent temperature profile; (1.8 × °C) + 32 = °F.

Subsurface temperature profiles. Mean soil temperature values tended to increase by electric heating cables and low tunnels in outdoor and high-tunnel settings (Fig. 3). This effect was most pronounced when cables were used in conjunction with low tunnels (treatment 4). And, cable use alone (treatment 2) tended to increase root-zone temperatures more than low tunnel use alone (treatment 3). Moreover, cable use demonstrated a potential to reduce the variability in root-zone temperature relative to the treatments in which cables were not used (Fig. 3). This trend was most evident in both the field and high tunnel when lower levels of solar radiation led to limited increases in daytime subsurface temperature.

Like aerial temperature differentials, field subsurface temperature differentials (Fig. 4A) tended to be greatest in aerial covered plots. In the field, subsurface heating in addition to aerial cover tended to reduce subsurface temperature differentials compared with aerial covering alone in all experiments. This trend was clearly observed in two of four high-tunnel experiments (Fig. 4B). Less ventilation of the high tunnel in Fall 2008 and Spring 2009 (Bumgarner et al., 2011) may have muted temperature variability and subsurface temperature differentials across microclimates in these experiments.

Plastic coverings applied as mulches, low tunnels or rowcovers, are commonly and effectively used to increase soil temperature and heat unit accumulation in horticultural systems (Diaz-Perez, 2009; Moreno et al., 2002; Nair and Ngouajio, 2010; Soltani et al., 1995; Wolfe et al., 1989). Still, data reported here underscore that increases in soil and, possibly, aerial temperatures may be lower and more variable when only a plastic covering is used compared with when soil heating is used alone or in conjunction

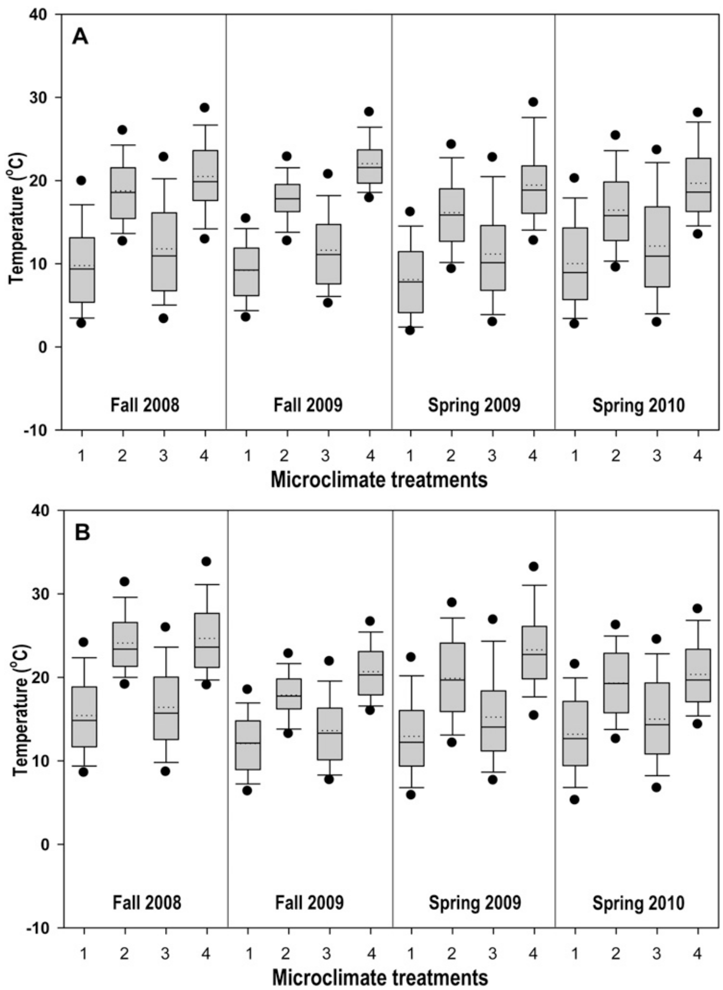

Fig. 3. Subsurface temperature profiles from four microclimates in field (A) and high-tunnel (B) settings in four leaf lettuce experiments in Wooster, OH, in 2008–10. Box plots represent fifth and 95th (dots), 10th and 90th (bars), 25th and 75th percentiles (boxes), median (solid line), and mean (dotted line) of all temperature values logged at 30- and 15-min intervals over the entire experimental period. Numbers represent microclimate treatments: 1 = control, 2 = subsurface heated, 3 = aerial covered, 4 = subsurface heated + aerial covered; (1.8 × °C) + 32 = °F.

with a plastic covering such as a low tunnel (Figs. 1–4). Passive heating (heat entrapment) hinging on solar radiation is less consistent and predictable than active heating provided via electric cables, warm water lines, or other approaches. Soil temperature is a key factor in lettuce emergence and early growth (Bierhuizen and Wagenvoort, 1974; Krug, 1997; Wien, 1997; Scaife, 1973), and active root-zone heating can facilitate both, especially when ambient temperature and solar radiation levels are low (Bumgarner et al., 2011, 2012). Warmer root-zone temperatures may stabilize plant growth processes when cooler air temperatures would otherwise disrupt them (Zeroni and Gale, 1987), but this hypothesis is largely untested in tunnel settings. Should the data continue to suggest that root-zone heating has separate and unique impacts on crop physiology important to growers, investments in scalable approaches to root-zone heating may be more appealing to incorporate with existing aerial covering systems.

Thermal energy: its accumulation and conversion to lettuce leaf biomass in low and high tunnels

Thermal time, heat unit, or GDD calculations can help describe or predict cumulative, growth-related outcomes associated with continuous exposure to biologically relevant, crop-specific temperatures (Diaz-Perez, 2009; Villordon et al., 2009; Waterer, 2003; Wolfe et al., 1989). In so doing, GDDs and related calculations bridge physical and crop science. These calculations are typically based on air or soil temperatures only. Here, we employed a 5 °C base temperature in calculating soil and aerial GDDs, in part to compare the relative associations between average temperature and GDD values as independent variables and yield as the dependent variable.

Yield and microclimate temperature values reported here and previously (Bumgarner et al., 2011) were positively related, regardless of season or setting (Table 1). GDDs tended to be more strongly correlated with yield than average temperature values in both experimental settings. In the high tunnel, aerial GDDs correlated most strongly with yield; yield associations with soil GDDs were significant but numerically lower. In the outdoor setting, total GDDs (Table 1) registered the highest correlation with lettuce biomass. Correlations with average soil temperature and soil GDDs were intermediate but greater than correlations with average aerial temperature and aerial GDDs. These relationships in outdoor plots are reasonable given that lettuce growth is heavily influenced by the temperature of the growing point that remains close to the soil and, thereby, affected more by shallow soil than air temperature (Scaife, 1973; Wien, 1997).

The effectiveness or efficiency of heating strategies could be defined in part by the ratio of cumulative thermal energy applied to growth observed. Such calculations could be made for various crop stages and units of time. Here, we combine yield (grams per square foot) recorded 4 weeks after sowing and aerial and subsurface GDDs into grams per GDD to estimate the efficiency of the conversion of heat units to marketable yield outdoors and in the high tunnel (Table 2). In both settings, grams per GDD values were generally greater in modified than control microclimates. Also, grams per aerial GDD values tended to be higher than grams per soil GDD values. However, it is important to note that grams per aerial GDD tended to be greater when root-zone heating was applied, and this was most apparent in the field setting. These results suggest that a synergy involving simultaneous increases in aerial and subsurface temperature,

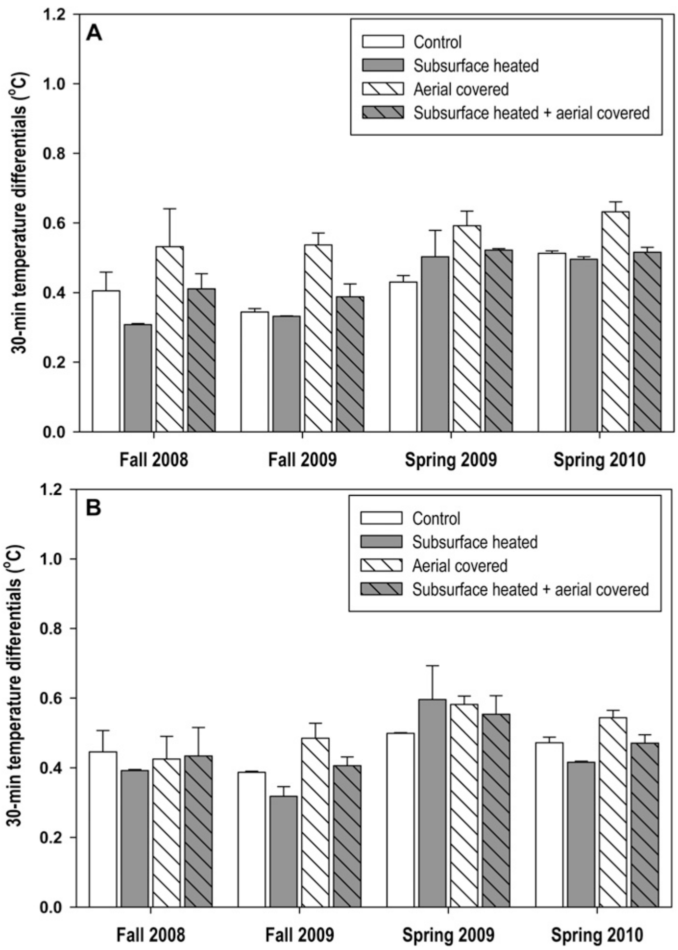

Fig. 4. Subsurface temperature differentials from four microclimates in field (A) and high-tunnel (B) settings in four leaf lettuce experiments in Wooster, OH, in 2008–10. Differential represents the mean ± SE of the difference in absolute value between consecutive data logger values representing 30-min intervals in all main plots throughout the experiment. A lower value suggests a more consistent temperature profile; (1.8 × °C) + 32 = °F.

inseparable in these calculations, may be at work. This speculation is supported by other authors who have reported that the utility of soil heating is linked with levels of other factors, such as light and aerial temperatures (Trudel and Gosselin, 1982; Zeroni and Gale, 1987).

In the outdoor setting, grams per GDD calculations illustrate that the conversion of both aerial and soil GDD units into plant biomass was less efficient in the field than in the high tunnel in most plots (Table 2). However, it is apparent that in some outdoor experiments, the combination of root- and shoot-zone heating resulted in grams per GDD efficiencies similar to some high-tunnel microclimates. Therefore, concurrent modification of root- and shoot-zone temperatures may be the most viable approach for producing a direct-seeded baby leaf lettuce crop outdoors under conditions experienced in this study. The separate and combined value of passive aerial and active root-zone heating should be investigated in high tunnels, especially since relative yield gains in modified environments were influenced by ambient conditions.

While temperature was the focus of this study, it alone does not shape lettuce yield or quality. Other environmental factors, such as light, also have major roles in this process. Furthermore, temperature profiles and solar radiation levels can be closely associated. Although monitored less vigorously than temperature in this study, the light readings recorded beneath low and high tunnels help illustrate system effects on yield. For example, higher solar radiation levels contributed to increased GDD accumulation under low and high tunnels (relative to GDD accumulation in control plots) in Spring 2009 compared with lower relative increases in GDD accumulation in Fall 2009 with lower ambient solar radiation.

Light may most affect lettuce growth when other factors, such as temperature, are less limiting (Wien, 1997). Here, as noted previously (Moreno et al., 2002; Nair and Ngouajio, 2010), yield was greatest in plots in which measured *PAR* levels were lowest, suggesting that temperature may have been more limiting to growth than light. Greater growth in warmer but dimmer microclimates could follow from an increased rate of reactions driving growth (Campbell, 1977; Krug, 1997) and/or reduced photoinhibition (Heatherington et al., 1989). Using correlations from the separate field and high-tunnels experiments, both average temperatures and GDDs appeared to have a stronger impact on yield than light (Table 1). In contrast to the field (r = –0.19), the correlation (r = 0.39) between light and yield was positive in the high-tunnel setting where temperatures may have been less limiting. However, neither correlation was statistically significant (Table 1). These correlations are based on cumulative data; therefore, they are incomplete indicators of whether light was limiting in specific instances. The correlations suggest that, overall, light is unlikely to have been the most consistently limiting factor (Elwell et al., 1985). A more complete description of solar radiation and physiological measures, such as chlorophyll fluorescence and CO_2 assimilation, is needed to further elucidate the relationships between plant productivity, light, and shoot- and root-zone temperature in these settings.

Study-period-specific and georeferenced historical temperature and light data: shaping the scope of inference of project conclusions and management recommendations

Reliable recommendations for managing crop microclimates hold across locations and seasons. Developing such recommendations requires testing microclimate–crop relationships

Table 2. Lettuce shoot fresh weight and aerial and subsurface growing degree days [GDD; 5 °C (41.0 °F) base] conversion efficiency measured ≈4 weeks after sowing in field and high-tunnel setting raised beds containing red romaine leaf lettuce in Wooster, OH, in 2008–10.

Mean shoot fresh wt (g/ft²), aerial GDD conversion efficiency (g/ft² per GDD), and subsurface GDD conversion efficiency (g/ft² per GDD)[z]					
		Fall 2008	Fall 2009	Spring 2009	Spring 2010
	Field				
Control	Shoot fresh wt	2.9 a[y]	4.0 a	2.0 a	2.6 a
	Aerial GDD conversion efficiency	0.02	0.03	0.02	0.02
	Subsurface GDD conversion efficiency	0.02	0.03	0.02	0.02
Subsurface heated	Shoot fresh wt	23.3 b	10.3 b	10.3 b	7.5 b
	Aerial GDD conversion efficiency	0.15	0.08	0.10	0.04
	Subsurface GDD conversion efficiency	0.06	0.03	0.03	0.02
Aerial covered	Shoot fresh wt	21.9 b	14.3 c	22.4 c	9.7 b
	Aerial GDD conversion efficiency	0.12	0.09	0.14	0.05
	Subsurface GDD conversion efficiency	0.10	0.07	0.11	0.05
Subsurface heated + aerial covered	Shoot fresh wt	75.0 c	51.3 d	89.1 d	37.4 c
	Aerial GDD conversion efficiency	0.34	0.26	0.45	0.17
	Subsurface GDD conversion efficiency	0.16	0.10	0.19	0.09
	High tunnel				
Control	Shoot fresh wt	113.1	21.7a	108.0 a	42.8 a
	Aerial GDD conversion efficiency	0.44	0.13	0.55	0.22
	Subsurface GDD conversion efficiency	0.35	0.10	0.42	0.18
Subsurface heated	Shoot fresh wt	111.2	45.0 b	159.6 b	67.9 b
	Aerial GDD conversion efficiency	0.43	0.27	0.78	0.34
	Subsurface GDD conversion efficiency	0.19	0.12	0.33	0.17
Aerial covered	Shoot fresh wt	135.5	48.1 b	194.5 c	92.2 c
	Aerial GDD conversion efficiency	0.45	0.22	0.66	0.35
	Subsurface GDD conversion efficiency	0.38	0.19	0.59	0.32
Subsurface heated + aerial covered	Shoot fresh wt	119.5	82.4 c	214.3 c	131.7 d
	Aerial GDD conversion efficiency	0.32	0.30	0.62	0.47
	Subsurface GDD conversion efficiency	0.20	0.18	0.36	0.30

[z]Grams per aerial GDD and grams per soil GDD calculated by dividing leaf lettuce yield (grams per square foot) by respective aerial and soil GDD for each microclimate in each experiment; 1 g/ft² = 10.7639 g·m⁻² = 0.0353 oz/ft².

[y]Means within settings and experiments followed by the same letter are not significantly different by a pdiff difference statement at $P \leq 0.05$ in Proc Mixed (SAS version 9.2; SAS Institute, Cary, NC).

across space and time, a challenging and resource-intensive process. Comparing abiotic conditions recorded during an experiment to historical weather data may aid in this process in three ways. First, it may help establish the probability of achieving similar results at other times and locations. Second, when coupled with yield data, the same exercise may help identify the relative influence of various factors (e.g., temperature, light) on system productivity at given locations and over specific periods. And, third, identifying yield-limiting factors may assist farmers in targeting investments designed to correct them.

Figure 5 depicts historical and experimental period ambient GDDs for OARDC in Wooster, OH (OARDC Weather Station, lat. 40.78°N); Alma, MI [National Climatic Data Center (NCDC) Station 200146, lat. 43.23°N]; and Frankfort, KY (NCDC Station 153028, lat. 38.14°N). Alma, MI, and Frankfort, KY, are each ≈2.5° north and south latitude, respectively, of an east–west transect set by Wooster, OH. We draw the following tentative conclusions from Fig. 5. First, GDD accumulation (pattern, total) was similar to historical trends in Wooster in two of four experimental periods (Fall 2008 and Spring 2009). This outcome suggests that results reported here are somewhat likely to recur there in similarly managed systems. And, second, given that historical trends in Michigan and Kentucky generally fall within the variability recorded during the project in Wooster, we hypothesize that temperature and light effects at those locations may mirror those in Wooster.

Collectively, these data suggest that the relative value of both shoot- and root-zone microclimate management in high-tunnel and outdoor settings should be more thoroughly examined, especially as they may be applied in producing a short-season, cool-tolerant crop such as lettuce in

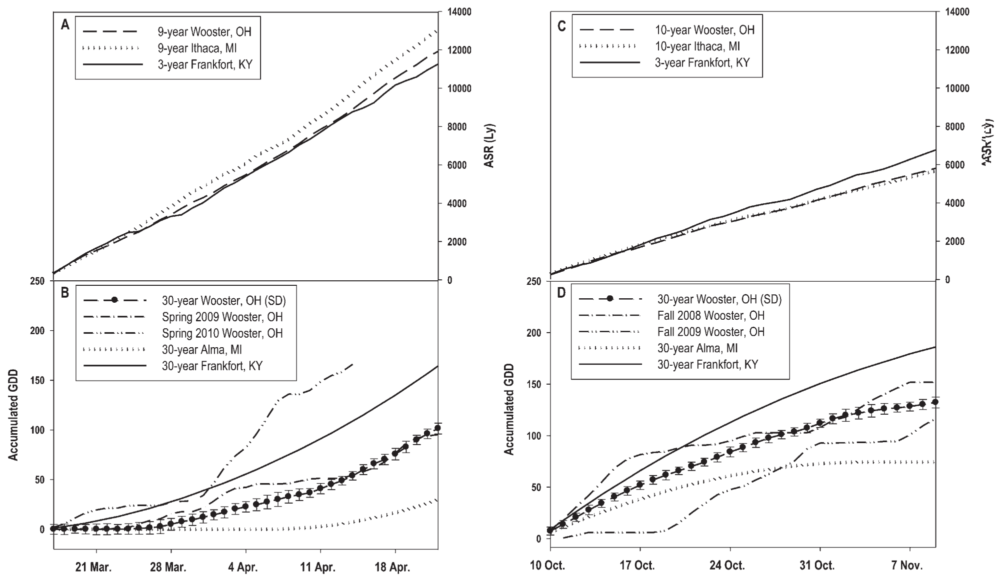

Fig. 5. Experimental period and average spring (A) and fall (C) solar radiation accumulation and spring (B) and fall (D) aerial growing degree days [GDD; 5 °C (41.0 °F) base] as calculated for Wooster, OH, Alma and Ithaca, MI, and Frankfort, KY. Experimental period GDD were calculated from data gathered in this study. Historical GDD were calculated using data from Wooster, OH collected by the Ohio Agricultural Research and Development Center (OARDC) weather station (lat. 40.78°N; The Ohio State University, 2012) for 1982–2011 and 1971–2000 National Climatic Data Center (NCDC) data for Alma, MI (lat. 43.23°N; Station 200146), and Frankfort, KY (lat. 38.14°N; Station 153028); (1.8 × °C) + 32 = °F. Accumulated solar radiation (ASR) data in langleys (Ly) were obtained from the OARDC weather station (2002–11) in Wooster, OH. Solar radiation data for KY and MI were obtained from stations nearest to the Frankfort, KY and Alma, MI, NCDC weather stations. Frankfort solar radiation data were calculated from 2009–11 data (lat. 38.12°N; Western Kentucky University, 2012). Solar radiation data from Ithaca, MI, approximately six miles from Alma, were calculated from 2002–11 data (lat. 43.32°N; Michigan State University, 2012); 1 Ly = 41.8400 kJ·m^{-2}.

transitional seasons. High tunnels alone can increase soil temperatures beneficially (Both et al., 2007; Knewtson et al., 2010), so commercial application of root-zone heating should maintain efficiency by avoiding overinvesting and producing temperatures higher than necessary, as has been suggested in previous leafy crop production under lower light conditions (Hicklenton and Wolynetz, 1987). In our high tunnel, cables combined with solar radiation may have increased root-zone temperatures more than needed to spur growth in some experiments (e.g., Fall 2008), thereby reducing efficiency. Further testing should involve greater control over the level, timing and/or duration of root-zone heating than possible here especially since temperature effects vary with crop growth stage. Future studies could incorporate crop microclimate, crop yield, and georeferenced, real-time, and historical climate data to help identify optimal aerial and/or root-zone heating strategies that result in more predictable outcomes, especially in low- and high-tunnel settings.

Literature cited

Bierhuizen, J.F. and W.A. Wagenvoort. 1974. Some aspects of seed germination in vegetables. 1. The determination and application of heat sums and minimum temperature for germination. Sci. Hort. 2:213–219.

Both, A.J., E. Reiss, J.F. Sudal, K.E. Holmstrom, C.A. Wyenandt, W.L. Kline, and S.A. Garrison. 2007. Evaluation of a manual energy curtain for tomato production in high tunnels. HortTechnology 17:467–472.

Bowen, G.D. 1991. Soil temperature, root growth, and plant function, p. 309–329. In: Y. Waisel, A. Eshel, and U. Kafkafi (eds.). Plant roots: The hidden half. Marcel Dekker, New York.

Bumgarner, N.R., J.C. Scheerens, R.W. Mullen, M.A. Bennett, P.P. Ling, and M.D. Kleinhenz. 2012. Root-zone temperature and nitrogen affect the yield and secondary metabolite concentration of fall- and spring-grown, high-density leaf lettuce. J. Sci. Food Agr. 92:116–124.

Bumgarner, N.R., M.A. Bennett, P.P. Ling, R.W. Mullen, and M.D. Kleinhenz. 2011. Canopy cover and root-zone heating effects on fall- and spring-grown leaf lettuce yield in Ohio. HortTechnology 21:737–744.

Burke, J.J., J.R. Mahan, and J.L. Hatfield. 1988. Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron. J. 80:553–556.

Campbell, G.S. 1977. An introduction to environmental biophysics. Springer-Verlag, New York.

Carey, E.E., L. Jett, W.J. Lamont, Jr., T.T. Nennich, M.D. Orzolek, and K.A. Williams. 2009. Horticultural crop production in high tunnels in the United States: A snapshot. HortTechnology 19:37–43.

Cooper, A.J. 1973. Root temperature and plant growth. Commonwealth Agricultural Bureaux, Slough, UK.

Diaz-Perez, J.C. 2009. Root zone temperature, plant growth and yield of broccoli [*Brassica oleracea* (Plenck) var. *italica*] as affected by plastic film mulches. Sci. Hort. 123:156–163.

Elwell, D.L., M.Y. Hamdy, W.L. Roller, A.E. Ahmed, H.N. Shapiro, J.J. Parker, and S.E. Johnson. 1985. Soil heating using subsurface pipes: A decade of research results at OSU/OARDC. Ohio Agr. Res. Dev. Ctr. Res. Bul. 1175.

Hay, R.K.M. and A.J. Walker. 1989. An introduction to the physiology of crop yield. Wiley, New York.

Heatherington, S.E., J. He, and R.M. Smillie. 1989. Photoinhibition at low temperature in chilling-sensitive and -resistant plants. Plant Physiol. 90:1609–1615.

Hicklenton, P.R. and M.S. Wolynetz. 1987. Influence of light- and dark-period air temperatures and root temperature on growth of lettuce in nutrient flow systems. J. Amer. Soc. Hort. Sci. 122:932–935.

Hunter, B., D. Drost, and B. Black. 2010. High tunnel lettuce in Utah. Utah State Ext. Publ. Horticulture/HighTunnels/2010-04pr.

Knewtson, S.J.B., E.E. Carey, and M.B. Kirkham. 2010. Management practices of growers using high tunnels in the central great plains of the United States. HortTechnology 20:639–645.

Krug, H. 1997. Environmental influences on development, growth, and yield, p. 101–180. In: H.C. Wien (ed.). The physiology of vegetable crops. CAB International, Wallingford, UK.

Lamont, W.J., Jr. 2005. Plastics: Modifying the microclimate for the production of vegetable crops. HortTechnology 15:477–481.

Lamont, W.J., Jr., M.D. Orzolek, E.J. Holcomb, K. Demchak, E. Burkhart, L. White, and B. Dye. 2003. Production system for horticultural crops grown in the Penn State high tunnel. HortTechnology 13:358–362.

Michigan State University. 2012. Enviro-Weather. 8 Feb. 2012. <http://www.agweather.geo.msu.edu/mawn/station.asp?id=ith>.

Moreno, D.A., G. Villora, J. Hernandez, N. Castilla, and L.R. Monreal. 2002. Yield and chemical composition of chinese cabbage in relation to thermal regime as influenced by row covers. J. Amer. Soc. Hort. Sci. 127:343–348.

Nair, A. and M. Ngouajio. 2010. Integrating rowcovers and soil amendments for organic cucumber production: Implications on crop growth, yield, and microclimate. HortScience 45:566–574.

Novak, S. and L.D. Albright. 1985. Thermal environment model for plastic tunnel row covers. Amer. Soc. Agr. Eng. Tech. Paper No. 85-4050.

Oebker, N.F. and H.J. Hopen. 1974. Microclimate modification and the vegetable crop ecosystem. HortScience 9:564–568.

Scaife, M.A. 1973. The early relative growth rates of six lettuce cultivars as affected by temperature. Ann. Appl. Biol. 74:119–128.

Shedlosky, M.E. and J.W. White. 1987. Growth of bedding plants in response to root-zone heating and night temperature regimes. J. Amer. Soc. Hort. Sci. 112: 290–295.

Soltani, N., J.L. Anderson, and A.R. Hamson. 1995. Growth analysis of watermelon plants grown with mulches and rowcovers. J. Amer. Soc. Hort. Sci. 120:1001–1009.

Tarara, J. 2000. Microclimate modification with plastic mulch. HortScience 35:169–179.

The Ohio State University. 2012. OARDC Weather System. 8 Feb. 2012. <http://www.oardc.ohio-state.edu/newweather/stationinfo.asp?id=1>.

Trudel, M.J. and A. Gosselin. 1982. Influence of soil temperature in greenhouse tomato production. HortScience 17:928–929.

Tsormpatsidis, E., R.G.C. Henbest, F.J. Davis, N.H. Battey, P. Hadley, and A. Wagstaffe. 2008. UV irradiance as a major influence on growth, development and secondary products of commercial importance in Lollo Rosso lettuce 'Revolution' grown under polyethylene films. Environ. Exp. Bot. 63:232–239.

Villordon, A., C. Clark, D. Ferrin, and D. LaBonte. 2009. Using growing degree days, agrometeorological variables, linear regression, and data mining methods to help improve prediction of sweet potato harvest date in Louisiana. HortTechnology 19:133–144.

Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. HortTechnology 13:339–343.

Wells, O.S. and J.B. Loy. 1985. Intensive vegetable production with row covers. HortScience 20:822–826.

Wells, O.S. and J.B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the northeastern United States. HortTechnology 3:92–95.

Western Kentucky University. 2012. Kentucky Mesonet. 8 Feb. 2012. <http://www.kymesonet.org/historical_data.php?site=LSML>.

Wien, H.C. 1997. Lettuce, p. 471–509. In: H.C. Wien (ed). The physiology of vegetable crops. CAB International, Wallingford, UK.

Wien, H.C. 2009. Microenvironmental variation within the high tunnel. HortScience 44:235–238.

Wittwer, S.H. and N. Castilla. 1995. Protected cultivation of horticultural crops worldwide. HortTechnology 5:6–23.

Wolfe, D.W., L.D. Albright, and J. Wyland. 1989. Modeling row cover effects on microclimate and yield: I. Growth response of tomato and cucumber. J. Amer. Soc. Hort. Sci. 114:562–568.

Zeroni, M. and J. Gale. 1987. The effect of root temperature on rose plants in relation to air temperature. Plant Soil 104:93–98.