Heat stress is a limiting factor of plant productivity throughout the world and kaolin-based particle films (PF) have demonstrated that the reflective nature of the resulting plant surface can increase plant productivity primarily by reducing temperature in fruit, leaf, and canopy. The purpose of this study was to evaluate the environmental mechanisms and related physiological responses of 'Empire' apple (Malus domestica) gas exchange at the canopy level to PF treatments to identify those parameters key to plant response and increased plant productivity. Trees received either no treatment or season-long applications of a PF treatment and each treatment either received no supplemental irrigation or full replacement of evaporative transpiration. Studies were begun in 1998 and continued to 2007. Fruit number and fruit weight were measured in all years. Whole canopy carbon dioxide assimilation rates (A) were measured in apple for a 4-year period to determine the relationship with incoming light and vapor pressure deficit (VPD) levels. The photosynthetic response to the irrigation and PF treatments varied between years as a result of environmental variation in VPD and photosynthetically active radiation (PAR) levels. There was a unique treatment response for PAR levels greater than 1600 μmol m⁻² s⁻¹ in which the combination of PF and irrigation maintained midday A at maximum levels compared with other treatments although A was reduced by increasing VPD. This response indicated that although VPD limited A, the combination of PF and adequate water could maintain maximum A rates at full sun levels during the midday period and minimize the midday depression of A that is commonly observed and reduces the daily carbon accumulation. The increased carbon accumulation during the midday period was likely partitioned to the fruit. Increased fruit weight resulting from the PF treatment, compared with the control, was positively correlated with the growing season air temperature and VPD indicating that as the environment becomes hotter and/or drier, the magnitude of the PF response increased as a result of the reduced leaf and fruit temperature and the subsequent physiological effect. The PF treatments reduced radiation and heat load on exposed leaves enabling them to better regulate leaf temperature and improved the light distribution inside the canopy resulting in increased carbon gain at the whole plant scale. Fruit hue angle was reduced and red color improved by PF treatments in 5 of 10 years. The use of PF may be an effective substitute for evaporative cooling to reduce solar injury and to improve apple quality through increased fruit weight. The results indicate that benefits of PF treatments would occur in agroecosystems with large VPDs and high temperatures and that use of irrigation would further enhance the benefits at high PAR levels.
canopy to increase the interior canopy photosynthetic rate, resulting in an estimated 9% increase in canopy photosynthesis. Steiman et al. (2007) similarly indicated that physiological responses of PF in coffee must be linked to plant growth, yield, or quality to understand their relationship and importance. The purpose of the present study was to evaluate the environmental mechanisms and related physiological responses of gas exchange in apple trees at the canopy level to PF treatments to identify those parameters key to plant response and increased plant productivity.

Materials and Methods

Materials. Apple trees received applications of a highly reflective, white, hydrophilic particle based on kaolin mineral (Surround WP™; NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) in addition to a conventional pesticide spray program. The mineral was processed to a bright white color of greater than 90% reflectance with mean particle size less than 2 μm diameter. In 1998, a prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall. A prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents.

In 1998, a prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall. A prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents.

The apple orchard was a moderate density planting (500 trees/ha) of ‘Empire’/’M.7A’ planted in 1992 at the U.S. Department of Agriculture, Agricultural Research Service, Appalachian Fruit Research Station, Kearneysville, WV. The trees were not irrigated in 1998, 2000, 2001, 2002, and 2004 as a result of adequate summer rainfall, defined as growing season rainfall greater than 85% of tree requirement based on pan evaporation. Tree water requirements were based on 70% of pan evaporation (Glenn, 1995, 1999). Irrigation treatments consisted of two drip emitters per tree receiving the daily water needs. Treatments were randomly assigned in 1998 in a randomized block design with six single-tree replicates. Treatments were randomly assigned in 1999. The treatment assignment from 1999 was used in 2000 and 2001 in a randomized block design with six replications and four trees per plot. Treatments were randomly assigned in 2002 and the same treatment assignments were maintained in 2003 and 2004 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. Irrigation was not applied in 2002 and 2004 as a result of adequate summer rainfall. In 2005, treatments were randomly assigned and the same treatment assignments were maintained in 2006 and 2007 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. In all years, the trees were hand-thinned postbloom. Trees were treated with Surround WP or were not treated. All treatments were oversprayed with conventional pesticides to protect from disease or insect damage. Conventional orchard practices were used in tree training and weed control. At harvest, all fruit were weighed and counted for each tree in a plot. Fruit from each tree were processed with an electronic grader that counted and weighed each fruit.

Fruit maturity parameters. In all studies, fruit were harvested at optimum maturity for storage based on firmness, starch, and soluble solids concentration (SSC). Ten randomly selected fruit/plot were collected to estimate harvest date. A starch index of 1 to 9 is used with a target value of 6 to harvest. Firmness was determined using the McCormick fruit pressure meter. A 5.0 A was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall. A prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall. A prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall. A prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents.

The apple orchard was a moderate density planting (500 trees/ha) of ‘Empire’/’M.7A’ planted in 1992 at the U.S. Department of Agriculture, Agricultural Research Service, Appalachian Fruit Research Station, Kearneysville, WV. The trees were not irrigated in 1998, 2000, 2001, 2002, and 2004 as a result of adequate summer rainfall, defined as growing season rainfall greater than 85% of tree requirement based on pan evaporation. Tree water requirements were based on 70% of pan evaporation (Glenn, 1995, 1999). Irrigation treatments consisted of two drip emitters per tree receiving the daily water needs. Treatments were randomly assigned in 1998 in a randomized block design with six single-tree replicates. Treatments were randomly assigned in 1999. The treatment assignment from 1999 was used in 2000 and 2001 in a randomized block design with six replications and four trees per plot. Treatments were randomly assigned in 2002 and the same treatment assignments were maintained in 2003 and 2004 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. Irrigation was not applied in 2002 and 2004 as a result of adequate summer rainfall. In 2005, treatments were randomly assigned and the same treatment assignments were maintained in 2006 and 2007 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. In all years, the trees were hand-thinned postbloom. Trees were treated with Surround WP or were not treated. All treatments were oversprayed with conventional pesticides to protect from disease or insect damage. Conventional orchard practices were used in tree training and weed control. At harvest, all fruit were weighed and counted for each tree in a plot. Fruit from each tree were processed with an electronic grader that counted and weighed each fruit.

Table 1. Effect of particle film and irrigation treatments on mean whole tree carbon assimilation of ‘Empire’ apple from 1100 to 1500 hr for four temperature ranges in 2003 and 2005–2007 at Kearneysville, WV.

| Year | Treatment | Irrigation | 10–20 °C | 20–25 °C | 25–30 °C | 30–35 °C |
|------|-----------|------------|---------|---------|---------|---------|
| 2003 | 3% Surround | Irrigated | 3.5 A | 4.5 A | 4.4 A w |
| 2003 | 3% Surround | Nonirrigated | 3.0 | 3.7 B | 3.4 B |
| 2003 | Control | Irrigated | 3.3 A | 4.6 A | 4.2 A |
| 2005 | 3% Surround | Irrigated | 2.6 AB | 3.9 B | 3.5 AB |
| 2005 | 3% Surround | Nonirrigated | 2.6 AB | 3.3 C | 3.1 B |
| 2005 | Control | Irrigated | 2.2 B | 2.9 C | 2.8 B |
| 2005 | Control | Nonirrigated | 3.9 A | 4.8 A | 5.3 A |
| 2006 | 3% Surround | Irrigated | 2.9 B | 3.6 B | 3.8 A |
| 2006 | 3% Surround | Nonirrigated | 3.1 B | 3.3 B | 3.2 B |
| 2006 | Control | Irrigated | 3.0 B | 3.3 B | 3.3 B |
| 2006 | Control | Nonirrigated | 5.1 A | 5.0 A | 5.3 A |
| 2007 | 3% Surround | Irrigated | 5.4 A | 5.4 A | 5.7 A |
| 2007 | 3% Surround | Nonirrigated | 4.2 B | 4.5 B | 4.4 B |
| 2007 | Control | Irrigated | 3.8 B | 3.6 C | 4.1 B |

aParticle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) was applied at a rate of 935 L ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

bNo data collected.

cAdjusted means are estimated carbon assimilation rates from analysis of covariance using photosynthetically active radiation as the independent covariate and mean separation within year uses SAS (Version 8.0; SAS Institute, Cary, NC) Proc PDIF at P = 0.05.
different letters within a column for each year indicate a significant difference (P ≤ 0.05) using Fisher’s protected least significant difference.

J. AMER. SOC. HORT. SCI. 134(3):314–321. 2009.
tester (EFFEGI, Alfonzine, Italy) equipped with a 11.1-mm probe with a range of 44 to 59 N. SSC was determined from an aliquant of expressed juice from a longitudinal slice from each of 10 fruit. SSC was measured with an Abbe-type refractometer (model 10450; American Optical Scientific Instruments, Buffalo, NY) with a sucrose scale calibrated at 20 °C and ranged from 11% to 12%. Skin color was determined with a Minolta Chroma meter (model CR-221; Minolta, Ramsey, NJ) using the Hunter L*, a*, b* system and calculated H° (Hunter and Harold, 1987) at four equally spaced locations around the equator of the fruit.

Whole Canopy Carbon Assimilation Chamber. The whole canopy carbon assimilation chamber used in 2003 and 2005 was constructed from 0.08-mm thick polyester film (Mylar Type D; Dupont, Wilmington, DE). Six vertical panels were attached with Velcro® tape to a circular top. The bottom was constructed from an oversized square of 0.15-mm thick polyethylene plastic that was rolled up with the Mylar sides and then clamped every 15 cm. The bottom panel had a radial cut to enclose the tree and was sealed with Velcro. The bottom panel was tied to the tree for a tight fit at a point immediately below the first scaffold branch, generally 30 to 50 cm above the soil. The top and bottom panels were 2.1 m in diameter and the vertical panels were 2.1 m high resulting in a volume of 7.5 m³. A hoop structure of 13-mm electrical conduit was erected over each tree. Four components of the structure were joined together at the apex of the tree and the four conduit legs were attached to steel rods hammered into the soil at the perimeter of the tree. The Mylar chamber was placed over the metal conduit structure. The vertical panels and the bottom panel were gathered and folded around the metal structure. The outlet port was a 30-cm hole in the top panel.

The whole canopy carbon assimilation chamber used in 2006 and 2007 was constructed of 0.762-mm thick polycarbonate (Makrolon GP; Sheffield Plastics–Bayer Material Sciences, Pittsburgh, PA) in a rigid cube 2.4 × 2.4 × 2.4 m. A framed polycarbonate pitched roof covered the cube and the floor was a polyethylene tarp material split to the center to slide onto the tree and was sealed with a Velcro strip.

Air was forced into each chamber with a 0.75-kW fan attached to a metal conduit with a cross-sectional area of 777 cm². Five holes were drilled in the conduit to measure air velocity with a velocimeter (Model 8346; TSI, Shoreview, MN) and 10 2.5-cm positions at each sample port were measured at the beginning and end of the sampling period. Velocity data were averaged to calculate mass air flux. Air was forced into the chamber by inserting the conduit into the seam of two vertical panels and the bottom panel in 2003 and 2005. In 2006 and 2007, air was forced into the chamber from below the cuvette through a diffusion grate located 50 cm from the tree trunk. Leaf movement was visually assessed to ensure no large eddies developed in the chamber. Approximately six chamber volumes were exchanged per minute and this air flow maintained internal air temperature 1 to 2 °C above ambient. Air temperature was measured with a shielded thermocouple hanging ≈30 cm into the chamber through the outlet port. Whole canopy net CO₂ and H₂O exchange were measured with an infrared gas analyzer (IRGA) (CIRAS-1; PP Systems, Haverhill, MA) from the difference in CO₂ and H₂O concentration between the inlet (reference) and the outlet (analysis) ports of each chamber. Equal lengths of tubing were inserted into the conduit and the outlet port, and the sampled air was drawn to the IRGA with a pump. Response time was 5 to 10 s. The sampled air was blown into a cylinder that was sampled by the IRGA with its own sampling pumps. Multiple chambers were sampled sequentially at 1-min intervals using a programmable controller (SDM-CD16AC; Campbell Scientific, Logan, UT) that controlled solenoid valves on the reference and analysis tubes of each chamber. The controller was programmed and data collected with a datalogger (CR-7; Campbell Scientific).

Diurnal data were collected on the following dates: 15 to 21 Aug. 2003, 5 to 11 Aug. 2005, 5 to 13 Aug. 2006, and 13 to 21 Sept. 2007. During each annual sampling study, two trees of each treatment were simultaneously measured for 2 to 3 d. The chambers were moved to two other trees within the treatment providing four single-tree replications of whole tree gas exchange. PAR, relative humidity, wind speed, pan evaporation, and air temperature were measured at a weather station ≈500 m from the measurement site. Data were collected for 24 h each day, but only data for the midday period, 1100 to 1500 hr, were analyzed.

After harvest, the trees sampled for whole canopy carbon assimilation were covered with netting to capture all the leaves when they absconded. The leaves were collected and air-dried at
Table 2. Mean midday whole canopy carbon assimilation between 1100 and 1500 hr of ‘Empire’ apple for particle film and irrigation treatments pooled over the vapor pressure deficit of 4 years at Kearneysville, WV, for six ranges of photosynthetically active radiation intensity.

| Treatment       | Irrigation     | Less than 750 | 750-1000 | 1000-1200 | 1200-1400 | 1400-1600 | Greater than 1600 |
|-----------------|----------------|---------------|----------|-----------|-----------|-----------|------------------|
| 3% Surround*    | Irrigated      | 3.2           | 3.2      | 4.7       | 4.6       | 4.9       | 4.6 A            |
| 3% Surround*    | Nonirrigated   | 3.0           | 3.2      | 4.8       | 4.6       | 4.6       | 3.8 B            |
| Control         | Irrigated      | 3.3           | 3.1      | 3.7       | 3.8       | 3.9       | 3.3 B            |
| Control         | Nonirrigated   | 3.0 R         | 3.0 NS   | 3.4       | 3.6       | 3.8       | 3.4 B            |

*Particle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) was applied at a rate of 935 L ha⁻¹ (50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

1Adjusted means are estimated carbon assimilation rates from analysis of covariance using the vapor pressure deficit as the independent covariate. Using SAS (Version 8.0: SAS Institute, Cary, NC) Proc PDIFF at P ≤ 0.05.

1Different letters within a column indicate a significant difference (P = 0.05) using Fisher’s protected least significant difference (LSD); NS = no significant difference (P ≤ 0.05) using LSD.

80 °C for ≈1 week. At sampling, a subsample of ≈3 kg fresh weight was separated, leaf area was measured, and the ratio of air-dried weight:leaf area calculated. This ratio was used to convert the total air-dried weight of each tree to total leaf area. Leaf area index was the quotient of the total leaf area divided by the area of the canopy shadow measured within 1 h of solar noon.

Particle density on the leaves was measured by washoff of four leaves per tree at each sampling and ranged from 2 to 4 g m⁻². Preweighed tissue paper was wetted and used to rub the residue from the upper surface of the leaf. The tissue paper was air-dried and reweighed. Leaf area was measured. Four control leaves were also measured. Particle density was calculated as the increase in tissue weight (grams) divided by the leaf area (square meters). The mean control leaf particle density was subtracted from each PF treatment.

Infrared images of two trees, untreated and treated, were collected at 1530 hr on 13 Sept. 2007 using an infrared camera (model A 40; FLIR Systems, North Billerica, MA). The distribution of canopy temperatures was measured with ThermacAM® Researcher software version 2.8 SR-1 (FLIR Systems) in which the entire canopy was defined and analyzed.

Whole canopy conductance (mmol m⁻² s⁻¹) was calculated according to Campbell and Norman (1998) using transpiration values from 1100 to 1500 hr pooled over all treatments and sampling dates within a year.

**Statistical Analysis.** Whole canopy gas exchange rate (μmol m⁻² s⁻¹ CO₂) from 1100 to 1500 hr was analyzed in all years. To evaluate the effect of PF and irrigation treatments on A over PAR levels, data for the PF and irrigation treatments were analyzed by year for air temperatures of 10 to 20, 20 to 25, 25 to 30, and 30 to 35 °C using analysis of covariance in each year with PAR as the independent covariate because there were annual differences in the response. To evaluate the effect of PF and irrigation treatments on A over the range of vapor pressure deficit (VPD), assimilation data for the PF and irrigation treatments were analyzed at PAR levels of less than 750, 750 to 1000, 1000 to 1200, 1200 to 1400, 1400 to 1600, and greater than 1600 μmol m⁻² s⁻¹ with VPD as the independent covariate. There was no interaction with year and the data were pooled over years. There was a PF × irrigation interaction. Data were analyzed using SAS (Version 8; SAS Institute, Cary, NC). Adjusted treatment means were compared using PDIFF, which compares least squares means from the analysis of covariance. Treatment means were compared using Fisher’s protected least significant difference (LSD) at P ≤ 0.05.

Fruit weight was analyzed using analysis of covariance in a randomized complete block design using SAS (Version 8). Fruit number per tree was the independent covariate because average fruit size is inversely related to the number of fruit on the tree. Adjusted treatment means were compared using PDIFF, which compares least squares means from the analysis of covariance. The increase in adjusted fruit weight with PF treatments from 1998 to 2007 was expressed as a percentage of the adjusted untreated control and regressed against the annual mean growing season temperature and VPD from May to September.

Fruit hue angle was analyzed by year in a randomized complete block design using SAS for 1998 to 2002 and 2004. Fruit hue angle was analyzed by year in a randomized complete block split plot design using SAS (Version 8) in which irrigation was the main plot and PF treatments were the subplots for 2003 and 2005–2007. Treatment means were compared using LSD.

**Results**

The photosynthetic response to irrigation and PF treatments varied between years as a result of environmental variation and
Table 3: Mean fruit weight, adjusted fruit weight from analysis of covariance using fruit number per tree as the covariate, and hue angle of 'Empire' apple for particle film and irrigation treatments over a 10-year period at Kearneysville, WV.

| Year | Fruit response | 3% Surround<sup>a</sup> | Treatments | Control | Nonirrigated |
|------|----------------|--------------------------|------------|---------|-------------|
|      |                | Irrigated                | Control    |         | Nonirrigated |
| 1998 | Mean fruit wt (g) | 119                      | 110        |         |             |
| 1998 | Adjusted fruit wt (g)<sup>b</sup> | 117 A                    | 105 B<sup>*</sup> |         |             |
| 1998 | Hue angle (*) | 40                       | 37 NS       |         |             |
| 1999 | Mean fruit wt 167 | 149                      | 119 B       | 117     |
| 1999 | Adjusted fruit wt 164 A<sup>*</sup> | 139 B                    | 126         |         |             |
| 1999 | Hue angle 42 B | 50 A                     | 37 NS       |         |             |
| 2000 | Mean fruit wt 124 | 124                      | 118 B       |         |             |
| 2000 | Adjusted fruit wt 63 | 134 A                    | 132         |         |             |
| 2000 | Hue angle 134 | 54 B                     | 131 B       |         |             |
| 2001 | Mean fruit wt 134 | 144                      | 142         |         |             |
| 2001 | Adjusted fruit wt 134 A | 144                     | 144         |         |             |
| 2001 | Hue angle 47 | 47                       | 54 NS       |         |             |
| 2002 | Mean fruit wt 110 | 108                      | 107         | 105     |
| 2002 | Adjusted fruit wt 118 A | 107 BCD                  | 103 CD      |         |             |
| 2002 | Hue angle 58 A | 45 B                     | 50 B        |         |             |
| 2004 | Mean fruit wt 152 | 152                      | 140         |         |             |
| 2004 | Adjusted fruit wt 152 A | 143 B                    | 143 B       |         |             |
| 2004 | Hue angle 63 | 63                       | 63 NS       |         |             |
| 2005 | Mean fruit wt 134 | 134                      | 126         |         |             |
| 2005 | Adjusted fruit wt 134 A | 134 AB                   | 123 C       |         |             |
| 2005 | Hue angle 54 B | 53 B                     | 71 A        |         |             |
| 2006 | Mean fruit wt 120 | 120                      | 114 B       | 111 B   |
| 2006 | Adjusted fruit wt 122 A | 120 A                    | 68 A        |         |             |
| 2006 | Hue angle 53 B | 53 B                     | 71 A        |         |             |
| 2007 | Mean fruit wt 126 | 127                      | 109         |         |             |
| 2007 | Adjusted fruit wt 126 A | 126 A                    | 106         |         |             |
| 2007 | Hue angle 58 B | 60 B                     | 73 A        |         |             |

<sup>a</sup> Particle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) was applied at a rate of 935 L ha<sup>-1</sup> (~50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

<sup>b</sup> No data collected.

<sup>c</sup> Adjusted means are estimated fruit weight from analysis of covariance using fruit number per tree as the covariate and mean separation within year uses SAS (Version 8.0 SAS Institute, Cary, NC) Proc PDIFF at P ≤ 0.05.

<sup>d</sup> Different letters within a row for each year indicate a significant difference (P ≤ 0.05) using Fisher’s protected least significant difference (LSD); NS = no significant difference (P ≥ 0.05) using LSD.

<sup>e</sup> Significant difference at P ≤ 0.12.

was analyzed by year (Table 1) using analysis of covariance of treatment A with PAR levels as the independent covariate in the specified temperature ranges. The irrigated PF treatment had greater A in each year than the irrigated control treatment. The effect of nonirrigated PF treatments on A varied according to temperature class and year. In 2003, the PF nonirrigated treatment had significantly higher mean A at hourly mean air temperatures of 25 to 30 and 30 to 35 °C. In 2005, the PF irrigated treatment had the highest mean A for temperatures of 20 to 25 °C, the control irrigated treatment had the lowest A, and the nonirrigated control and PF treatments were intermediate. The PF irrigated treatment had significantly higher A at 25 to 30 °C, the PF nonirrigated treatment was significantly lower, and both PF treatments had higher A than the irrigated or nonirrigated controls. For temperatures of 30 to 35 °C, the PF irrigated treatment had the highest A, the irrigated and nonirrigated control treatments had the lowest A, and the PF nonirrigated treatments had intermediate A levels. In 2006, the PF irrigated treatment had higher A levels than the other treatments at temperatures from 20 to 30 °C and both PF irrigated and nonirrigated treatments had greater A than the irrigated and nonirrigated control treatments. In 2007, irrigated and nonirrigated PF treatments had higher A than the irrigated and nonirrigated control treatments at temperatures from 10 to 30 °C. At temperatures of 20 to 25 °C, the irrigated control treatment had higher A than the nonirrigated control.

VPD was a controlling factor of the overall A rates for the study. The regression of mean A versus mean VPD for the annual study period indicated a significant negative relationship (Fig. 1A) pooled over the diurnal measurements, whereas there was not a significant correlation with PAR levels for the sampling periods (Fig. 1B). The interaction of VPD, PAR levels, and the treatments on mean midday A was analyzed.
using analysis of covariance of A pooled over years with VPD as the independent covariate. The analysis of covariance was applied to narrow PAR ranges from 750 to greater than 1600 μmol-m⁻²-s⁻¹ (Table 2). At PAR levels below 1000 μmol-m⁻²-s⁻¹, there were no treatment differences. For PAR levels from 1000 to 1600 μmol-m⁻²-s⁻¹, the irrigated and nonirrigated PF treatments had higher A than the irrigated or nonirrigated control treatments. For PAR levels greater than 1600 μmol-m⁻²-s⁻¹, the PF irrigated treatment had A levels greater than the other treatments (Fig. 2).

Mean fruit weight response to PF treatments was measured over 10 years (Table 3). Six years of the study did not have an irrigation treatment. In the 6 years with only PF treatments, the PF treatment significantly increased mean fruit weight in 4 years; in 1 year, the difference was significant at P = 0.12; and in 1 year, there was no significant difference. In the 4 years with both PF and irrigation treatments, mean fruit weight was largest in the irrigated PF treatment and least in the nonirrigated control treatment. In 2003, the mean fruit weight of the PF irrigated treatment was significantly greater than the nonirrigated PF treatment but equivalent in 2005, 2006, and 2007. The irrigated and nonirrigated control treatments were equivalent in 2003 and 2006, whereas the control irrigated treatments had larger mean fruit weight than the control nonirrigated treatments in 2005 and 2007.

The percentage increase in fruit weight of the PF treatment compared with the control was regressed against environmental variables for the irrigated and nonirrigated treatments. The percentage increase in fruit weight of the PF treatment compared with the control was not significantly correlated with the growing season cumulative PAR levels or the pan evaporation amounts (data not presented). The percentage increase in fruit weight of the PF treatment compared with the control was significantly correlated to the mean growing season temperature (Fig. 3A) and the mean growing season VPD (Fig. 3B). The irrigation treatments were not significantly different in their respective regression analyses (data not presented).

Fruit hue angle was reduced and red color increased by the PF treatment in 1999, 2001, 2002, and 2005 to 2007. PF treatments did not significantly affect hue angle in 1998, 2000, and 2004. In 2003, the nonirrigated treatments had lower hue angle than the irrigated treatments.

Analysis of the temperature distribution in infrared images (Fig. 4A) indicated that the PF treatment reduced the mean (26.0 versus 24.4 °C) and the range (21.5 to 33.5 versus 21.5 to 30.5 °C) of leaf temperatures (Fig. 4B) for control and PF treatments, respectively.

**Discussion**

Midday whole canopy A was limited most by VPD across all treatments and canopy conductance was highly correlated with the VPD indicating significant stomatal control in apple (Fig. 1), whereas A levels were not correlated with mean daily PAR that ranged from 783 to 976 μmol-m⁻²-s⁻¹. The application of a reflective PF generally increased whole canopy gas exchange (Tables 1 and 2), but the effect varied with year and irrigation treatment. The trend of increased A associated with PF treatments could also be associated with partitioning of the additional dry matter to the fruit sink and increased fruit weight (Table 3).

Analyzing the midday A for each year of the study did not indicate any consistent treatment effect of temperature, averaged over PAR levels, because the order of treatment response was as similar for the 20 to 25 °C range as it was for the 30 to 35 °C range (Table 1). The midday A, pooled over years and regressed against VPD as a covariate, indicated that A was limited by PAR levels below 1000 μmol-m⁻²-s⁻¹ and there were no treatment effects. Similar to the effect of temperature, the order of treatment response was as similar for PAR levels at 1000 to 1200 μmol-m⁻²-s⁻¹ as for 1400 to 1600 μmol-m⁻²-s⁻¹, suggesting that PAR was not the limiting factor for the midday hours. There was a unique treatment response for PAR levels greater than 1600 μmol-m⁻²-s⁻¹ in which the combination of PF and irrigation maintained midday A at maximum levels (Fig. 2) compared with other treatments although A was reduced by increasing VPD. This response indicated that although VPD limited A, the combination of PF and adequate water could maintain maximum A rates at full sun levels during the midday period and minimize the midday depression of A that is commonly observed and reduces the daily carbon accumulation. The increased carbon accumulation during the midday period was likely partitioned to the fruit (Table 3).
Increased fruit weight with the PF treatment, compared with the control, was positively correlated with the growing season air temperature (Fig. 3A) and VPD (Fig. 3B) indicating that as the environment becomes hotter and/or drier, the magnitude of the PF response increased as a result of the reduced leaf and fruit temperature (Fig. 4) and the subsequent physiological effect. The regression of growing season air temperature with the increase in fruit weight in the PF treatment (Fig. 3A) had an outlier at (21.5 °C, 24%). This datum has a VPD of 1.0 kPa (Fig. 3A) indicating that the VPD was the greater of the two limiting factors mitigated by the PF treatment. The regression of growing season VPD with the increase in fruit weight (Fig. 3B) indicated no consistent response until VPDs were greater than 0.9 kPa and the three largest increases in fruit weight by the PF treatment occurred at VPDs greater than 0.9 kPa during the 10 years of the study. Fruit red color was improved in 5 of 10 years by the PF treatments; similar fruit color responses have been reported (Glenn et al., 2005).

Evaporative cooling increases dry matter partitioning to fruit and increases fruit weight (Parchomchuk and Meheriuk, 1996; Unrath and Sneed, 1974) by reducing canopy temperature and the VPD. The reduction of leaf and canopy temperature (Fig. 4) with the PF treatment enhanced whole canopy gas exchange and mitigated the effects of increasing VPD similar to evaporative cooling. The use of PF may be an effective substitute for evaporative cooling, not only to reduce solar injury (SI) to fruit, but to improve apple quality through increase fruit weight. The present study differed from other studies using PF for SI control in the duration of the PF treatment. Studies to reduce SI generally apply the PF treatment for a 4- to 6-week period before harvest (Gindaba and Wand, 2005, 2007a, 2007b; Le Grange et al., 2004; Schupp et al., 2002). Goffinet et al., (1995) found that thinning ‘Empire’ apples increased apple weight by allowing the remaining fruits to continue cell division during the first few weeks after bloom rather than increasing cell size or increasing the proportion of intercellular spaces in the fruit. Therefore, any environmental stress that reduces carbon allocation to the fruit during the cell division phase of fruit development will reduce fruit size, or conversely, any treatment that improves carbon allocation to the fruit will increase fruit size. Glenn et al. (2001) demonstrated that improvement in the carrying capacity in ‘Empire’ apples with PF treatments was associated with application in May and June but not later application times. These data suggested that there was a reduction in stress, presumably heat, that increased carbon allocation to the developing fruit to aid in cell division and increase final fruit weight. Similarly, Lapointe (2000) used season-long PF treatments for insect control and demonstrated increased citrus growth and Steiman et al. (2007) applied kaolin over the growing season and increased coffee fruit yield.

The present study evaluated both daily responses to environmental factors as well as seasonal means and demonstrated that effects of both temperature and VPD at the daily and season scale are related to the final fruit weight. The PF treatments reduced radiation and heat load on exposed leaves enabling them to better regulate leaf temperature and improved the light distribution inside the canopy resulting in increased carbon gain at the whole plant scale (Glenn and Puterka, 2007; Rosati et al., 2007). The results indicate that benefits of PF treatments would occur in agroecosystems with large VPDs and high temperatures. The inclusion of irrigation would further enhance the benefits when PAR levels are greater than 1600 μmol-m⁻²-s⁻¹.

**Literature Cited**

Berry, J. and O. Bjorkman. 1980. Photosynthetic response and adaptation to temperature in higher plants. Annu. Rev. Plant Physiol. 31:491–543.

Campbell, G.S. and J.M. Norman. 1998. Heat and mass transport. In: An introduction to environmental biophysics. 2nd Ed. Springer-Verlag, New York, NY.

Gindaba, J. and S.J.E. Wand. 2005. Comparative effects of evaporative cooling, kaolin particle film, and shade net on sunburn and fruit quality in apples. HortScience 40:592–596.
Gindaba, J. and S.J.E. Wand. 2007a. Do fruit sunburn control measures affect leaf photosynthetic rate and stomatal conductance in 'Royal Gala' apple? Environ. Exp. Bot. 59:160–165.

Gindaba, J. and S.J.E. Wand. 2007b. Climate-ameliorating measures influence photosynthetic gas exchange of apple leaves. Ann. Appl. Biol. 150:75–80.

Glenn, D.M. 1995. Irrigation scheduling, p. 161–168. In: Hogmire, H. (ed.). Mid-Atlantic orchard monitoring guide. Northeast Regional Agricultural Engineering Service, Ithaca, NY.

Glenn, D.M. 1999. Analysis of trickle and pulse microsprinkler irrigation of processing apples. J. Tree Fruit Production 2:11–17.

Glenn, D.M., S. Drake, E. Prado, J.R. MeFerson, and G.J. Puterka. 2006. Season and cultivar influence the fruit quality response of apple cultivars to particle film treatments. HortTechnology 15:249–253.

Glenn, D.M., E. Prado, A. Erez, J.R. McFerson, and G.J. Puterka. 2002. A reflective, processed kaolin particle film affects fruit temperature, radiation reflection, and solar injury in apple. J. Amer. Soc. Hort. Sci. 127:188–193.

Glenn, D.M., A. Erez, G.J. Puterka, and P. Gundrum. 2003. Particle films affect carbon assimilation and yield in 'Empire' apple. J. Amer. Soc. Hort. Sci. 128:356–362.

Glenn, D.M. and G.J. Puterka. 2005. Film particles: A new technology for agriculture. Hort. Rev. (Amer. Soc. Hort. Sci.) 31:1–44.

Glenn, D.M. and G.J. Puterka. 2007. The use of plastic films and sprayable reflective particle films to increase light penetration in apple canopies and improve apple color and weight. HortScience 42:91–96.

Glenn, D.M., G.J. Puterka, S.R. Drake, T.R. Unruh, A.L. Knight, P. Baherle, E. Prado, and T.A. Baugher. 2001. Particle film application influences apple leaf physiology, fruit yield, and fruit quality. J. Amer. Soc. Hort. Sci. 126:175–181.

Glenn, D.M., G.J. Puterka, T. van der Zwet, R.E. Byers, and C. Feldhake. 1999. Hydrophobic particle films: A new paradigm for suppression of arthropod pests and plant diseases. J. Econ. Entomol. 92:759–771.

Goffinet, M.C., T.L. Robinson, and AN. Lakso. 1995. A comparison of 'Empire' apple fruit size and anatomy in unthinned and hand-thinned trees. J. Hort. Sci. 70:375–387.

Hunter, R.S. and R.W. Harold. 1987. The measurement of appearance. 2nd Ed. Wiley, New York, NY.

Jifon, J.L. and J.P. Syvertsen. 2003. Kaolin particle film applications can increase photosynthesis and water use efficiency of 'Ruby Red' grapefruits leaves. J. Amer. Soc. Hort. Sci. 128:107–112.

Lapointe, S.L. 2000. Particle film deters oviposition by Diaprepes abbreviatus (Coleoptera: Curculionidae). J. Econ. Entomol. 93:1459–1463.

Le Grange, M., S.J.E. Wand, and K.I. Theron. 2004. Effect of kaolin applications on apple fruit quality and gas exchange of apple leaves. Acta Hort. 636:545–550.

Lombardini, L., M.K. Harris, and D.M. Glenn. 2005. Effects of particle film application on leaf gas exchange, water relations, nut yield, and insect populations in mature pecan trees. HortScience 40:1376–1380.

Melgarejo, P., J.J. Martinez, F. Hernandez, R. Martinez-Font, P. Barrows, and A. Erez. 2004. Kaolin treatment to reduce pomegranate sunburn. Scientia Hort. 100:349–353.

Pace, B., F. Boari, V. Cantore, L. Leo, S. Vanadia, E. De Palma, and N. Phillips. 2007. Effect of particle film technology on temperature, yield and quality of processing tomato. Acta Hort. 758:287–293.

Parchomchuk, P. and M. Meheriuk. 1996. Orchard cooling with pulsed overtree irrigation to prevent solar injury and improve fruit quality of 'Jonagold' apples. HortScience 31:802–804.

Rosati, A., S.G. Metcalf, R.P. Buchner, A.E. Fulton, and B.D. Lampinen. 2006. Physiological effects of kaolin applications in well-irrigated and water-stressed walnut and almond trees. Ann. Bot. (Lond.) 98:267–275.

Rosati, A., S.G. Metcalf, R.P. Buchner, A.E. Fulton, and B.D. Lampinen. 2007. Effects of kaolin application on light absorption and distribution, radiation use efficiency and photosynthesis of almond and walnut canopies. Ann. Bot. (Lond.) 99:255–263.

Russo, V.M. and J.C. Diaz-Pérez. 2005. Kaolin-based particle film has no effect on physiological measurements, disease incidence or yield in peppers. HortScience 40:98–101.

Saavedra, D.R.G., M.G. Escaff, and J.V. Hernandez. 2006. Kaolin effects in processing tomato production in Chile. Acta Hort. 724:191–198.

Saour, G. 2005. Efficacy of kaolin particle film and selected synthetic insecticides against pistachio psyllid Agromosca taurionti (Homo-ptera: Psyllidae) infestation. Crop Prot. 24:711–717.

Saour, G. and H. Makee. 2004. A kaolin-based particle film for suppression of the olive fruit fly [Bactrocera oleae Gmelin (Dipl. Tephritidae) ] in olive groves. J. Appl. Entomol. 128:28–31.

Schupp, J.R., E. Fallahi, and I.J. Chun. 2002. Effect of particle film on fruit sunburn, maturity and quality of 'Fuji' and 'Honeycrisp' apples. HortTechnology 12:87–90.

Steiman, S.R., H.C. Bittenbender, and T.W. Idol. 2007. Analysis of kaolin particle film use and its application on coffee. HortScience 42:1605–1608.

Thomas, A.L., M.E. Muller, B.R. Dodson, M.R. Ellersiek, and M. Kaps. 2004. A kaolin-based particle film suppresses certain insect and fungal pests while reducing heat stress in apples. J. Amer. Pomol. Soc. 58:42–51.

Unrath, C.R. and R.E. Sneed. 1974. Evaporative cooling of 'Delicious' apples—The economic feasibility of reducing environmental heat stress. J. Amer. Soc. Hort. Sci. 99:372–375.

Wand, S.J.E., K.I. Theron, J. Ackerman, and S.J.S. Marais. 2006. Harvest and post-harvest apple fruit quality following applications of kaolin particle film in South African orchards. Scientia Hort. 107:271–276.

Wunschke, J.N., L. Lombardini, and D.H. Greer. 2004. 'Surround' particle film applications—Effects on whole canopy physiology of apple. Acta Hort. 636:565–571.