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Research Reports

Effects of Shading Using a Retractable Liquid Foam Technology on Greenhouse and Plant Microclimates

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SUMMARY. Climate control is an important aspect of greenhouse crop management. Shading is one popular method for reducing excess solar heat radiation and high air temperatures in the greenhouse during the summer season. A new innovative technology has recently been developed and is based on the injection of liquid foam between the double layers of polyethylene of the greenhouse roof. The foam can be used as a shading method during the warm days of the summer. This is the first investigation into the effect of shading using the liquid foam technology on greenhouse and plant microclimates. Our research was conducted over 2 years in two different areas of Canada. Experimental greenhouses were retrofitted with the new technology. Tomato (*Solanum lycopersicum*) and sweet pepper (*Capsicum annuum*) were transplanted. Two shading strategies were used: 1) comparison of a conventional nonmovable shading curtain to the liquid foam shading system and application of liquid foam shading based only on outside global solar radiation; and 2) application of foam shading based on both outside global solar radiation and greenhouse air temperature. Data on the greenhouse microclimate (global solar radiation, air temperature, and relative humidity), the canopy microclimate (leaf and bottom fruit temperatures), and ventilation (opening/closing) were recorded. Our study showed that the retractable liquid foam technology improved greenhouse climate. Under some conditions (very sunny and hot days), a large difference in air temperature (up to 6 °C) was noted between the unshaded and shaded greenhouses as a result of liquid foam application (40% to 65% shading). Foam shading also increased relative humidity by 5% to 12%. Furthermore, bottom fruit temperatures stayed cooler 3 h after shading treatment was stopped. As well, a reduction in ventilation needs was observed with liquid foam shading.

Excess temperature, excess solar radiation, and high vapor pressure deficit (VPD) are major greenhouse concerns during the summer season. These conditions increase plant physiological stress and decrease crop productivity and fruit quality (Gent, 2007). Diurnal high light intensity in the summer may increase photochemical damage to leaf chloroplast and reduce net photosynthesis in leaves receiving direct sunlight (Powles and Björkman, 1982). Many cooling methods such as cooling pads and fogging systems have been used to prevent plant heat stress during the day. In fact, shading is one of the conventional and familiar techniques used by growers to decrease solar radiation and reduce air and leaf temperatures (Sandri et al., 2003). Many methods of shading such as curtains (Lorenzo et al., 2004), whitewash (Fernandez-Rodriguez et al., 2000), and new covering materials (Kittas and Baille, 1998) have been used to reduce plant damage related to high radiation and excess temperature in the summer. Shade helps plants by providing optimum conditions for leaf transpiration (Medrano et al., 2004) and carbone dioxide (CO_2) uptake (Fanjul et al., 1985), lowering air VPD (Lorenzo et al., 2003) and preventing high temperature stress (Jackson et al., 1983). Previous studies showed that shade cloths reduced the amount of solar energy entering the greenhouse and consequently decreased air temperature by partially cutting the heat portion of the solar radiation (Kittas et al., 1999). This incoming energy usually contains more than 50% heat (infrared radiation), which is not useful for plant growth in the summer (Kempkes et al., 2008). That energy also contains 40% to 45% photosynthetic active radiation, which is useful for photosynthesis and carbohydrate assimilation but, unfortunately, is partially cut by the shade (Öztürk and Başçetinçelük, 2003).

Sunarc of Canada Inc. has developed a new shading technology that generates a retractable liquid foam and distributes it between two layers of polyethylene film used as a greenhouse covering material (Villeneuve et al., 2005). To our knowledge, there have been no experiments to date studying the effects of shading using a liquid foam technology on greenhouse and plant microclimates. The aim of the present study was to determine, during few typical days of the summer season, the effects of

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
100	bar	kPa	0.01
0.3048	ft	m	3.2808
0.0929	ft²	m²	10.7639
2.54	inch(es)	cm	0.3937
10.7639	W/ft²	W·m⁻²	0.0929
°F − 32 ÷ 1.8	°F	°C	(1.8 × °C) + 32

different shading strategies using liquid foam technology on greenhouse and plant microclimates.

Materials and methods

Experiments were conducted during two seasons (Summer 2005 and 2007) at two research stations, the Center de Recherche en Horticulture (CRH), Université Laval, Quebec City, QC, Canada (lat. 71°17′ W, long. 46°46′ N), and the Greenhouse and Processing Crops Research Center (GPCRC), Agriculture and Agri-Food Canada, Harrow, Ontario, Canada (lat. 82°58′ W, long. 42°16′ N). Crops of tomato and sweet pepper were transplanted inside the experimental greenhouses (more description is provided subsequently). The first shading strategy was studied at CRH in 2005 and the second strategy was studied at GPCRC in 2007.

Strategy 1: Nonmovable shading curtain versus foam shading based only on external global solar radiation

This experiment was conducted at CRH, in Quebec City, from 26 June 2005 to 11 Oct. 2005. Two greenhouses, a prototype and a control, were used for this experiment. The prototype and control greenhouses were identical except for the retractable foam technology; they were both equipped with two forced-air circulation fans (two exhaust fans and one side louver). Both greenhouses were gothic-type (80.1 ft long × 21.0 ft wide × 16.4 ft gutter) oriented to the northeast covered with a double layer of polyethylene film (ultraviolet-stabilized, 73% light transmission).

The prototype greenhouse was modified to accommodate the installation of a dynamic liquid foam-generating system. The liquid foam was generated from a mixture of water and a foaming agent (Sunarc of Canada, Montreal, Quebec, Canada) and was injected during the day between the double polyethylene films in the roof. A conventional pump was used for generating the liquid foam from the reservoir to inside the roof. In addition, a sloped drain was set up in the system to remove the excess liquid foam. The liquid foam required 20 to 30 min to shade the whole roof (95% to 100% coverage) and usually took the same duration to disappear after the system was shut off. Liquid from collapsed foam was drained back into the surfactant reservoir and recycled to be used again. Figure 1 shows further details about the liquid foam shading system.

For this shading strategy, outside global radiation in excess of 500 $W \cdot m^{-2}$ triggered distribution of the foam by sprinklers (small nozzles located at the roof and generated liquid foam at high pressure) between 0900 and 1100 HR and between 1300 and 1700 HR to provide 15% to 20% shading. Between 1100 and 1300 HR (also, if the solar radiation was above 500 $W \cdot m^{-2}$), large nozzles located at the roof generated, at low pressure, a large amount of liquid foam to reduce solar radiation by 40% to 60% (more shading than the sprinkler system).

A conventional shading screen [black material; 45% shading (Harnois, St-Thomas-de-Joliette, Quebec, Canada)] was installed above the cover of the control greenhouse for the first portion of the summer experiment (from 12 July 2005 to 28 Aug. 2005). The goal was to compare the liquid foam shading with this type of the conventional curtain, usually used by growers in the Quebec area.

Tomato seedlings (cv. Trust) were transplanted on 2 June 2005 in rockwool slabs [3.0 × 7.9 × 35.4 inches (Fibergro Horticultural Products, Sarnia, Ontario, Canada)]. Plant density was 2.20 $plants/m^2$. Microclimate parameters were monitored using temperature sensors [± 0.5 at 25 °C (aspirated HOBO Water Temp Pro v1; Onset Computer, Bourne, MA)]. A pyranometer [daily precision ± 10% (HOBO; Onset Computer)] was used to measure solar radiation. Day/night temperatures were 25/17 °C, and the ventilation temperature was set at 25 °C. The light and temperature sensors were positioned 11.5 and 6.6 ft above ground level, respectively. These parameters were continuously measured at three points inside each greenhouse (center, northeast, and southwest).

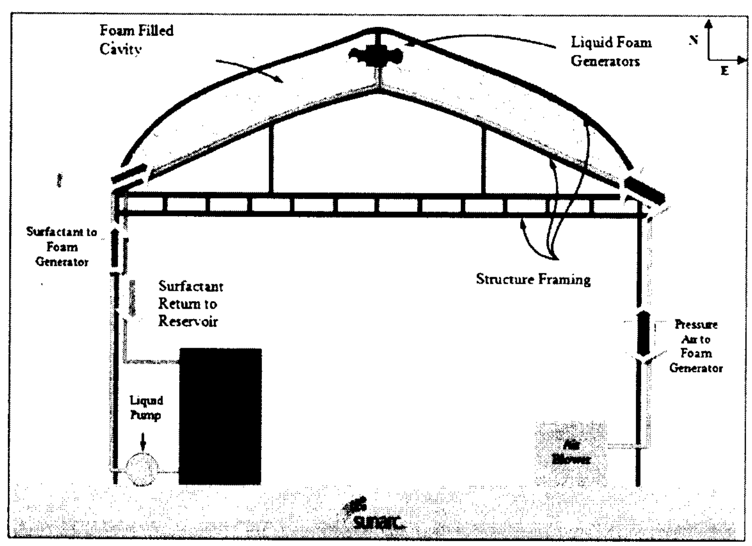

Fig. 1. Schematic view and general concept of the retractable liquid foam technology (Sunarc, Montreal, Canada).

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Leaf temperature was measured using an infrared thermometer [± 0.5 at 25 °C (Raynger ST Pro; Raytek, Santa Cruz, CA)] and was obtained from the fifth expanded developed leaf from the apex of the plant (3 Aug. 2005 and 5 Sept. 2005).

Strategy 2: Foam shading based on both external global solar radiation and greenhouse air temperature

At GPCRC, in Harrow, three identical and independent air-inflated, forced air-heated and -vented greenhouses (24.6 ft long × 21.8 ft wide × 11.4 ft gutter) made of double-layer polyethylene (ultraviolet-stabilized, 73% light transmission) were retrofitted into gutter-vented greenhouses and equipped with natural gas furnaces. The three greenhouses were oriented to the north and equipped with one exhaust fan, three side louvers, and one roof vent. The experiment was conducted from 21 June 2007 to 20 Sept. 2007. The liquid foam was generated from a mixture of water and a foaming agent and according to the same design presented in the first strategy (Fig. 1). However, the sprinklers used for the second shading strategy differed from the design of those used for the first strategy. At CRH, the sprinklers provided 15% to 20% shading, whereas at GPCRC, they provided just 5% to 10% shading.

In case of this second strategy, the liquid foam technology was used for shading based on greenhouse air temperature and external global solar radiation. An unshaded greenhouse (control) and two prototype greenhouses shaded with the retractable foam technology (Shade 1 and Shade 2) were used for treatments. When the air temperature in the Shade 1 greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading). For the Shade 2 greenhouse, when the greenhouse air temperature exceeded 27 °C and outside solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinklers were used (5% to 10% shading); when the inside air temperature exceeded 30 °C, the liquid foam was used (45% to 65% shading). Shading treatments were controlled automatically by a computer system (Priva Computers, Vineland, Ontario, Canada).

Old and young crops of tomato (cv. Macarena) and sweet pepper (cv. Triple-4) were planted. The old crops were planted on 15 Dec. 2006, and the young crops were planted on 17 June 2007. The transplants were planted onto rockwool slabs (3.9 × 9.1 × 39.4 inches) inside the three greenhouses. Each pepper plant was allowed two stems and trained into a V-system. Plant density was 2.80 plants/m^2. Day and night temperatures were set at 20 °C, and ventilation was set at 25 °C. The greenhouse roof vent could open automatically even with the presence of the foam between the roof's double layers of film (Fig. 2). The temperature set values for vent opening were 28 °C for 75% to 100% roof opening, 27 °C for 50% to 75% roof opening, 26 °C for 25% to 50% roof opening, and 25 °C for 0% to 25% roof opening. Ventilation operation (opening/closing) was recorded by the computer system. In the absence of shading treatments, ventilation of each compartment was calibrated to make sure that they had the same operation rate.

Outside and inside climate conditions were monitored by data logger with four 39-channel multiplexers (CR21X; Campbell Scientific, Edmonton, Alberta, Canada). Data were recorded every 5 min. Air temperature and relative humidity were

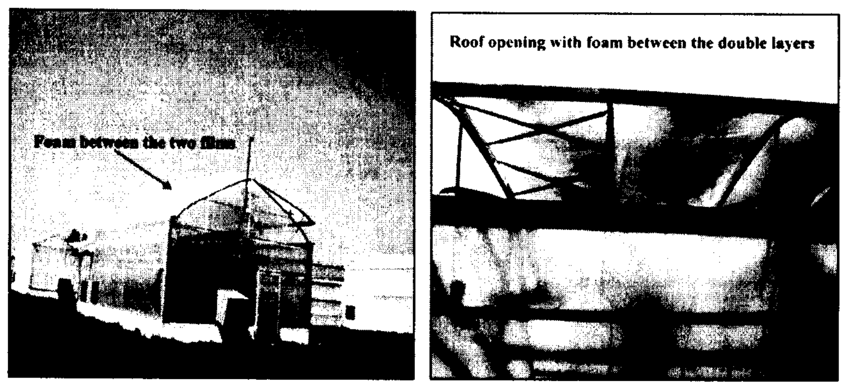

Fig. 2. Roof opening in the presence of liquid foam shading between the double layers of polyethylene of the greenhouse.

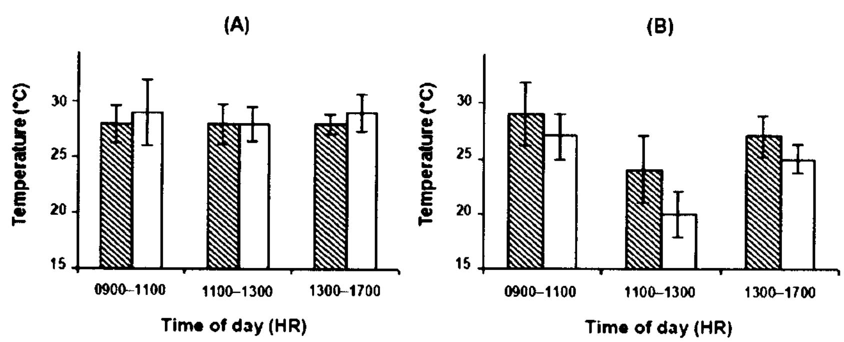

Fig. 3. Temperature of the fifth developed leaf from the apex of tomato plants grown in the control greenhouse (hatched bar) (A) with a shading screen (45% shading) (3 Aug. 2005) and (B) without a shading screen (5 Sept. 2005) and in the prototype shaded greenhouse (open bar). If the outside radiation exceeded 500 $W \cdot m^{-2}$, the sprinklers were used between 900 and 1100 HR and between 1300 and 1700 HR, and the liquid foam was used between 1100 and 1300 HR. Leaf temperature was measured using an infrared thermometer. Data are the means of 16 replicates ± SD. This experiment was conducted at the Center de Recherche en Horticulture in Quebec City, QC, Canada; (1.8 − °C) + 32 = °F; 1 $W \cdot m^{-2}$ = 0.0929 W/ft^2.

monitored at one location inside, at the center of the greenhouse. They were monitored at one height (4.5 ft inside the canopy) above the ground level. Temperature and humidity probes [± 0.1 °C and ± 2% at 25 °C for temperature and relative humidity, respectively (Model IH 3602; Hycal, El Monte, CA)] were calibrated against factory reference and standard solutions (relative humidity) installed inside nonaspirating polyvinyl chloride tubes and were used for measurements. Global solar radiation was monitored by point sensor at one location in the center of each greenhouse and outside one of the greenhouse at 11.1 and 19.7 ft above ground level, respectively, with CM3 pyranometers (daily precision ± 10%; Kipp and Zonen, Bohemia, NY). Sensors measuring leaf temperature [± 0.5 at 25 °C (Type T; Campbell Scientific)] were taped under the fifth developed expanded leaf from the apex of the plant. Temperatures of bottom fruit (of the same size) were measured by needle sensor (cryogenic to 200 °C, ± 0.5 at 25 °C; Campbell Scientific). The fruit needle was inserted into the center of the bottom fruit (at the apex). Skin temperatures of the same bottom fruit were measured by thermocouples. Then, temperature differential between the fruit skin and inside the fruit ($\Delta T = T_{fruit\ skin} - T_{inside\ fruit}$) was calculated. All sensors were positioned in the same place for each greenhouse, in a shaded place. The main goal behind shading the sensors was to measure the real temperature (air, leaf, skin, or fruit) and to prevent error readings because of any interference by the solar radiation.

The shading percentage was calculated by dividing the global solar radiation intercepted inside the prototype greenhouse by the global solar radiation intercepted inside the control greenhouse.

Statistical analysis

The fact that only two or three greenhouses microclimates were compared during this study, no appropriate statistical analysis of the results was allowed. However, the main objective of the current work was only to show a trend of the liquid foam shading effects during few typical warm and sunny days on greenhouse and plant microclimates.

Results

Strategy 1: Nonmovable shading curtain versus foam shading based only on external global solar radiation

AIR TEMPERATURE. From a typical warm day of August and under clear sky conditions (Quebec City), the sprinkler system reduced the air temperature by 1 °C between 900 and 1100 HR and between 1300 and 1700 HR, and the liquid foam reduced the air temperature by up to 2 °C between 1100 and 1300 HR compared with the shading curtain. In late summer (during a typical clear sky and warm conditions of September), when the curtain was

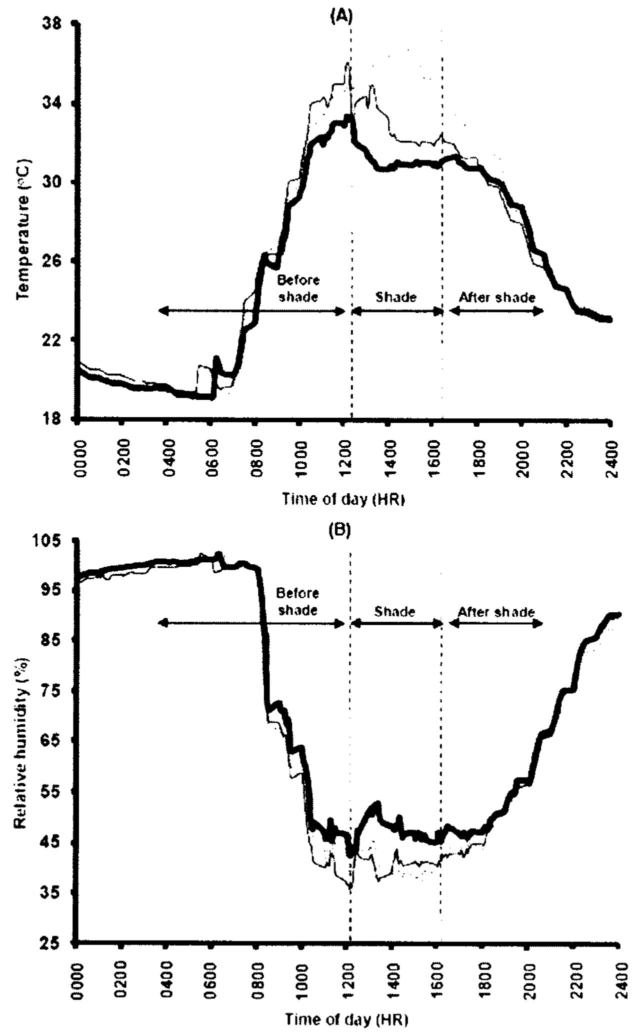

Fig. 4. (A) Air temperature and (B) relative humidity (RH) in the unshaded greenhouse (control.........) and in the greenhouses shaded by the liquid foam technology (Shade 1: ——— and Shade 2: ———) measured on 31 July 2007. This experiment was conducted at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada. For Shade 1, when the air temperature in the greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 W·m^{-2} (before 1300 HR) or 700 W·m^{-2} (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading). For Shade 2, when the air temperature in the greenhouse exceeded 27 °C and outside global solar radiation exceeded 800 W·m^{-2} (before 1300 HR) or 700 W·m^{-2} (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 30 °C, the liquid foam was injected to provide shading (45% to 65% shading). Sensors were monitored at one location inside, at the center of the greenhouse, at one height [4.5 ft (1.37 m), inside the canopy and above the ground level]; (1.8 – °C) + 32 = °F; 1 W·m^{-2} = 0.0929 W/ft^2.

removed on the control greenhouse, the liquid foam technology reduced the air temperature by 1 °C between 900 and 1100 HR and between 1300 and 1700 HR (sprinkler system) and by up to 2 °C between 1100 and 1300 HR (liquid foam shading) (data are not shown).

Leaf temperature. Temperatures of the fifth developed leaves from the apex of tomato plants did not differ between the control greenhouse equipped with a shading screen and the prototype greenhouse shaded with the retractable liquid foam technology (conditions of 3 Aug. 2005) (Fig. 3A). In September, when the shading curtain was removed from the control greenhouse, leaf temperatures of plants grown in the prototype greenhouse shaded by the retractable foam technology were reduced by 1 °C under 15% to 20% shading and by 4 °C under 40% to 60% shading as compared with leaf temperatures measured in the unshaded control greenhouse (conditions of 5 Sept. 2005) (Fig. 3B).

Strategy 2: Foam shading based on both external global solar radiation and greenhouse air temperature

Greenhouse microclimate. On one of the hottest and sunniest days of the year, 31 July 2007 (Harrow area), liquid foam shading reduced global solar radiation by 63% (data not shown) and greenhouse air temperature by up to 6 °C, resulting in an increase in relative humidity of 6% to 12% (Fig. 4). However, the sprinkler system (5% to 10% shading) did not affect greenhouse air temperature and relative humidity (data not shown).

Leaf temperature. On that same day (31 July 2007), shading reduced the temperatures of the fifth leaves of tomato and sweet pepper plants by up to 2 to 3 °C (Table 1). During the shade period (between 1215 and 1615 HR), leaf temperatures were 30.8, 28.0, and 28.1 °C for the old tomato plants and 29.0, 27.8, and 27.8 °C for the young tomato plants in the control, Shade 1, and Shade 2 greenhouses, respectively. For the pepper plants, leaf temperatures were 30.4 and 28.6 °C for the old pepper plants and 30.7 and 27.9 °C for the young pepper plants in the control and Shade 1 greenhouses, respectively.

Table 1. Leaf temperature (fifth developed leaf from the apex) for tomato and sweet pepper plants (old and young crops) grown in the unshaded greenhouse (control) and in the prototype greenhouses shaded with the retractable foam technology (Shade 1 and Shade 2) at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada.

	Leaf temp [mean ± SD (°C)][y]		
Crop/shading treatment[z]	Before shade (0800–1215 HR)	During shade (1215–1615 HR)	After shade (1615–2015 HR)
Tomato (old crop)			
Control[x]	28.4 ± 0.6	30.8 ± 1.6	29.1 ± 0.5
Shade 1[w]	27.4 ± 1.3 (−1.0)[u]	28.0 ± 0.2 (−2.8)	28.0 ± 0.3 (−1.1)
Shade 2[v]	27.5 ± 1.5 (−0.9)	28.1 ± 0.4 (−2.7)	28.2 ± 0.2 (−0.9)
Tomato (young crop)			
Control	26.4 ± 0.6	29.0 ± 0.4	28.0 ± 0.3
Shade 1	26.6 ± 0.3 (+0.2)	27.8 ± 0.6 (−1.2)	28.0 ± 0.4 (±0.0)
Shade 2	27.5 ± 1.4 (+0.9)	27.8 ± 0.3 (−1.2)	27.7 ± 0.3 (−0.3)
Sweet pepper (old crop)			
Control	27.1 ± 0.5	30.4 ± 0.9	29.6 ± 0.7
Shade 1	27.3 ± 1.2 (+0.2)	28.6 ± 0.8 (−1.8)	28.9 ± 0.3 (−0.7)
Shade 2	27.5 ± 0.7 (+0.4)	29.1 ± 0.3 (−1.3)	29.6 ± 0.7 (±0.0)
Sweet pepper (young crop)			
Control	26.5 ± 0.9	30.7 ± 0.7	29.3 ± 0.4
Shade 1	26.4 ± 0.6 (−0.1)	27.9 ± 0.8 (−2.8)	28.3 ± 0.3 (−1.0)
Shade 2	—	—	—

[z]Old and young crops were planted on to rockwool slabs inside three greenhouses on 15 Dec. 2006 and 17 June 2007, respectively.

[y]Data were recorded every 5 min. Data are the means of three sensor readings. Sensors were taped under the fifth developed expanded leaf from the apex of the plant; (1.8 × °C) + 32 = °F.

[x]Control = greenhouse without shade.

[w]Shade 1 = when the air temperature in the greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ before 1300 HR or 700 $W \cdot m^{-2}$ after 1300 HR, the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading); 1 $W \cdot m^{-2}$ = 0.0929 W/ft^2.

[v]Shade 2 = when the air temperature in the greenhouse exceeded 27 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 30 °C, the liquid foam was injected to provide shading (45% to 65% shading).

[u]Data within parentheses represent the difference between the leaf temperature values and the control treatment.

Bottom fruit temperature. No obvious difference in bottom fruit temperature was measured between the tomato plants (old and young crops) grown in the control greenhouse and those grown in the shaded greenhouse (on the same day, 31 July 2007) (Table 2). Bottom fruit temperatures were 30.9, 30.7, and 30.7 °C for the old tomato plants and 30.8, 29.4, and 29.6 °C for the young tomato plants in the control, Shade 1, and Shade 2 greenhouses, respectively. However, there was a difference between treatments for the bottom fruit of the pepper plants. Bottom fruit grown in the shaded greenhouses were cooler by 2 to 3 °C. Bottom fruit temperature values were 33.0, 30.5, and 31.8 °C for the old pepper plants and 32.0, 30.5, and 30.2 °C for the young pepper plants in the control, Shade 1, and Shade 2 greenhouses, respectively.

Bottom fruit temperatures for the tomato and sweet pepper plants grown in the shaded greenhouse stayed lower (1.5 °C) than the control for 3 h (between 1615 and 1915 HR) after the shading was stopped (Fig. 5). Bottom fruit temperatures in the control greenhouse dropped and were equal to bottom fruit temperatures in the shaded greenhouses at 1915 HR. However, this time delay recorded after shading was higher in case of tomato (Fig. 5A) than sweet pepper (Fig. 5B). In other words, bottom fruit temperatures dropped faster in case of sweet pepper than tomato. This trend observed for bottom fruit temperatures after the shade period also happened during other sunny and warm days conditions (data not shown).

In addition, our results indicate that diurnal temperature differential (ΔT) between the bottom fruit skin and inside the fruit was much higher in case of the tomato (1 °C) than the sweet pepper (−0.2 °C). This observation was recorded between 1200 and 1600 HR inside the unshaded

Table 2. Bottom fruit temperature for tomato and sweet pepper plants (old and young crops) grown in the unshaded greenhouse (control) and in the prototype greenhouses shaded with the retractable foam technology (Shade 1 and Shade 2) at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada.

	Bottom fruit temp [mean ± SD (°C)][y]		
Crop/shading treatment[z]	Before shade (0800–1215 HR)	During shade (1215–1615 HR)	After shade (1615–1915 HR)
Tomato (old crop)			
Control[x]	24.7 ± 0.7	30.9 ± 0.7	32.2 ± 0.4
Shade 1[w]	25.1 ± 0.7 (+0.4)[u]	30.7 ± 0.3 (−0.2)	30.7 ± 0.6 (−1.5)
Shade 2[v]	25.3 ± 0.3 (+0.6)	30.7 ± 0.2 (−0.2)	31.1 ± 0.3 (−1.1)
Tomato (young crop)			
Control	24.7 ± 1.7	30.8 ± 2.1	31.6 ± 0.4
Shade 1	23.6 ± 0.1 (−1.1)	29.4 ± 0.1 (−1.4)	30.1 ± 0.2 (−1.5)
Shade 2	24.0 ± 0.2 (−0.7)	29.6 ± 0.3 (−1.2)	30.6 ± 0.4 (−1.0)
Sweet pepper (old crop)			
Control	27.3 ± 0.2	33.0 ± 0.8	32.9 ± 1.4
Shade 1	27.3 ± 1.6 (±0.0)	30.5 ± 0.5 (−2.5)	31.0 ± 1.3 (−1.9)
Shade 2	28.3 ± 1.0 (+1.0)	31.8 ± 1.8 (−1.2)	32.3 ± 2.1 (−0.6)
Sweet pepper (young crop)			
Control	26.2 ± 0.4	32.0 ± 0.3	32.1 ± 0.0
Shade 1	27.5 ± 1.5 (+1.3)	30.5 ± 0.1 (−1.5)	30.5 ± 0.3 (−1.6)
Shade 2	27.2 ± 0.4 (+1.0)	30.2 ± 0.5 (−1.8)	30.4 ± 0.5 (−1.7)

[z]Old and young crops were planted on to rockwool slabs inside three greenhouses on 15 Dec. 2006 and 17 June 2007, respectively.

[y]Data were recorded every 5 min. Data are the means of two needle thermocouple readings sensor readings. The fruit needle was inserted into the center of the bottom fruit (at the apex); (1.8 × °C) + 32 = °F.

[x]Control = greenhouse without shade.

[w]Shade 1 = when the air temperature in the greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ before 1300 HR or 700 $W \cdot m^{-2}$ after 1300 HR, the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading); 1 $W \cdot m^{-2}$ = 0.0929 W/ft^2.

[v]Shade 2 = when the air temperature in the greenhouse exceeded 27 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 30 °C, the liquid foam was injected to provide shading (45% to 65% shading).

[u]Data within parentheses represent the difference between the bottom fruit temperature values and the control treatment.

control greenhouse on very hot day conditions and under clear sky conditions (observation recorded on 16 July 2008; very similar weather conditions of 31 July 2007) (Fig. 6).

GREENHOUSE VENTILATION. Under sunny and clear sky days, all cooling fans (exhaust fan and three side louvers) were completely opened (100% operation) in the three greenhouses (data not shown). However, the roof vent was opened at a low level when the shade was provided by the liquid foam (1115 to 1615 HR). For example, on 12 July 2007, the roof vents were opened at 96% in the control greenhouse, 53% in the Shade 1 greenhouse (liquid foam), and 82% in the Shade 2 greenhouse (sprinkler system) (Table 3). On 13 Aug. 2007, the roof vents were opened at 86% in the control greenhouse, 48% in the Shade 1 greenhouse (foam), and 67% in the Shade 2 greenhouse (sprinkler system and liquid foam shading).

Discussion

AIR TEMPERATURE. Reduction in air temperature by liquid foam shading depended on external weather conditions, geographical location (Quebec City, Quebec, versus Harrow, Ontario). The liquid foam technology decreased air temperatures by up to 6 °C in hot weather and sunny conditions (in the case of Harrow). Moreover, our results for the first strategy showed that liquid foam shading (40% to 65% shading) decreased air temperatures more than a conventional shading curtain (45%) (in the case of Quebec City). Previous work has shown different reductions in the greenhouse air temperature by shading. As demonstrated by Kittas et al. (2001), the real temperature reduction with shade screens was not proportional to the percentage of shading. Beppu and Kataoka (2000) reported that shading levels of 53% and 78% reduced the daily maximum air temperature by 1.9 and 3.3 °C, respectively, compared with the unshaded control. Ghosal et al. (2003) found that the air temperature was reduced by 6 and 2 °C in shaded greenhouses with roof water evaporative flow and a shading curtain, respectively, as compared with unshaded conditions.

RELATIVE HUMIDITY. Usually, the most obvious effect of diurnal low humidity or high leaf VPD (more than 2 kPa) is the induction of leaf stress when water uptake through the root system cannot balance the transpiration rate. The low relative humidity and high VPD during the day could cause an increase in fruit calcium deficiency (blossom-end rot) and fruit cracking and could also decrease leaf photosynthesis (Xu et al., 1991). Shading with liquid foam increased greenhouse relative humidity and few studies supported our results (Schütz et al., 2008). These phenomena can be explained by the fact that decreasing greenhouse air temperature by shading will increase the air capacity to hold water vapor and that will increase greenhouse relative humidity.

The increase in greenhouse relative humidity and the decrease in air temperature found in the present study helped decrease leaf–air VPD (data not shown) and that could improve the environment for stomatal conductance, photosynthesis, and leaf transpiration (Katsoulas et al., 2001). Increase in relative humidity by the liquid foam shading could also reduce fruit physiological disorders. However, this aspect was not studied yet in our current work.

Furthermore, Perdigones et al. (2008) conducted an experiment combining the effect of shading and fogging and showed that this combination improved greenhouse relative humidity. A combination of liquid foam shading and misting could be an interesting application for improving the environment (by decreasing VPD and air temperature) for plant growth during hot and dry weather (Leonardi et al., 2000). In our research, diurnal relative humidity reached 50% to 52% (mean values extracted from Fig. 4) in the greenhouse shaded by the liquid foam technology. Misting or fogging the shaded greenhouse could decrease

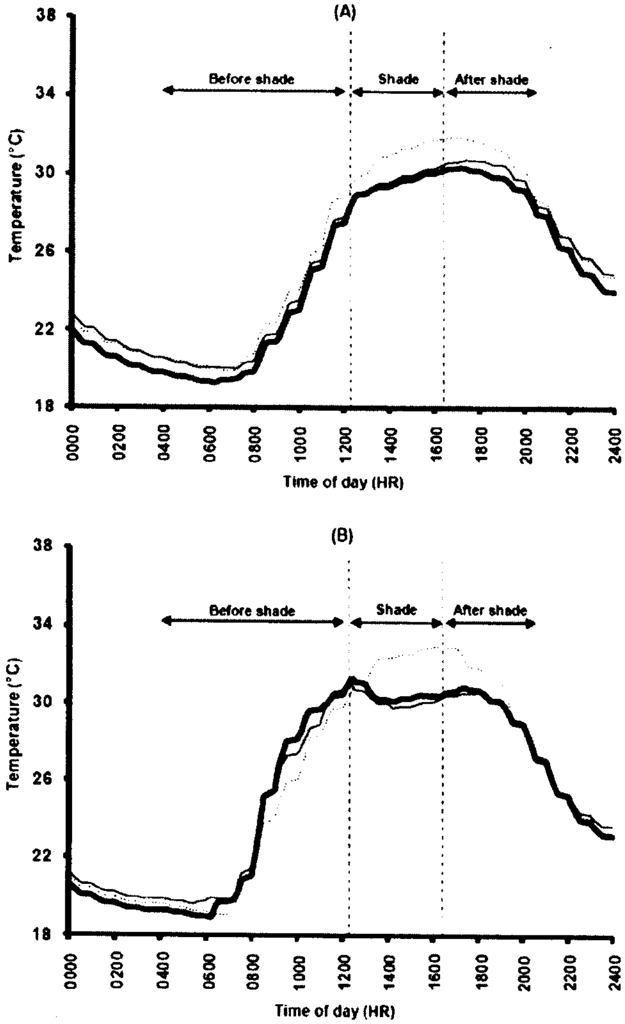

Fig. 5. Temperature of the bottom fruit of (A) the young tomato and (B) the young sweet pepper plants grown inside the unshaded greenhouse (control: ....) and inside the greenhouses shaded by the liquid foam technology (Shade 1: ━━━ and Shade 2: ———) measured on 31 July 2007. Data are the means of two needle thermocouple readings. This experiment was conducted at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada. For Shade 1, when the air temperature in the greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading). For Shade 2, when the air temperature in the greenhouse exceeded 27 °C and outside global solar radiation exceeded 800 $W \cdot m^{-2}$ (before 1300 HR) or 700 $W \cdot m^{-2}$ (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 30 °C, the liquid foam was injected to provide shading (45% to 65% shading). Young crops of tomato and sweet pepper crops were planted in 17 June 2007, and the young crops were planted in 17 June 2007 onto rockwool slabs and inside the three greenhouses. The fruit needle was inserted into the center of the bottom fruit (at the apex); (1.8 °C) + 32 = °F; 1 $W \cdot m^{-2}$ = 0.0929 W/ft^2.

the air temperature and increase air and leaf water potential and help achieve 75% relative humidity, which has been suggested as the optimum value for plant growth.

Leaf temperature. In this study (Quebec City and in the Harrow area), we also found that leaf temperature decreased less than air temperature with liquid foam shading. This observation is supported by Willits (2001), who reported that the decrease in leaf temperature from shade (30%, 50%, and 55% shading) was less than the decrease in greenhouse air temperature. Leaf transpiration inside the unshaded control greenhouse could provide some natural cooling (Katsoulas et al., 2002) and this phenomenon could explain our observations.

Moreover, in the first shading strategy, the difference in leaf temperature values between the three periods of the day shown in Figure 3B could be explained by variations in outside air temperature, which were different between 1100 and 1300 HR compared with the morning (between 0900 and 1100 HR) and the afternoon (between 1300 and 1700 HR). Cooler air entering the greenhouse between 1100 and 1300 HR decreased leaf temperatures during that period.

Bottom fruit temperature. According to the results of the second shading strategy, no large difference in bottom fruit temperatures was noted between the tomato plants grown in the control and those grown in the shaded greenhouses (Table 2) compared for the case of sweet pepper. That finding could be explained by the fact that bottom fruit were more shaded by leaves in the case of tomato than sweet pepper. This leaf shading partially helped to decrease bottom tomato fruit temperatures in the control greenhouse and compensated for the cooling provided by the foam shading in the shaded greenhouses. Also, the bottom fruit of the tomato plants were closer to the greenhouse floor than the bottom fruit of the pepper plants (9.8 inches above floor level for bottom tomato fruit versus 39.4 inches above floor level for bottom pepper fruit). The greenhouse floor evidently received cooler air flow through air convection. Consequently, the tomato fruit (at the bottom of the plants) might benefit from the convection caused by this cooler air flow inside the control greenhouse and that explains the lack of difference in bottom fruit temperatures between the treatments. For this purpose, Table 2 supports this observation and shows also that inside the unshaded control greenhouse, bottom fruit temperatures for the tomato plants were cooler (30.8 and 30.9 °C) than bottom fruit temperatures for the sweet pepper plants (32.0 and 33.0 °C) during the shade period.

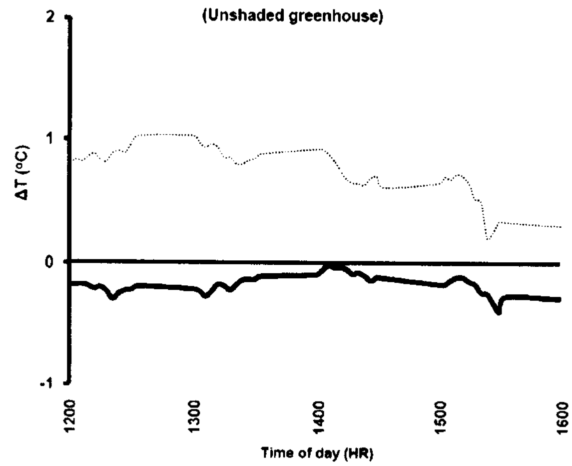

Fig. 6. Temperature differential ($\Delta T = T_{fruit\ skin} - T_{inside\ fruit}$) of the fruit at the bottom of the old tomato plants (.........) and the old pepper plants (———) grown inside the unshaded control greenhouse measured on 16 July 2008 (similar climate conditions than 31 July 2007). Data are the means of two thermocouple readings. This experiment was conducted at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada. Old crops of tomato and sweet pepper crops were planted on to rockwool slabs on 15 Dec. 2006. The fruit needle was inserted into the center of the bottom fruit (at the apex) and the skin temperatures of the same bottom fruit were measured by thermocouples; (1.8 – °C) + 32 = °F; 1 W·m^{-2} = 0.0929 W/ft^2.

Table 3. Percentage opening of the roof vent measured on 12 July 2007 and 13 Aug. 2007 in the unshaded control greenhouse and in the greenhouses shaded by the liquid foam technology at the Greenhouse and Processing Crops Research Center in Harrow, Ontario, Canada.

Date	Opening of the roof vent(%)[z]		
	Control[y]	Shade 1[x]	Shade 2[w]
12 July 2007	96	53 (foam)	82 (sprinklers)
13 Aug. 2007	86	48 (foam)	67 (sprinklers and foam)

[z]Data are the means of measurements recorded between 1115 and 1630 HR; the greenhouse roof vent could open automatically even with the presence of the foam between the roof's double layers of film. The temperature set values for vent opening were 28 °C for 75% to 100% roof opening, 27 °C for 50% to 75% roof opening, 26 °C for 25% to 50% roof opening, and 25 °C for 0% to 25% roof opening. In the absence of shading treatments, ventilation of each compartment was calibrated to make sure that they have the same operation rate; (1.8 – °C) + 32 = °F.
[y]Control = greenhouse without shade.
[x]Shade 1 = when the air temperature in the greenhouse exceeded 24 °C and outside global solar radiation exceeded 800 W·m^{-2} before 1300 HR or 700 W·m^{-2} after 1300 HR, the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 27 °C, the liquid foam was injected to provide shading (45% to 65% shading); 1 W·m^{-2} = 0.0929 W/ft^2.
[w]Shade 2 = when the air temperature in the greenhouse exceeded 27 °C and outside global solar radiation exceeded 800 W·m^{-2} (before 1300 HR) or 700 W·m^{-2} (after 1300 HR), the sprinkler system was used (5% to 10% shading); when the greenhouse air temperature exceeded 30 °C, the liquid foam was injected to provide shading (45% to 65% shading).

After the shade period, bottom fruit temperatures for the tomato and sweet pepper plants grown in the shaded greenhouse stayed lower (1.5 °C) than those grown in the control greenhouse for 3 h after the shading was stopped (between 1615 and 1915 HR). The bottom fruit temperatures in the control greenhouse dropped and were equal to the bottom fruit temperatures in the shaded greenhouses until 1915 HR (Table 2; Fig. 5). The presence of foam residues on the greenhouse roof might also have been responsible for this cooling delay between the shaded and control greenhouses. After the shade was stopped (at 1615 HR), residues remained for 30 min before the foam disappeared completely from the roof.

Moreover, it has shown that after the shading period, bottom fruit temperatures dropped faster in case of sweet pepper than in the case of tomato (Fig. 5A–B). This could be explained by the fact that temperatures of the bottom sweet pepper fruit were more influenced with changes in outside air temperature than the bottom tomato fruit. This could be explained by the fact that temperatures of the bottom sweet pepper fruit were more influenced with changes in outside air temperature than the bottom tomato fruit. This hypothesis was supported by higher diurnal ΔT between the bottom fruit skin and inside the fruit for tomato (1 °C) than sweet pepper (–0.2 °C) (Fig. 6).

VENT OPERATION. Roof vent opening was decreased during the shading period. The decrease in greenhouse air temperature with liquid foam shading led to a decrease in vent operation. Table 3 shows that the roof vent of the Shade 1 greenhouse was open at 48% to 53% (average of the period 1115 to 1630 HR). In that case, the greenhouse air temperature was 26 °C in the presence of liquid foam shading and above 29 °C in the unshaded control greenhouse (data not shown).

Few studies reported that shading could decrease the ventilation rate (Luo et al., 2005). This decrease was dependent on the outside weather conditions and the temperature set for ventilation. This finding that vent operation is affected by shade can be valuable for reducing losses through ventilation with respect to enriched CO_2, especially during the fall and spring seasons, when air temperatures are cooler. Decreasing the operation of greenhouse ventilation can be valuable in terms of reducing enriched CO_2 losses and can be economically beneficial for growers. Also, early in the spring and fall seasons, application of liquid foam shading on warm and sunny days can completely prevent the opening of the ventilation and save the CO_2 enrichment. In such conditions (closed ventilation in spring and fall, and sunny and warm days), plants benefit from the high CO_2 concentration provided by the enrichment inside the greenhouse. One consideration that should be taken into account for this strategy is whether the CO_2 saved from ventilation could compensate for the loss in production because of light reduction by shading. Also, the increase in relative humidity because of closed ventilation should be taken into consideration to prevent high VPD and crop disease. In our study, we did not investigate this strategy further (liquid foam shading and CO_2 enrichment).

In summary, this research reported, for the first time, the effects of application of the liquid foam technology as a shading method on greenhouse and plant microclimates. As presented, only a few typical days from the summer were chosen in both areas (sunny and warm). Our results showed that the retractable liquid foam technology improved greenhouse and plant microclimates. A large difference in air temperature was noted between the unshaded control greenhouse and the greenhouses shaded by the liquid foam technology. This difference in air temperature was as high as 6 °C. The results also showed that liquid foam shading decreased air temperature more than the conventional shading curtains did (usually used by greenhouse growers). In addition, an important effect was noted for greenhouse relative humidity: foam shading increased the relative humidity value by up to 12%. Moreover, it was found that with foam shading, bottom fruit temperatures stayed cooler for 3 h after the shading was stopped and this time delay was higher in case of tomato than sweet pepper. Also, roof ventilation opened at a low level when the shade was provided by the liquid foam technology.

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