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Impact of Shade and Fogging on High Tunnel Production and Mineral Content of Organically Grown Lettuce, Basil, and Arugula in Georgia

Savanah Laur ¹, Andre Luiz Biscaia Ribeiro da Silva ² , Juan Carlos Díaz-Pérez ³  and Timothy Coolong ^{4,*}

¹ Cooperative Extension Service, North Carolina State University, Carthage, NC 28327, USA; savanah_laur@ncsu.edu

² Department of Horticulture, Auburn University, Auburn, AL 36849, USA; azb0207@auburn.edu

³ Department of Horticulture, University of Georgia, Tifton, GA 31793, USA; jcdiaz@uga.edu

⁴ Department of Horticulture, University of Georgia, Athens, GA 30602, USA

* Correspondence: tcoolong@uga.edu

Abstract: This study evaluated the impact of shade cloth and fogging systems on the microclimate at the plant canopy level and yield of basil (*Oscimum basilicum* L.), arugula (*Eruca vesicaria* subsp. *Sativa* L.), and lettuce (*Lactuca sativa* L.) planted in mid-September and early October in high tunnels. Fogging systems were installed at canopy level in plots within shaded (30%) and non-shaded high tunnels. Average air temperatures in the shaded high tunnels were 0.9 °C lower than non-shaded high tunnels during the day. Shade cloth significantly reduced soil temperatures during the day and night periods by 1.5 °C and 1.3 °C, respectively, compared to non-shaded treatments. Fogging systems did not have an impact on air temperature, soil temperature, or relative humidity, but did increase canopy leaf wetness. Shade and fogging did not impact the yield of any of the crops grown. Yield was impacted by planting date, with earlier planting result in higher yields of lettuce and basil. Yields for arugula were greater during the second planting date than the first. Planting date and shade cloth interacted to affect the concentrations of macronutrients.

Keywords: heat; microclimate; misting; season extension



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1. Introduction

High tunnels are passively heated and cooled structures that have been used for protected culture of crops worldwide for many years [1]. While high tunnels have become increasingly popular with growers in the United States, more than 360,000 and 55,000 ha of land are used for high tunnel production in leading countries such as China and Spain, respectively [1]. The number of high tunnels used in the United States is lower, ranging from 100 to 700 per state in 2007, though this number and has continued to grow [2,3]. The season extension properties of high tunnels have been well documented in a range of climate regions around the world and in the U.S. [1,4–7]. Studies conducted in the Southeastern U.S. reported improved marketable yields for strawberries grown in high tunnels compared to open field conditions [8,9]. Another study conducted in North Carolina found that organic tomatoes could be harvested three weeks earlier in the high tunnel than those grown in the open field [10]. Further, high tunnels have shown promise for early spring lettuce production, with improved yields being reported in temperate climate regions of the U.S. [11,12].

While high tunnels provide many growing opportunities; in warm climates they are accompanied by several challenges. One of these is managing excessive heat, during early fall and late spring production periods. Early harvests and higher yields are possible through use of high tunnels; though variable weather conditions encountered during spring and fall seasons can also lead to greater biotic and abiotic issues in many crops [12,13].

High temperatures in late summer and early fall can be challenging for growers planting lettuce or other crops in high tunnels trying to take advantage of early-winter markets. The optimum air temperature for lettuce production is approximately 18.5 °C, and high temperatures found in high tunnels in late summer or early fall in many regions of the world can result in in tip burn, bolting, and bitter flavors [14].

Two techniques used to reduce air temperatures in greenhouses and high tunnels include covering the structures in shade cloth and water fogging systems to provide evaporative cooling. Cool-season vegetables can be successfully grown in high tunnels covered with shade cloth during summer months [15–17]. High tunnels shaded with a white shade cloth had average reductions in daily maximum air temperatures of 0.4 °C, reductions in daily maximum soil temperatures of 3.4 °C, and reduced leaf surface temperatures of 1.5 to 2.5 °C [17].

Summer production of lettuce and other leafy greens under shade cloth and evaporative cooling systems could result in less bolting compared to open field production [17]. Evaporative cooling systems, consisting of sprinklers that deliver mist or fog throughout a structure, reduce air temperatures within greenhouses [18–20]. In arid environments, such as in Egypt, mist/fogging systems reduced air temperatures up to 6.2 °C during summer months [21]. The effectiveness of mist or fogging for evaporative cooling varies based on climate, with the greatest impact occurring in regions with high air temperatures and low humidity [21]. Although well documented for use in greenhouses, less information is available evaluating the effectiveness of shade cloth and fogging/misting systems in passively cooled structures such as high tunnels in hot humid climates, such as the Southeastern United States, is limited. Research is needed to develop cultural practices that can be used to mitigate heat stress, which often limits production in regions of the world with similar climates to the Southeastern United States [22]. The objectives of this study were to determine the impact of fogging systems and shade cloth on high tunnel microclimates and growth of fall planted, high tunnel-grown basil, lettuce, and arugula.

2. Materials and Methods

2.1. Experimental Location

These studies were conducted in the Fall of 2018 and 2019 at the organic farming unit of the University of Georgia, Durham Horticulture Research Farm in Watkinsville, GA (lat. 33°5' N, long. 83°3' W). The soil is a Cecil sandy loam series (0% to 2% slope). The project site has been certified organic since 2012 and all practices in the studies were performed according to USDA National Organic Program standards. Studies were conducted in two snow-arch design high tunnels (9.1 m by 27.4 m, Atlas Greenhouse Systems Inc., Alapaha, GA, USA) covered with two layers of polyethylene plastic (6 mil, SunView 4; Poly-Ag Crop., San Diego, CA, USA). The tunnels had automated side curtains set to open when air temperatures in the tunnel reached 29.5 °C, measured approximately 1.8 m above the soil line. Side curtains were closed again after a 5.5 °C differential (24 °C) had been reached. One high tunnel was covered with 30% black shade cloth (Atlas Greenhouse Systems) with the other being unshaded. There were two planting dates in each study year. Within each tunnel (shaded and non-shaded) there were four replicates of each treatment (fogging × planting date) combination arranged in a randomized complete block design (Figure S1). A similar design with multiple replications of a treatment within a single tunnel has previously been utilized [13].

2.2. Growing Conditions

Soil analyses were conducted before planting in the high tunnels. Prior to planting, soil pH ranged from 6.0–6.6 with an average of 403, 285, and 2970 kg·ha^{−1} of phosphorus (P), potassium (K), and calcium (Ca), respectively (Mehlich 1 extract; Waters Agricultural Laboratories, Camilla, GA, USA). Soil organic matter ranged from 2.5–3.5%. Certified organic seeds of arugula, (*Eruca vesicaria* subsp. *Sativa* L.), basil (*Oscimum basilicum* L.) 'Genovese', and lettuce, (*Lactuca sativa* L.) 'Salanova Red Butter' (Johnny's Selected Seeds,

Albion, ME, USA) were sown into 200-cell trays (Speedling, Ruskin, FL, USA) filled with soilless media (Sunshine No. 1 Natural and Organic, Sungro Horticulture, Agawam, MA, USA). The soilless mix was peat moss-based and contained coarse perlite, dolomitic limestone and an organic wetting agent. The crops utilized in this study were chosen to represent commonly grown crops for high tunnel growers in the region during the fall months. They represented a mix of warm (basil) and cool (arugula) season crops. Seeds were sown on 20 August and 11 September 2018 and 3 and 14 August 2019 for the first and second planting dates in 2018 and 2019, respectively. Seeds were sown earlier in 2019 to better capture higher temperatures encountered in early September. Seedlings were greenhouse grown at temperature set points of 26.7/18.3 °C day/night. Plants were watered daily as needed and fertilized at approximately three weeks after seeding with a 50 mg·L⁻¹ nitrogen (N), 32.5 mg·L⁻¹ P, and 10 mg·L⁻¹ K solution of fertilizer (Fish and Seaweed Blend, 2N-1.3P-0.4K, Neptune's Harvest, Gloucester, MA, USA).

High tunnel soils were tilled to a depth of approximately 20 cm using a tractor-mounted rotary tiller (Maschio model A tiller; Maschio Gaspardo, DeWitt, IA, USA). In both study years, preplant poultry-litter-based organic fertilizer was broadcast incorporated at a rate of 56 kg·ha⁻¹ N (5N-1.7P-2.5K; Harmony Organic Fertilizer, Environmental Products LLC, Roanoke, VA, USA). Seedlings were transplanted into high tunnel plots on 20 September and 4 October 2018 and 11 and 28 September 2019. Each high tunnel contained 16 plots with four receiving fog and four without fogging for each planting date. Plots consisted of beds (10 cm tall) spaced approximately 1.5 m center to center in the tunnels. Each bed contained two rows of plants with approximately 30 cm between row spacing and 25 cm within row spacing for a total of 10 plants of each crop per plot. Each plot contained three beds with one bed planted with either arugula, lettuce, or basil. Each plot was approximately 2.7 m long by 3.0 m wide. Adjacent plots within a row had approximately 0.6 m of spacing between plots to reduce drift from the fogging system, while adjacent rows were spaced 1.5 m away. The fogging system consisted of 6 foggers (50-micron droplet, 0.635 cm barb, 8825BB, DIG Corp., Vista, GA, USA) operated at approximately 50 psi spaced with two foggers approximately 1.2 m apart within each bed in a plot. Foggers were connected using 0.635 cm polyethylene tubing set approximately 30 cm above the ground and were slightly above or at canopy level for the duration of the trial. Using a timer, the fog system was turned on for 5 min every 30 min between 11:00 am and 5:00 pm daily. By the first week of October, the run time on the fog system was reduced to 3 min every 30 min between 11:00 am and 5:00 pm daily. Plants were irrigated for 30–60 min daily, unless overcast, with a single row of drip irrigation tubing per bed (30 cm emitter spacing, 1.5 L·min⁻¹ per 30.5 m, Chapin DLX; Jain USA Inc., Haines City, FL, USA) equidistant between the two planted rows. All plots within a high tunnel were irrigated on the same schedule. During the study, an additional 56 kg·ha⁻¹ N (5N-1.7P-2.5K; Harmony Organic Fertilizer, Environmental Products LLC) was applied in a surface band adjacent to planted rows approximately 3–4 weeks after the first planting date in both study years.

2.3. Environmental Monitoring

Soil volumetric water content (VWC) and temperature, air temperature, relative humidity (RH), leaf wetness and solar radiation were measured within three replicates of each treatment combination (fog or no fog) within each high tunnel (shade or no shade). Soil VWC and temperatures were measured with probes placed 10 cm below the soil surface, equidistant between plants and drip irrigation tubing in the center of each plot (5TM and 5TE, Meter Group Inc., Pullman WA, USA). Air temperature, RH, and photosynthetic photon flux density (PPFD) were measured with sensors placed approximately 45 cm above the soil on stakes positioned perpendicular to the soil surface in the center bed of each plot (VP3, VP4, QSO-S; Meter Group Inc., Pullman, WA, USA). Average PPFD was measured with a sensor placed parallel to the soil on top of the air temperature sensors. Leaf wetness was measured with a sensor positioned at a 60-degree angle to the soil surface, approximately 45 cm above the top of the planted bed (LWS, Meter Group Inc., Pullman

WA, USA) in the center of each plot. Leaf wetness was measured in millivolts (mV). When no water is present, the leaf wetness sensor has a reading of 445 mV (Meter Group Inc., Pullman WA, USA), with a threshold of 450 representing a mild wetting event (dew/frost) and 1400 mV being considered completely wet (heavy rain). Sensors were connected to data loggers (EM 50G, Meter Group Inc., Pullman WA, USA). Data from sensors were recorded once every 60 s and an average value was obtained every 30 min and recorded to data loggers.

2.4. Harvest and Data Collection

Crops were harvested at marketable maturity. Basil was harvested 28 days after planting for both planting dates in 2018. Arugula was harvested 28 and 35 days after planting for the first and second planting dates, respectively in 2018. Basil and arugula were harvested 26 and 34 days after planting for the first and second planting dates, respectively in 2019. Basil plants were stripped of leaves and fresh leaf weights were obtained. Lettuce was harvested 40 days after planting for the second planting date in 2018 and 32 and 34 days after planting for first and second planting dates in 2019, respectively. Arugula and lettuce were cut at the soil surface for harvest. Entire plots were harvested and plant materials within a harvested plot were combined to obtain fresh weights. Subsamples of approximately 10–15 of newly expanded mature leaves were taken from each plot and dried in a gravity oven at 65 °C for one week to determine foliar concentrations of N, P, K, Ca, magnesium (Mg), sulfur (S), boron (B), iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) in each crop (Waters Agricultural Lab, Camilla, GA, USA).

Environmental data from day (6 am to 6 pm) and night (6 pm to 6 am) hours were analyzed separately, since the fogging system was only in use during daytime hours (from 11:00 am to 5:00 pm).

2.5. Statistical Analysis

Statistical analyses were performed using linear mixed techniques, as implemented in SAS PROC GLIMMIX (SAS/STAT 14.2; SAS Institute Inc. Cary, NC, USA). Block was treated as a random effect. Yield and nutrient content (i.e., N, P, K, Mg, Ca, S, B, Zn, Fe, and Cu) were analyzed individually within each crop (lettuce, basil, and arugula) using planting date (PD1 and PD2), shade (shaded and non-shaded), mist (fogging and non-fogging), and their interaction as fixed effects. There were no year–treatment interactions based on initial statistical analyses. Thus, year was treated as a repeated measurement allowing for the replication of shade treatments in time. Least square means comparisons were performed using Tukey's Honest Significant Difference Test, adjusted at a *p* value of 0.05, and means were portioned using the *slice* command in SAS.

3. Results

3.1. Microclimate Data

There were no interactions between year and any treatments for microclimate, yield, or nutrient data. There were differences between treatments for microclimate data. Fogging did not affect average soil temperatures within each plot during day or night (Table 1). Average air temperatures measured in plots were not affected during the day or night by fogging treatments. Average daytime air temperatures from planting dates one and two to harvest were in 28.5 °C and 24.2 °C, respectively (data not shown). Plots receiving fog treatments had a greater soil VWC than those without fogging. During the day, soil VWC levels were 28.3% and 23.6% in the fogged and non-fogged plots, respectively.

Table 1. Day and night soil volumetric water content (VWC) and temperature, air temperature, relative humidity (RH), leaf wetness, and photosynthetic photon flux density (PPFD) in high tunnels with shade or fogging.

Treatment	Soil Temp.		Air Temp.		Soil VWC		RH		Leaf Wetness		PPFD	
	(°C) ^z		(%)		(%)		mV ^z		(μmol/m ² s) ^y		(°C) ^z	
Day ^z												
Shade	22.5	b ^x	24.1	b	25.8	a	65.0	a	467.3	a	415	c
No Shade	24.0	a	25.0	a	25.9	a	63.0	a	460.2	a	591	b
Outdoor	22.2	b	22.5	c	NA ^w		61.0	a	470.2	a	849	a
Fog	23.1	a	24.5	a	28.3	a	64.0	a	485.9	a	564	a
No Fog	23.3	a	24.6	a	23.6	b	63.0	a	442.9	b	572	a
Night ^z												
Shade	21.0	b	16.0	a	29.2	a	90.4	a	455.7	b	NA ^w	
No Shade	22.3	a	16.3	a	25.8	b	90.0	a	453.5	b	NA ^w	
Outdoor	20.9	b	15.5	a	NA		85.0	b	563.1	a	NA ^w	
Fog	21.7	a	16.1	a	31.8	a	89.7	a	464.3	a	NA ^w	
No Fog	21.6	a	16.1	a	23.6	b	90.8	a	445.0	b	NA ^w	

^z Daytime hours were 6 am to 6 pm and night-time hours were 6 pm to 6 am; ^y the threshold for wetness was set to 450 mV; ^x values within the same column and treatment group followed by the same letter are not significantly different at ($p \leq 0.05$) according to Tukey's honestly significant difference test; ^w NA = not applicable.

In the evening, after fogging had been turned off, soil VWC levels were 31.8% and 23.6% in the fogged and non-fogged plots, respectively. Average RH levels were not affected by the fogging treatment during day or night hours. Fogged plots had a leaf wetness (485.9 mV) compared to plots non-fogged plots (442.9 mV) during daylight hours. During night hours, fogged plots also had significantly greater leaf wetness than non-fogged plots, despite the fogging system turning off at 5 pm daily. Fogging had no impact on average PPFD plots.

The presence of shade cloth reduced soil temperatures during day and night periods by 1.5 °C and 1.3 °C, respectively compared to the non-shaded tunnel. Outdoor soil temperatures were not different than those in the shaded tunnels but were significantly lower compared to the non-shaded structure. Average air temperatures in the shaded high tunnel were 0.9 °C lower than the non-shaded tunnel during the day but were not different during night hours. Average outdoor air temperatures were 1.6 °C lower than the shaded tunnel and 2.5 °C lower than the non-shaded tunnel during the day (Table 1). Soil VWC was not affected by shading during the day. During night hours soil VWC was greater in the shade tunnel than the non-shaded tunnel. Soil VWC increased in the shaded tunnel between day and night. Shading did not affect average RH levels during day or night. However, RH levels were lower outside during the night than in either of the high tunnels. Leaf wetness counts were not affected by shade cloth during the day or night hours. As expected, PPFD levels were significantly lower (29.7%) in shaded tunnels compared to non-shaded tunnels. Average outdoor PPFD levels were 30.3% greater than those in the non-shaded tunnels, suggesting that significant shading was occurring in the tunnels due to the plastic covering. Daily average PPFD decreased during the study and was 476 μmol·m⁻²·s⁻¹ and 659 μmol·m⁻²·s⁻¹, in the shaded and non-shaded tunnels, respectively, during the harvest period of the first planting. Average PPFD decreased to 393 μmol·m⁻²·s⁻¹ and 555 μmol·m⁻²·s⁻¹ in the shaded and non-shaded tunnels, respectively, during harvest in the second planting (data not shown).

3.2. Yield

There were no interactions between year and planting date or fog treatments for marketable yield of lettuce, basil, and arugula. There were also no significant interactions between planting date and fog treatments for yield of the three crops grown. Neither fogging treatment or shade affected yields of the crops grown. Marketable yields of all three crops were impacted by planting date. Lettuce yields significantly decreased in the

second planting date ($3204 \text{ kg} \cdot \text{ha}^{-1}$) compared to the first ($4279 \text{ kg} \cdot \text{ha}^{-1}$) (Figure 1). For basil, the second planting date had a lower yield ($1660 \text{ kg} \cdot \text{ha}^{-1}$) compared to the first planting date ($2420 \text{ kg} \cdot \text{ha}^{-1}$). Conversely, the yield of arugula was lower for the first planting date ($4900 \text{ kg} \cdot \text{ha}^{-1}$) compared to the second ($6478 \text{ kg} \cdot \text{ha}^{-1}$).

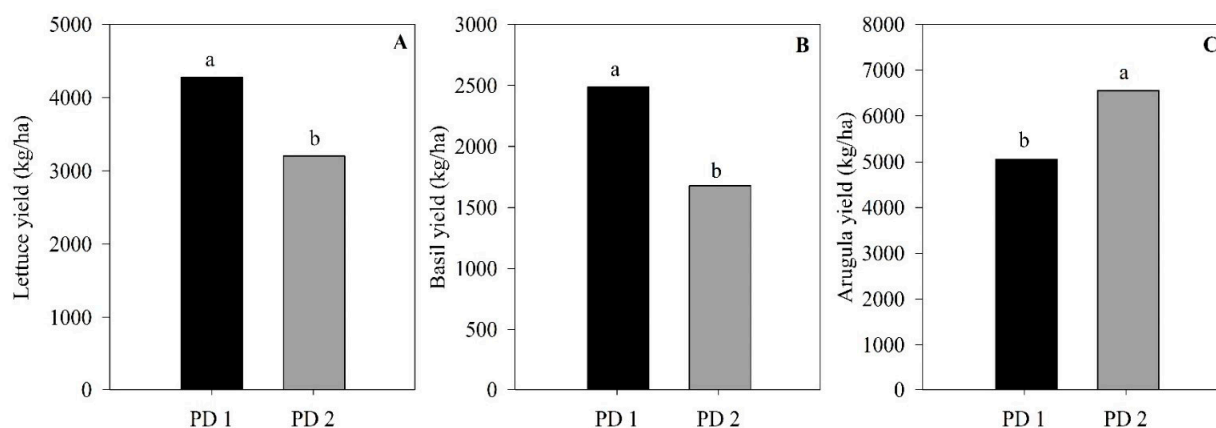


Figure 1. The main effects of two planting dates (PD) on the fresh weight yield of lettuce ‘Salanova Red Butter’ (A), basil ‘Genovese’ (B), and arugula ‘Astro’ (C) grown in high tunnels. Columns followed by the same letter(s) are not significantly different according to Tukey’s Honest Significant Difference Test ($p < 0.05$).

Foliar macronutrient concentrations were evaluated at harvest. In lettuce, foliar macronutrient concentrations were impacted by several interactions between planting date, fogging, and shading as well as the main effects of planting date and shading. Foliar levels of N, P, Mg, and Ca were affected by a planting date by shade interactions (Table 2). Lettuce N concentrations increased from the first (3.80%) to second (5.98%) planting dates in the non-shaded tunnel, they were not impacted by planting date in the shaded high tunnel. Foliar P concentrations in lettuce increased in the second planting date for both shaded and non-shaded plants, but the increase was relatively greater in the non-shaded plants. For foliar Mg, there was no impact of planting date for shaded plants, but for non-shaded plants there was an increase in Mg concentrations from 0.28% to 0.35% in the first to second planting dates, respectively. Calcium concentrations were impacted differently between shaded and non-shaded plants. In shaded plants, Ca levels decreased from 1.63% to 1.31% in the first and second planting dates, respectively, while they were similar for both planting dates in the non-shaded plants.

There were also interactions between fogging treatment and shade cover for foliar concentrations of Mg, Ca, B and Mn (Table 3). Foliar Mg concentrations were not impacted by fogging in the shaded high tunnel, while they were significantly less in the non-fogged plants (0.28%) compared to the fogged plants (0.33%) in the non-shaded high tunnel. Foliar Ca concentrations responded in a similar manner to Mg concentrations. Calcium concentrations were significantly higher in the fogged plants grown in the non-shaded tunnel but were not affected by fogging treatment in the shaded tunnel. Boron and Mn had similar interactions. The concentrations of B and Mn were not impacted by fogging in the non-shaded tunnel but were affected by fogging in the shaded tunnel. There were significant interactions between planting date and fogging treatment for Zn and Fe concentrations in lettuce (Table 4). Zinc levels were not affected by planting date in lettuce plants exposed to the fogging treatment. However, Zn levels were significantly greater in lettuce that was not exposed to fogging treatments (68.8 ppm) compared to those in the first planting date (40.4 ppm). Foliar Fe concentrations in contrast were significantly lower in the second planting date (175.2 ppm) than the first (277.8 ppm) in plants exposed to fogging but were not affected by planting date in those that were not fogged.

Table 2. Interaction between planting date (PD) and shading for foliar nitrogen (N), phosphorous (P), magnesium, (Mg), and Calcium (Ca) concentrations in high tunnel-grown lettuce ‘Salanova Red Butter’.

Planting Date	Cover				
	Shade		Non-Shade		
	(%)				
			N		
PD 1	4.82	A ^z A ^y		3.80	b B
PD 2	6.15	a A		5.98	a A
			P		
PD 1	0.66	a B		0.38	b B
PD 2	0.83	a A		0.78	a A
			Mg		
PD 1	0.35	a A		0.28	b B
PD 2	0.34	a A		0.35	a A
			Ca		
PD 1	1.63	a A		1.39	a A
PD 2	1.31	b B		1.41	a A

^z Values within same cover treatment (columns) followed by similar lowercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between planting date (row). ^y Values within same planting date treatment (row) followed by similar uppercase letters indicate no significant difference Tukey’s Honest Significant Difference Test ($p < 0.05$) between planting date (column).

Table 3. Interaction between fogging and shading for foliar magnesium (Mg), calcium (Ca), boron (B), and manganese (Mn) concentrations on a dry weight basis in high tunnel-grown lettuce ‘Salanova Red Butter’.

Fog	Shade		Non-Shade	
			(%) Mg	
Fog	0.34	A ^z A ^y	0.33	a A
No Fog	0.36	a A	0.28	b B
			Ca	
Fog	1.41	a A	1.51	a A
No Fog	1.53	a A	1.29	b B
			(mg·kg ⁻¹) B	
Fog	23.9	b B	27.0	a A
No Fog	26.6	a A	26.0	a A
			Mn	
Fog	48.6	b B	67.4	a A
No Fog	63.1	a A	55.4	a A

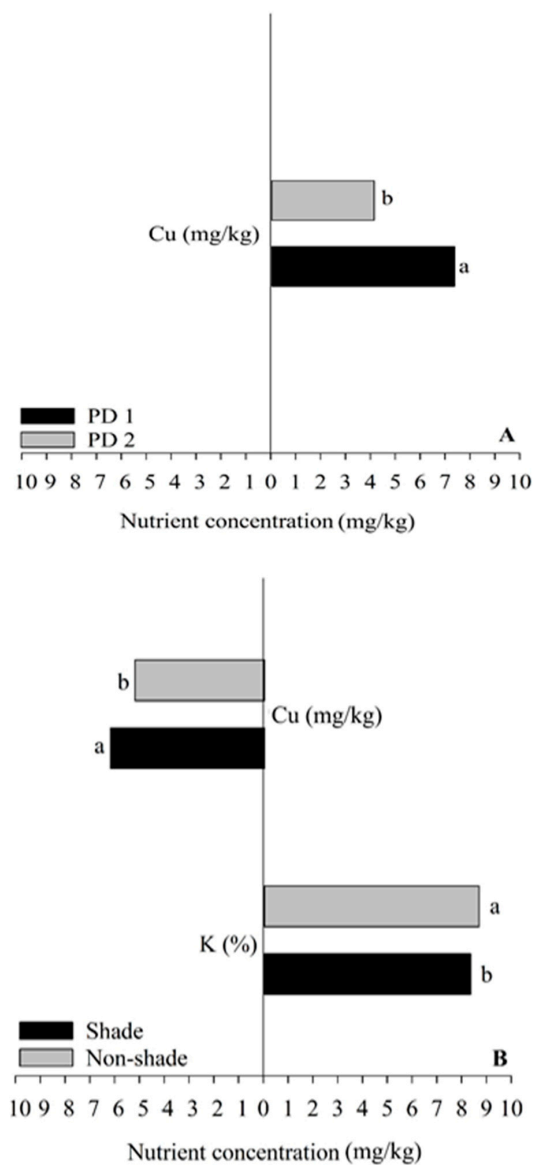
^z Values within same cover treatment (columns) followed by similar lowercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between fog (row). ^y Values within same fog treatment (row) followed by similar uppercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between cover (column).

Lettuce K and Cu levels were not impacted by treatment interactions but were affected by treatment main effects. Foliar Cu concentrations in lettuce were significantly higher in the first planting date compared to the second (Figure 2a). Further, Cu concentrations were higher in non-shaded lettuce compared to those plants grown under shade. Lettuce K concentrations were elevated in all treatments, but were significantly greater in the non-shaded plants (8.7%) compared to shaded plants (8.1%) (Figure 2b). Foliar S concentrations were not affected by any treatment or interaction and averaged 0.36% (data not shown).

Table 4. Interaction between fogging and planting date (PD) for foliar zinc (Zn) and iron (Fe) concentrations on a dry weight basis in high tunnel-grown lettuce ‘Salanova Red Butter’.

Planting Date	Fog				
	Fog			No Fog	
	(mg·kg ⁻¹)				
			Zn		
PD 1	62.4	A ^z A ^y		40.4	b B
PD 2	69.2	a A		68.8	a A
			Fe		
PD 1	277.8	a A		211.5	a B
PD 2	175.2	b A		194.2	a A

^z Values within same fog treatment (columns) followed by similar lowercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between planting date (row). ^y Values within same planting date treatment (row) followed by similar uppercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between fog (column).

**Figure 2.** The main effects of two planting dates (PD) (A) and shade cloth (B) on the foliar concentrations of copper (Cu) and potassium (K) in high tunnel-grown lettuce. Columns followed by the same letter(s) are not significantly different according to Tukey’s Honest Significant Difference Test ($p < 0.05$).

Foliar P and K concentrations in basil were affected by planting date and shade interactions (Table 5). Foliar P concentrations increased significantly in the second planting date compared the first. Plants grown without shade saw a relatively larger increase (0.38% to 0.78%) compared to those grown with shade (0.66% to 0.83%). In contrast, foliar K concentrations decreased from the first (5.98%) to the second (4.50%) planting date for plants growth with shade.

Table 5. The interaction between planting date (PD) and shading for foliar phosphorous (P) and potassium (K) concentrations on a dry weight basis in high tunnel-grown basil ‘Genovese’.

Planting Date	Cover				
	Shade		Non-Shade		
	(%)				
			P		
PD 1	0.66	A ^z B ^y		0.38	b B
PD 2	0.83	a A		0.78	a A
			K		
PD 1	5.98	a A		5.27	a B
PD 2	4.50	b B		4.88	a A

^z Values within same cover treatment (columns) followed by similar lowercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between planting date (row). ^y Values within same planting date treatment (row) followed by similar uppercase letters indicate no significant difference according to Tukey’s Honest Significant Difference Test ($p < 0.05$) between planting date (column).

In addition to the interactions for P and K, main effects of planting date and shading affected concentrations of several other nutrients in basil. Calcium concentrations were significantly lower in the earlier planting date (one) compared to the second planting date (Figure 3a). Calcium concentrations were 2.30% and 3.04% in the first and second planting dates, respectively. Similarly, Zn concentrations in basil were greater in the first planting compared to the second. In contrast, basil grown on the second planting date had greater Mg concentrations (0.55%) than those planted on the first planting date (0.50%). Basil Cu and Mn levels were also greater in the second planting date compared to the first. Foliar micronutrients, Cu, Fe, and Zn were also impacted by the main effects of shading in basil. Foliar Fe and Zn were significantly reduced in the non-shaded tunnels compared to those that were shaded (Figure 3b). Copper levels in contrast were slightly reduced in the shaded tunnels compared to the non-shade tunnels. Basil foliar N and S concentrations were not affected by any treatment and averaged 4.63% and 0.46%, respectively, across all treatments (data not shown).

There were no significant treatment interactions affecting plant nutrient concentrations measured in arugula. There were significant main effects of planting date and shading on several micro and macronutrients in arugula. Foliar S and P concentrations were significantly lower in arugula from the first planting date compared to the second (Figure 4a). Sulfur concentrations were 1.64% on the first planting date compared to 1.76% on the second. Similarly, P concentrations were 0.58% in the first planting date and 0.64% in the second. Foliar Cu concentrations also increased from the first to second planting date and were 5.6 ppm and 7.4 ppm in planting date one and two, respectively. In contrast, boron concentrations decreased from 31.4 ppm to 27.6 ppm in planting dates one and two, respectively.

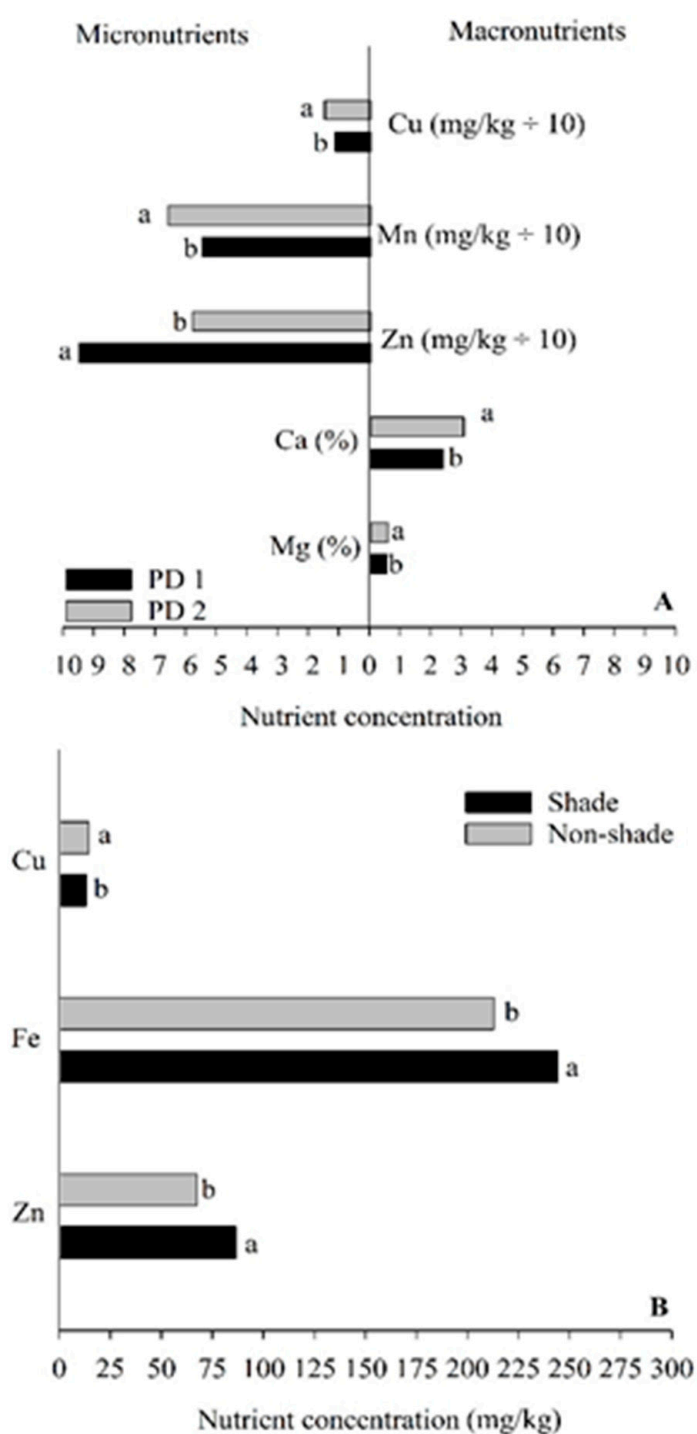


Figure 3. Main effects of planting date (PD) (A) and shade cloth (B) on the dry weight concentrations of copper (Cu), manganese (Mn), zinc (Zn), calcium (Ca), magnesium (Mg), and iron (Fe) in high tunnel-grown basil. Columns followed by the same letter(s) are not significantly different according to Tukey's Honest Significant Difference Test ($p < 0.05$).

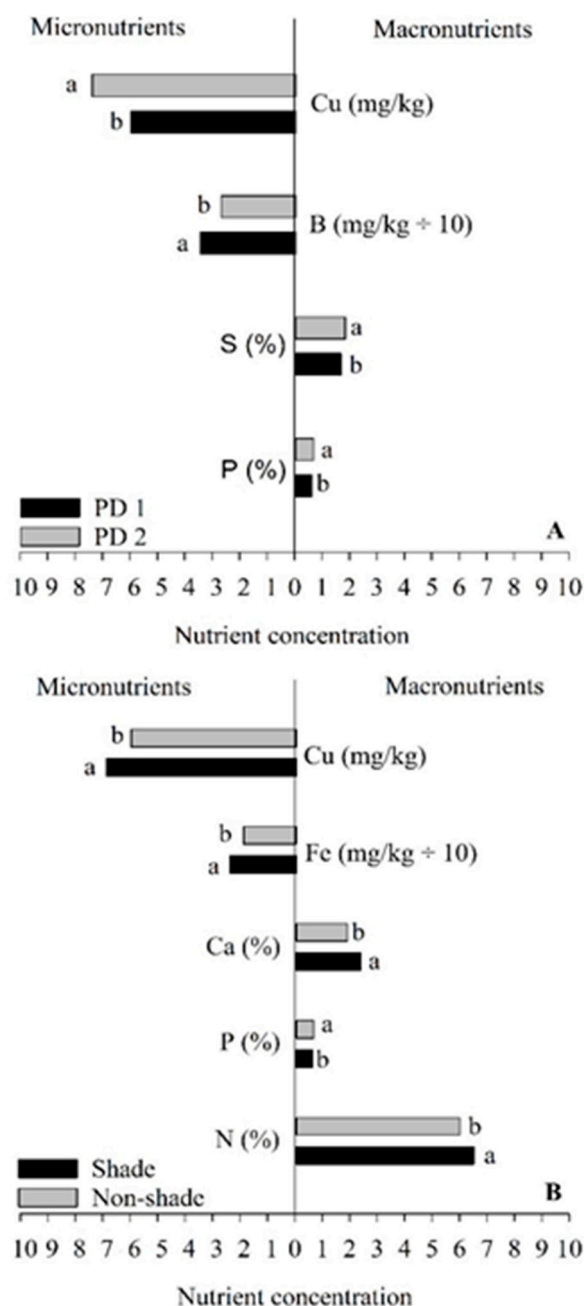


Figure 4. Main effects of planting date (PD) (A) and shade cloth (B) on the dry weight concentrations of copper (Cu), boron (B), sulfur (S), phosphorous (P), iron (Fe), calcium (Ca), and nitrogen (N) in high tunnel-grown arugula. Columns followed by the same letter(s) are not significantly different according to Tukey's Honest Significant Difference Test ($p < 0.05$).

There were significant effects of shading on the concentration of several nutrients in arugula. Nitrogen, Ca, Cu, and Fe concentrations were significantly higher in shade-grown arugula compared to those grown in an unshaded high tunnel. Foliar N concentrations were 6.45% and 5.93% in shaded and non-shaded tunnels, respectively. Calcium concentrations were also significantly higher in the shaded tunnels (2.34%) compared to unshaded tunnels (1.88%). Micronutrient concentrations of Fe and Cu were significantly higher in shade-grown arugula than those grown in the non-shaded tunnel. These concentrations of Fe in the shaded and non-shaded arugula were 238.4 ppm and 188.8 ppm, respectively. Phosphorus was the only nutrient that was found in higher concentrations in the nonshaded arugula plants. Foliar P levels were 0.59% and 0.64% in the shaded and nonshaded arugula,

respectively. Average K, Mg, and Mn concentrations in arugula were not affected by any treatment and were 5.9%, 0.3%, and 44.4 ppm, respectively (data not shown).

4. Discussion

As expected, the high tunnel with 30% shade cloth had lower PPFD levels (29.7% less) than the non-shaded tunnel. As such, the non-shaded high tunnel experienced higher average soil and air temperatures. Similar results have been found in other shade studies. Willits and Peet [23] reported that by using shade cloth (55%) on top of a greenhouse, average air and soil temperatures were reduced by 18.5% and 13.9%, respectively. Other studies have suggested that using shade cloth (50% and 70%) for production of tomatoes and peppers reduced air and soil temperatures compared to exposure to full sunlight, resulting in lower rates of evaporation and elevated soil moisture levels [24]. This agrees with the results of the present trial, where the shaded high tunnel had significantly lower soil temperatures and significantly higher soil moisture levels at night.

It is also noteworthy that the non-shaded high tunnel had a reduction in PPFD of 30.3% compared to outdoor ambient conditions. Other studies have reported similar effects of plastic deterioration on shading in high tunnels [22]. The combination of shading from both plastic and the shade cloth, resulting in a reduction in PPFD of 51% in the shaded high tunnel compared to outdoor conditions.

Relative humidity was greater in both tunnels at night compared to outdoor conditions, suggesting that despite the lack of rain, the high tunnels prevented moisture from dissipating into the atmosphere. Fogging increased soil moisture and leaf wetness levels compared to the not fogging. In the evening, after fogging termination, leaf wetness counts remained higher in the fogged treatments, which was likely the result of greater soil moisture levels in the fogged plots. Other studies have reported misting under a shade cloth reduced air and soil temperatures significantly compared to shade cloth alone [23]. In the present study, fogging emitters were placed at canopy level, where microclimate measurements were made. In other trials, treatments were applied from emitters at the top of the greenhouse [23], which would allow for more time for evaporation prior to the mist reaching the surface of the canopy [18]. Studies have shown that fogging cycles of 1.5 min of fogging and 2.0 min between cycles would be result in optimal cooling of a greenhouse structure [25]. In the present study, intervals between fogging cycles were longer (25 or 27 min).

Lettuce and basil had significantly lower yields for planting date two. Although not affected by shade treatment, decreased PPFD observed in both high tunnels combined with lower air temperatures, may have resulted in lower yields of lettuce in the second planting date [26–29]. Walters and Currey [30] reported that yields of basil increased with increasing air temperatures up to 29 °C. Unlike lettuce and basil, yields for arugula were significantly greater for the growing period associated with the second planting date. Following the second planting date, daytime air temperatures averaged 24.2 °C, compared to the first planting date, when air temperatures averaged 28.5 °C. This suggests that the air temperatures in the second planting date may have been closer to those required for optimal growth for arugula. Coolong et al. [31] reported yields of ‘Astro’ arugula that were 42% greater in variety trials conducted in the fall compared to those in the spring. In the higher yielding fall trial, average air temperatures were 23 °C, compared with 17 °C in the spring [31].

Macronutrient levels in all crops were adequate to high, suggesting nutrients were not limiting to growth [32]. Fogging alone had no impact on foliar macronutrient concentrations in the crops grown. Although soil moisture levels were greater in plots subjected to fogging, plant nutrient uptake was not impacted. Fogging did interact with planting date and shade level to impact nutrient levels in lettuce; however, there were no clear trends of shading and fogging acting synergistically or antagonistically to impact nutrient uptake. In lettuce, Mn was lower in the non-fogged plots compared to those that were fogged, which was likely due to changes in soil moisture levels, which can affect Mn availability [33].

Planting date also impacted nutrient uptake for all three crops. While lettuce and basil had higher yields with the first planting date, nutrient concentrations did not necessarily align with these data. Arugula yields were higher in the second planting date, which also corresponded with greater P, S, and Cu concentrations.

Shading increased nutrient concentrations for most nutrients in the three crops evaluated. For macronutrients, the exceptions were K and P concentrations being lower in shaded lettuce and arugula, respectively. Copper concentrations were slightly higher in non-shaded basil than the shade-grown basil. Arugula had higher concentrations of N and Ca in shaded crops. Shading often resulted in higher concentrations of nutrients in lettuce and basil during the first planting date, when both crops yielded better. Concentrations of Fe and Zn were greater in shade-grown basil and shading has previously been reported to increase concentrations of several micronutrients, including Fe and Zn in crops such as tomatoes [34]. Further, decreased soil (root zone) temperatures in lettuce can increase yield and photosynthesis when plants are grown under supra-optimal air temperatures [35]. In contrast, increased root zone temperatures can result in increased Zn uptake in lettuce through enhanced transpiration when lettuce was grown without heat stress [36]. The impact of shade and plant date on nutrient accumulation was due to the reduction in heat stress encountered early in the season. Others have reported an increase in foliar nutrients for crops grown under shade cloth as well [37–39]. In those studies, air and soil temperatures were generally lower under shade cloth. It has been reported that the increase in N under shaded conditions may be attributed to an associated increase in leaf chlorophyll [40]. By reducing air temperatures, shading may reduce heat stress in plants, allowing for increased nutrient uptake [39].

5. Conclusions

In the present study, the impact of shade and fogging on the microclimate in the plant canopy was evaluated. Shading resulted in reduced PPFD, air and soil temperatures, and increased night-time soil moisture. Fogging treatments resulted in increased soil moisture and canopy leaf wetness. Fog and shading did not affect yield of basil, arugula, or lettuce. An earlier planting date in August may have resulted in differences in yield due to either fogging or shade cloth when air temperatures were higher and more stressful for plants. In the present trial, shade cloth was an effective tool at managing heat when planting in a high tunnel in early fall, but the canopy-level fogging system was limited in affecting air temperatures.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agriculture11070625/s1>, Figure S1: Experimental Design Layout.

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