Root Zone Temperature, Plant Growth, and Fruit Yield of Tomatillo as Affected by Plastic Film Mulch

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Abstract. Tomatillo (*Physalis ixocarpa* Brot. ex Hornem) is a popular crop in Mexico and other Latin American countries. There is an increasing demand for this vegetable in the United States, particularly from the growing Latino population. However, there is limited information about tomatillo production. The objectives of this study were to determine the effects of plastic mulches on plant growth, yield, and root zone temperature in two cultivars of tomatillo. The study was conducted in Spring and Summer 2000. The design was a randomized complete block with a split plot arrangement, where plastic film mulch (black, gray, and silver mulches, and bare soil) was the main plot and cultivar ('Toma Verde' and 'Verde Puebla') the subplot. In the spring, mulch treatments had little effect on plant growth during the first 30 days after transplanting and there were no significant differences in fruit yields. In the summer planting, both early growth and fruit yields were greatest with the silver and gray mulch treatments and lowest on bare soil. Plant growth during the establishment was related with subsequent plant growth and yield. In mature plants, vegetative top fresh weight and total fruit yield were higher ($P < 0.01$) in the spring than in the summer. Total fruit yield (both seasons), marketable yield (spring) and cull yield (spring) were lower in 'Toma Verde' than in 'Verde Puebla'. Root zone temperatures (RZTs) in the spring (mean = 26.4 °C) were lower than in the summer (mean = 29.3 °C). In both seasons, mean RZT was highest under black mulch and lowest in bare soil. In the summer, plant growth and fruit yields tended to decrease with increasing RZTs. Tomatillo plants grown on mulches with a mean seasonal RZT of 30 °C had fruit yields that were 65% ('Toma Verde') or 50% ('Verde Puebla') lower respectively than those of plants on mulches with a RZT of 27 °C. There were no significant differences in foliar concentrations of N, Ca, Mg, S, B, Zn, Cu and Na among mulches. Foliar concentrations of the majority of mineral nutrients were not related with the mean RZT for the season.

Tomatillo (*Physalis ixocarpa* Brot. ex Hornem) or husk tomato is a solanaceous crop that originated in Mesoamerica and is popular in Mexico, Guatemala, and other Latin American countries (Montes-Hernández and Aguirre-Rivera, 1994; Martínez, 1954; Waterfall, 1967). Tomatillo has been part of the diet of

the Mexican population since pre-Columbian times (Sahagún, 1956). The fruit has a sour taste and is eaten cooked or fresh, and can be used in combination with peppers and spices to make a green sauce (salsa verde). This fruit is primarily grown in Mexico, although it is also grown in central and southern California in small areas (Smith et al., 1999) on about 65 ha with a gross value of \$12,700/ha and an average yield of 4.3 t·ha⁻¹ in 1997 (California Department of Food and Agriculture, 1999).

There is an increasing demand for this vegetable in the United States, particularly from the growing Mexican/Latino population. However, there is limited information about tomatillo production (Freyre and Loy, 2000; Montes-Hernández and Aguirre-Rivera, 1994; Moriconi et al., 1990; Smith et al., 1999), botany (Cartujano-Escobar et al., 1985a; Cartujano-Escobar et al., 1985b) and genetics (Pandey, 1957; Quiros, 1984). In Mexico, tomatillo plants grow in a wide range of altitudes from sea level to about 2,600 m (Montes-Hernández and Aguirre-Rivera, 1994). There are many local or indigenous varieties of tomatillo that growers recognize by fruit size and color or by

the plant's growth habit. Wild tomatillo plants are often found growing in cultivated fields of tomato (*Lycopersicon esculentum* Mill.), corn (*Zea mays* L.) and cucurbits (*Cucurbita* spp.). Tomatillo plants require cross-pollination because of self-incompatibility (Pandey, 1957). Tomatillo is a warm season crop, sensitive to freezing temperatures, and production of this crop in Mexico occurs in similar areas and growing seasons as those for tomato and pepper. There is no information on the optimum temperature for tomatillo growth, although plants grow poorly at <16 °C, grow well at >18 °C, and set fruit poorly at high temperatures (Smith et al., 1999).

In the southeastern United States, tomato and pepper (*Capsicum annum* L. var. *annuum*) are commonly produced on plastic film mulch, while tomatillo has been grown in bare soil (Smith et al., 1999) or on plastic mulch (Freyre and Loy, 2000). The benefits associated with use of plastic mulches include higher yields, earlier harvests, improved weed control and increased efficiency in the use of water and fertilizers (Lamont, 1993). Plastic mulches affect plant microclimate by modifying the soil energy balance and restricting soil water evaporation (Liakatas et al., 1986; Tarara, 2000), thereby affecting plant growth and yield (Voorhees et al., 1981).

Root-zone temperature (RZT) is important in plant growth and development because it affects physiological processes in roots such as uptake of water and mineral nutrients (Cooper, 1973; Dodd et al., 2000; Tindall et al., 1990; Wien and Minotti, 1987). RZT may also be critical for plant survival, because roots have a lower temperature optimum and are less adapted to extreme fluctuations than shoots (Paulsen, 1994). Under controlled conditions, root growth increases nearly linearly with increased temperature from a minimum to an optimum temperature. Further increases in RZT are accompanied by a decline in root and shoot growth (Cooper, 1973; Miller, 1986; Voorhees et al., 1981). High RZT can have a drastic effect on plant growth, fruiting, water and mineral nutrient uptake, assimilate partitioning, and root respiration (Cooper, 1973; Dodd et al., 2000; Tindall et al., 1990; Tindall et al., 1991). The objectives of this study were to determine the effects of plastic mulches on RZT, plant growth, and fruit yield in two cultivars of tomatillo.

Materials and Methods

The study was conducted at the Coastal Plain Experiment Station, Tifton, Ga., during Spring and Summer 2000. The soil was a Tifton Sandy Loam (a fine loamy-siliceous, thermic Plinthic Kandiodults) with a pH of 6.5. The design was a randomized complete block with three replications and a split plot arrangement, where plastic film mulch was the main plot and cultivar the subplot. The mulches were black on black (black), gray on black (gray, Leco, Montreal, Canada); silver on black (silver, Clarke Ag Plastics, Greenwood Va.), and bare soil. The cultivars were 'Toma Verde' and 'Verde Puebla' (both from Seminis, Oxnard, Calif.).

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The experimental plot consisted of a 7.6-m-long, 0.9-m-wide bed formed on 1.8-m centers. The soil was fumigated on 21 Feb. 2000 with a mixture of 3 methyl bromide : 1 chloropicrin (by weight) at 450 kg·ha⁻¹. In the spring, before laying the mulches with a mulch-laying machine, the soil was fertilized with N, P, and K at 90, 90 and 112 kg·ha⁻¹, respectively. At the same time the mulches were laid, drip irrigation tape (T-Tape; T-Systems Intl., San Diego, Calif.), with 30.5-cm emitter spacing and a 17 mL·min⁻¹ emitter flow, was placed 5 cm deep in the center of the bed.

In the spring, 4-week-old transplants were planted to the field on 5 Apr. and replanted on 5 May ('Toma Verde' only) in a single row per bed at 60-cm spacing. In the summer, transplanting to the same field was on 12 Jul. 2000. After transplanting, 240 mL of starter fertilizer solution (555 ppm N; 821 ppm P; 0 ppm K) was applied directly to the base of each transplant. Three weeks after transplanting, plants were fertilized weekly through the drip system with N and K at rates of 1.5 kg·ha⁻¹·d⁻¹ at early stages, 1.8 kg·ha⁻¹·d⁻¹ during plant and fruit development, and 1.3 kg·ha⁻¹·d⁻¹ at late stages of plant development. The total amount for each, N and K received by the plants after transplanting was 113 kg·ha⁻¹.

Irrigation and soil water potential. Drip irrigation was applied as necessary to maintain soil water potential at more than -15 kPa. Plants were typically irrigated 13 mm of water 3 to 4 times a week. Soil water potential (SWP) was monitored manually with granular matrix sensors (model 200SS; Water Mark soil moisture sensor, Irrometer Co., Riverside, Calif.) at 0.15 m deep, located midway between two plants within the row.

Root-zone temperature. RZT was measured by determining soil temperature midway between the plants at 10 cm below the mulch and the soil surface. RZT over the growing season was measured with copper-constantan thermocouples (model 107; Campbell Scientific, Logan, Utah) connected to a datalogger (CR10X; Campbell Scientific) and a relay multiplexer (AM416; Campbell Scientific). The data logger was programmed to record readings every 10 min and store hourly averages for each plot. Air temperature data were obtained from a University of Georgia weather station located within 3 km of the plots.

Soil and foliar nutrients. Soil and leaf samples were collected on 29 Aug. 2000 (summer season). Leaves were dried at 70 °C for 2 d and analyzed for mineral nutrient concentration. Concentrations of P, K, Ca, Mg, Fe, Mn, Zn, and Cu were determined by atomic absorption spectrophotometry. Tissue N concentration was determined by the copper catalyst method (Association of Official Analytical Chemists, 1990).

Plant growth. On days 7, 14, 21, and 28 after transplanting, two randomly-selected plants (top plus roots) from each replication were removed from the soil. Plant tops and roots were dried at 70 °C and their dry weights (DWs) were determined.

Harvest. For the spring crop, a once-over harvest was made on 21 June, and the summer

crop was harvested on 8 Sept. and 27 Sept. Only total yield data for the summer are reported. At the once-over harvest or at the last harvest, plants were excised at the soil level, enclosed individually in plastic bags and kept at 10 °C until their vegetative fresh weight (FW) and fruit yield (including both developing and fully developed fruit) were determined within 24 h. A fruit is considered ripe when the berry fills the husk and in some cases breaks it (Moriconi et al., 1990). Fruit were graded as marketable

and culls (fruit with rots, insect damage, or mechanical injury). Harvest ratio was calculated as the ratio of fruit FW relative to total FW of individual plants.

Statistical analysis. Data were analyzed using the Analysis of the Mixed Procedure of SAS (SAS Inst. Inc., 2000). Average, maximal, and minimal RZTs for the season were calculated from daily values of mean, maximal, and minimal RZTs for each of the mulches during the entire season. The means

Fig. 1. Vegetative top dry weight of tomatillo plants grown on plastic mulches during the establishment period in the spring and the summer. Within the same day after transplanting, values with different letter are significantly different ($P \leq 0.05$; $n = 3$ replications, number of plants = 4).

Fig. 2. Changes in root to top ratio of tomatillo plants during the establishment. Solid line was fit by linear regression.

Table 1. Growth and yield of tomatillo plants as affected by cultivar and plastic film mulch during the spring season.

Treatment	Vegetative fresh wt (kg/plant)	Total fruit yield (kg/plant)	Marketable yield (kg/plant)	Cull yield (kg/plant)	Harvest ratio
Cultivar					
Toma Verde	2.2 b ^a	1.1 b	1.1 b	0.01 b	0.33
Verde Puebla	2.7 a	1.9 a	1.6 a	0.3 a	0.41
Mulch					
Bare	2.0 b	1.5	1.4	0.1	0.42
Black	2.5 a	1.4	1.2	0.2	0.35
Gray	2.8 a	1.6	1.5	0.1	0.35
Silver	2.6 a	1.4	1.2	0.2	0.35

^aMeans separated within columns by Fisher's protected LSD test ($P \leq 0.05$).

Table 2. Growth of mature plants, yield and soil water potential of tomatillo plants as affected by cultivar and plastic film mulch during the summer season.

Treatment	Vegetative fresh wt (kg/plant)	Total fruit yield (kg/plant)	Harvest ratio
Cultivar			
Toma Verde	2.2 a ^a	0.8 b	0.25 b
Verde Puebla	1.9b	1.2 a	0.39 a
Mulch			
Bare	1.2 b	0.5 b	0.27
Black	2.4 a	0.9 ab	0.28
Gray	2.5 a	1.3 a	0.34
Silver	2.2 a	1.3 a	0.36

^aMeans separated within columns by Fisher's protected LSD test ($P \leq 0.05$).

for RZT, plant growth attributes and fruit yields were separated by the Fisher's protected LSD test. Relationships of plant growth attributes with RZT were constructed using the means of the interaction of season, mulch and cultivar. Various models were evaluated to determine whether there were differences in the relationship of plant growth and yield to RZT among seasons and mulch types.

Results and Discussion

Effect of mulch and cultivar on plant growth

during the establishment period (first 28 DAT). During the establishment period, plant growth measured as vegetative top DW in the spring was lower than in the summer, possibly as a result of the presence of low temperatures during early stages of plant growth during the spring (Fig. 1). In the spring, vegetative top DW of 'Verde Puebla' plants was not affected by plastic mulch during the first 28 DAT (Fig. 1). In the summer, vegetative top DW was highest in gray and silver mulches and lowest in bare soil in both cultivars (Fig. 1). Vegetative top DW and root DW of 'Toma Verde' were similar ($P \leq 0.05$) to those of 'Verde Puebla'. Vegetative top DW was highly correlated with root DW ($r = 0.998$). In both cultivars, the root to top ratio decreased from about 0.25 at transplanting to about 0.08 at about 14 DAT, and then remained about constant until day 28 (Fig. 2). We did not measure root to top ratios of mature field-grown tomatillo plants, but mature tomatillo plants under greenhouse conditions had a root to top ratio of 0.08 (unpublished data).

Effect of mulch and cultivar on mature plant growth and fruit yield. Mean vegetative FWs were 2.47 kg/plant and 2.05 kg/plant, total fruit yields were 1.49 kg/plant and 0.98 kg/plant, and harvest ratios were 0.37 and 0.32 in the spring and summer, respectively. These rates of fruit production correspond to 13.4 t·ha⁻¹ and 8.8 t·ha⁻¹ for spring and summer, respectively. In

Mexico, tomatillo yields range from 15 t·ha⁻¹ to 25 t·ha⁻¹, while in a Louisiana trial yield was 13.5 t·ha⁻¹ (Moriconi et al., 1990). Thus, yields in this study were low but acceptable in the spring and unacceptably low in the summer. Yields were low in part because plants were harvested only once in the spring or twice in the summer, while under typical growing conditions tomatillo is harvested four to six times (Moriconi et al., 1990).

Vegetative FWs and total fruit yields among mulches and between cultivars are presented in Tables 1 and 2. 'Toma Verde' vegetative FW growth in the spring was less than that of 'Verde Puebla' (Table 1), but the growing season was only 47 d for 'Toma Verde', compared to 77 d for 'Verde Puebla'. In the summer the growing season was the same for both cultivars, and vegetative FW growth of 'Toma Verde' was significantly greater than that of 'Verde Puebla' (Table 2). Total fruit yield (both seasons), marketable yield (spring) and cull yield (spring) were lower in 'Toma Verde' than in 'Verde Puebla'. Average fruit weight was higher in 'Verde Puebla' (17.1 g) compared to that in 'Toma Verde' (11.8 g). In the spring, harvest ratio (HR) tended to be higher in 'Verde Puebla' (Table 1), and in the summer HR was higher in 'Verde Puebla' than in 'Toma Verde' (Table 2).

In both seasons, plants on bare soil had the lowest vegetative FW and there were no differences in vegetative FW among the three plastic mulch treatments (Tables 1 and 2). In the spring there were no differences in total fruit yields among bare soil and mulch treatments (Table 1), while in the summer fruit yield was lowest with the bare soil treatment and highest with the gray and silver mulch treatments. Fruit yield was intermediate with the black mulch treatment, but not statistically different from the other treatments (Table 2). Harvest ratios were similar among mulch treatments in both seasons. Mean soil water potential was maintained at more than -18 kPa for all mulch treatments (Table 2), thus, soil moisture was probably not a major factor determining the differences in vegetative FW and fruit yield among mulch treatments.

Plant growth during the establishment period may significantly affect subsequent plant growth and fruit yield, as shown for tomato (Díaz-Pérez et al., 2004). In the spring, top DW during the establishment was not related with subsequent growth (vegetative top FW) and yield of mature plants. In the summer, vegetative top FW of mature plants of both cultivars was linearly related with top DW during the establishment (Fig. 3). Fruit yields of both cultivars were also linearly related with top DW during the establishment in the summer, although yields in 'Verde Puebla' were more affected than 'Toma Verde' by changes in the top DW during the first 28 DAT.

Effect of plastic mulch on root zone temperature. Plastic film mulches differed in their soil-warming ability. For all mulch treatments, root zone temperatures (RZTs) in the spring (average = 26.4 °C) were lower than in the summer (average = 29.3 °C) (Table 3, Figs. 4 and 5). As the season progressed, RZTs increased

Fig. 3. Relationship of vegetative growth of mature plants and fruit yield with plant growth during the establishment period in two tomatillo cultivars. Solid lines were fit by linear regression.

linearly ($P < 0.01$) with time after transplanting in the spring and decreased linearly ($P < 0.01$) in the summer (Fig. 4). Changes in mean daily RZTs under mulch were proportional ($P < 0.01$) to changes in air temperature through both of the seasons. Over the two seasons, the mean air temperature [22.3 °C (spring) and 25.6 °C (summer)] was lower than mean RZTs in either bare soil or under the plastic mulches. The differences between the daily mean air temperature and the daily mean RZTs under the mulch treatments tended to decrease with time as both seasons progressed.

In both seasons, mean RZT was highest under black mulch and lowest in bare soil. Maximal RZT was highest under black mulch in both seasons and lowest under silver mulch and gray mulch (only in the summer). In both seasons, lowest values of minimal RZT occurred in bare soil, and there were no consistent differences in minimal RZT among plastic mulches (Table 3). The largest RZT range (highest daily mean RZT – lowest daily mean RZT = 2.0 °C) among mulches occurred within the first 35 (spring) or 42 (summer) d after transplanting

(Fig. 4). In the second half of both seasons, the RZT range among mulches was about 0.7 °C. The differences in RZT among mulches were significant ($p < 0.01$) over the entire season in both spring and summer plantings. Possibly, shading of the mulch surface by the plant's canopy, particularly after plants reached full canopy development (after 42 DAT), contributed to reducing the RZT differences among mulches. These results suggest that under shady conditions or at night the energy balance tends to be similar in all plastic mulches. In mulches under shady conditions, most of the warming is through conduction and convection and only a small portion of the soil warming is via direct solar radiation (Tarara, 2000).

On a diurnal basis, differences in RZTs among mulch treatments were largest during daytime (9:00 to 21:00 HR) and smallest between midnight and 8:00 HR (Fig. 5). Black mulch exhibited appreciably higher maximum RZTs in the midday and afternoon than the other mulch treatments. Bare soil had the lowest RZT during the nighttime and exhibited a larger diurnal fluctuation in RZT [difference

between maximal RZT and minimal RZT (9.9 °C in the spring and 9.6 °C in the summer)] compared to any of the mulch treatments (Fig. 5). Among mulch treatments, silver mulch had the smallest diurnal fluctuation in RZT (6.2 °C in the spring and 6.9 °C in the summer). These diurnal responses of mulches are consistent with previous reports (Díaz and Batal, 2002).

Relationship of RZT with plant growth and yield. During the establishment period (first 28 d after transplanting), plant growth (top DW) in the spring increased with increases in the mean RZT (as affected by plastic mulches), while in the summer top DW decreased with increases in the mean RZT during the establishment (Fig. 6). Subsequent plant growth (vegetative FW) was not significantly related to RZT, although vegetative FW tended to decrease with increasing values of RZT. Total fruit yield in 'Toma Verde' decreased with increasing values of both maximal RZT and mean RZT, while in 'Verde Puebla', total fruit yield increased with increasing RZTs to an 'optimum' RZT and then decreased at RZTs above the optimum (Fig. 7). Quadratic equations were used to compute optimum RZTs for plant growth during the establishment and for total fruit yield of cultivar Verde Puebla. The optimum RZTs were calculated by setting the first derivative of the equations equal to 0. The predicted optimum mean RZTs for plant growth during the establishment and fruit yield were 27.7 °C ($y = -0.600x^2 + 33.27x - 430.5$; $r^2 = 0.861$) and 27.3 °C, respectively.

The effect of RZT on fruit yield, however, was more marked in the summer, when RZTs were higher, than in the spring. Possibly, yields in the spring were higher than in the summer because of presence of more favorable air temperatures and RZTs in the spring (mean RZT = 26.4 °C) than in the summer (mean RZT = 29.3 °C). The high RZTs under black mulch in the afternoon are probably associated with the major detrimental effect of this mulch on the growth and yield of tomatillo during the summer. In southern Georgia, tomato yields in the spring are typically higher than in the summer and fall in part because excessively high air temperatures and high RZTs in the summer/fall reduce tomato plant growth and yield (Díaz-Pérez and Batal, 2002). In addition to RZT, other environmental factors such as daylength and amount of solar radiation that plants received may have also had an effect on tomatillo yields, as has been reported for tomato (Kinet and Peet, 1997). Insect and disease pressures in southern Georgia are also usually higher in the summer/fall than in the spring season.

Plant growth in tomato and other crops has been found to fit a quadratic relationship with RZT (Cooper, 1973; Díaz-Pérez and Batal, 2002). Optimal mean seasonal RZT for tomato growth and fruit yield is 26.3 °C (Díaz-Pérez and Batal, 2002). In the current study, we found a quadratic relationship with RZT for fruit yield in 'Verde Puebla', with an optimal at 27.3 °C. Fruit yield of 'Toma Verde' did not have a significant quadratic relationship with RZT, instead yield decreased linearly

Fig. 4. Seasonal trend of root zone temperature (RZT) and air temperatures under plastic mulches during two seasons. Each symbol represents the weekly mean RZT under each mulch.

with increasing mean RZTs. Fruit yield on bare soil during the summer was lower than with any of the mulches and did not fit into the same relationship, suggesting that yield of plants on bare soil was affected more by factors other than RZT.

Tomatillo plants grown on mulches with a mean seasonal RZT of 30 °C had fruit yields that were 65% ('Toma Verde') and 50% ('Verde Puebla') lower respectively than those of plants on mulches with a mean RZT of 27 °C. These results suggest that tomatillo may be more tolerant to heat stress than tomato, since yields are nil when tomato plants are grown at a mean seasonal RZT of ≥ 29.3 °C (Díaz-Pérez and Batal, 2002).

Fruit yield was consistently higher in 'Verde Puebla' than in 'Toma Verde' over the RZT ranges (Fig. 7), although as mean RZT increased above 27 °C, yield differences between cultivars tended to be smaller. Harvest ratios (HRs) tended to decrease with increasing values of mean RZT [$y = -0.0272x + 1.047$, $r^2 = 0.439$, $P = 0.073$ ('Toma Verde'); $y = -0.0113x + 0.713$, $r^2 = 0.199$, $P = 0.268$ ('Verde Puebla')] and maximal RZT [$y = -0.0047x^2 + 0.279x$

$- 3.846$, $r^2 = 0.492$, $P = 0.184$ ('Toma Verde'); $y = -0.0064x^2 + 0.405x - 5.937$, $r^2 = 0.657$, $P = 0.069$ ('Verde Puebla')]. The decrease in HR with increases in RZT was possibly due to the stronger effect of high RZTs on fruit yield than on vegetative FW. Similarly, RZTs above the optimal range in tomato result in plants with a decreased HR (Díaz-Pérez and Batal, 2002).

In tomato, high RZTs are more deleterious to fruit yield than to vegetative growth, and the effect of heat stress is primarily by reducing the number of fruit per plant (Díaz-Pérez and Batal, 2002). In pepper and tomato, high air temperatures (> 32 °C) can drastically affect pollination and fruit set (Kinet and Peet, 1997; Wien, 1990). Presence of high air temperatures are expected to be associated with high RZTs, as shown by the relationship of RZT with air temperature among mulches ($P < 0.01$). In several agronomic crops, root temperature stress has been found to influence anthesis and seed development (Zobel, 1992). High RZTs can have a strong effect on vegetative growth, water and mineral nutrient uptake, assimilate partitioning and root respiration (Cooper,

1973; Dodd et al., 2000; Tindall et al., 1990). Plant organs may differ in their sensitivity to RZT, as in greenhouse-grown tomato where the optimal RZT for shoot dry matter production is 24 °C and that for roots is 26 °C. In the present study there were differences in thermal sensitivity among tomatillo cultivars, which is not surprising because tomatillo cultivars are highly variable genetically (Montes-Hernández and Aguirre-Rivera, 1994). Our results on the effect of RZT on tomatillo yield, however, cannot be conclusive since they are based on relatively few data points [8 (four mulches $\times$ two seasons)] over a limited temperature range (seasonal mean RZT = 25.8 – 30.2 °C).

Root zone temperature as affected by mulches can have a major impact on plant growth and yield but under certain conditions, other factors such as high insect pressure, may be more important. In both seasons, there was a higher incidence of silverleaf whiteflies (*Bemisia argentifolii* Bellows & Perring) and western flower thrips (*Frankliniella occidentalis* Pergande) in plants grown in bare-soil relative to those on plastic mulch (Díaz-Pérez, personal observation), which possibly explains the reduced yields of plants grown in bare soil. Thus, from the thermal point of view, bare soil may be a better option than black mulch during high-temperature conditions. However, bare soil may result in increased incidence of insects. In addition, colored mulches have been shown to affect plant growth and yield by modifying insect behavior (Schalk and Robbins, 1987).

Incidence of TSWV. Presence of TSWV was observed in the spring but not in the summer season. Incidence of TSWV (mean = 5.7%) was not affected ($P \leq 0.05$) by plastic mulches or cultivars, and it was not related with mean seasonal RZT. The infection of TSWV in symptomatic plants was confirmed by enzyme-linked-immunosorbent assay (ELISA), using a commercially available kit (Agdia Inc., Elkhart, Ind.). Preliminary results of this study were documented previously (Díaz-Pérez and Pappu, 2000).

Mineral nutrient concentration in the soil and leaf (summer season). Concentrations of P, Mn, and Fe in bare soil were the lowest, while concentrations of K, B, and Zn in bare soil were among the highest (Table 4). There were no differences in soil nutrient concentrations among plastic mulches, except for black mulch which had the highest B concentration and silver mulch which had among the lowest K and Zn concentrations. There were no differences in concentrations of soil mineral nutrient between cultivars.

Foliar concentrations of P and K were among the highest in bare soil and among the lowest in gray mulch (Table 5). Foliar concentration of Mn was among the lowest in silver mulch, while that of Mo was highest in bare soil. There were no significant differences in foliar concentrations of N, Ca, Mg, S, B, Zn, Cu, and Na among mulch treatments. Except for the higher concentration of Na in 'Verde Puebla' than in 'Toma Verde', foliar concentrations of mineral nutrients were similar between cultivars. Foliar concentrations of the

Fig. 5. Diurnal trends in root zone temperature (RZT) under plastic mulches during two growing seasons. Each symbol represents the hourly mean RZT for the entire season.

Table 3. Seasonal root zone temperature (RZT) of tomatillo plants in the spring and summer seasons as affected by plastic film mulch.

Mulch	Mean RZT (°C)	Max. RZT (°C)	Min. RZT (°C)
Spring			
Bare soil	25.8 d ^{xy}	31.2 b	21.3 c
Black	27.0 a	31.7 a	23.0 b
Gray	26.8 b	30.8 b	23.2 a
Silver	26.0 c	29.1 c	22.9 b
Summer			
Bare soil	28.4 c	34.2 b	24.6 b
Black	30.2 a	35.4 a	26.3 a
Gray	29.2 b	33.2 c	26.3 a
Silver	29.4 b	33.2 c	26.3 a

^xMeans separated within columns and season by Fisher's protected LSD test ($P \leq 0.05$).

^yValues represent the seasonal average of daily values of mean, maximum or minimum root zone temperature for each of the plastic mulches.

majority of mineral nutrients were not related with the mean RZT for the season, except for the concentrations of P, Zn and Na which tended to be related to the mean RZT but their

relationships were nonsignificant at $P \leq 0.05$. Fruit yield was related to foliar P ($r = 0.997$, $P < 0.01$) and K ($r = 0.957$, $P < 0.05$) concentrations while vegetative FW was not related to concentrations of these nutrients. Increased foliar concentrations of P and K as occurred in low fruit yielding treatments (bare soil and black mulch) are probably due to a reduced competition for mineral nutrients between the fruits and the vegetative top, as suggested by the reduction in harvest ratio with increasing foliar P concentrations ($r = 0.918$; $P = 0.083$). The foliar concentrations of N, Ca, Mg, S, Fe, Mn, B, Mo, Cu, Zn, and Na were not associated with vegetative FW or fruit yield. Thus, mean RZT for the season probably had a small effect on foliar concentration of the majority of mineral nutrients.

In conclusion, plastic mulch type and root zone temperature affected tomatillo plant growth and fruit yield during the summer and to a lesser degree during the spring, although plant responses to root zone temperature varied between cultivars. Tomatillo appears to be more tolerant to high RZT than other solanaceous crops such as tomato.

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Fig. 6. Relationship of mean root zone temperature during the establishment period (first 28 d after transplanting) with the top dry weight of two tomatillo cultivars in the spring and summer seasons. Each symbol represents the mean top dry weight for a given mulch and tomatillo cultivar. Solid lines were fit by linear regression. The quadratic curve (dotted line) was constructed from the pooled data from both seasons.

Fig. 7. Relationships of the average seasonal values of maximal and mean root-zone temperature (RZT) with the total fruit yield of two tomatillo cultivars. Graphs were constructed with data from the Spring and Summer seasons in 2000. Each symbol represents the mean fruit fresh weight for a given mulch and tomatillo cultivar. Solid lines were fit by linear regression.

Table 4. Mineral nutrient concentration in the soil of two tomatillo (*Physallis ixocarpa* Brot. ex Hornem.) cultivars grown on plastic film mulch during the summer season.

Treatment	Nutrient concn ($\mu\text{g}\cdot\text{g}^{-1}$)										
	P	K	Ca	Mg	Mn	B	Fe	Zn	Mo	Cu	Na
Mulch											
Bare	42.8 b ²	22.0 a	327	15.2	11.6 b	0.32 a	48 b	5.8 a	0.15	0.81	16.3
Black	58.1 a	18.3 ab	334	16.8	13.8 a	0.31 a	59 a	4.9 ab	0.02	0.66	17.1
Gray	55.4 a	19.4 ab	340	14.5	14.2 a	0.23 b	60 a	4.1 bc	0.13	0.64	16.7
Silver	55.5 a	17.4 b	323	15.2	14.0 a	0.22 b	63 a	3.7 c	0.00	0.53	16.8
Cultivar											
Toma Verde	50.4	18.3	323	15.2	13.2	0.26	59	4.7	0.00	0.62	16.9
Verde Puebla	55.5	20.3	340	15.6	13.5	0.27	56	4.6	0.14	0.69	16.5
Significance											
Mulch	**	NS	NS	NS	*	*	**	**	NS	NS	NS
Cultivar	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**
M × C	NS	NS	NS	NS	NS	*	*	NS	NS	NS	NS

²Means separated within columns by Fisher's protected LSD test ($P \leq 0.05$).

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Table 5. Mineral nutrient concentration in tomatillo (*Physalis ixocarpa* Brot. ex Hornem.) leaves as affected by plastic film mulch and cultivar (summer).

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Mn ($\mu\text{g}\cdot\text{g}^{-1}$)	B ($\mu\text{g}\cdot\text{g}^{-1}$)	Fe ($\mu\text{g}\cdot\text{g}^{-1}$)	Zn ($\mu\text{g}\cdot\text{g}^{-1}$)	Mo ($\mu\text{g}\cdot\text{g}^{-1}$)	Cu ($\mu\text{g}\cdot\text{g}^{-1}$)	Na ($\mu\text{g}\cdot\text{g}^{-1}$)
Mulch													
Bare	3.3	0.60 a ^z	3.16 a	1.57	0.55	0.22	62 ab	30	150 ab	35	0.9 a	6	87
Black	3.4	0.56 ab	2.98 ab	1.49	0.52	0.22	86 a	31	135 b	40	0.4 b	6	97
Gray	3.4	0.51 c	2.88 b	1.50	0.55	0.22	84 a	30	141 ab	39	0.4 b	6	99
Silver	3.3	0.52 bc	2.96 ab	1.36	0.48	0.22	52 b	31	161 a	38	0.4 b	7	103
Cultivar													
Toma Verde	3.3	0.56	2.98	1.45	0.52	0.21	70	29 b	146	39	0.5	6	85 b
Verde Puebla	3.4	0.53	3.00	1.53	0.53	0.23	72	32 a	147	37	0.5	6	108 a
Significance													
Mulch	NS	**	NS	NS	NS	NS	*	NS	*	NS	**	NS	NS
Cultivar	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	**
M × C	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zMeans separated within columns by Fisher's protected LSD test ($P \leq 0.05$).

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