Effects of Soil Moisture and Temperature on Reproduction and Development of Twospotted Spider Mite (Acari: Tetranychidae) in Strawberries

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ABSTRACT The effects of soil moisture and temperature on the reproduction of twospotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), were examined in laboratory and field tests in strawberries, *Fragaria* × *ananassa* Duchesne, in Florida. Different soil moisture levels (low, moderate, and high) were compared to determine how soil moisture affects the reproduction and development of twospotted spider mite. In addition to soil moisture, different irrigation techniques (drip versus drip/overhead) were compared to determine their effects on twospotted spider mite reproduction as well as the incidence of angular leaf spot, *Xanthomonas fragaria* Kennedy & King disease. Similar studies were conducted to determine how different temperatures (18, 27, and 35°C) affect the reproduction and development of twospotted spider mites. In the laboratory, low soil moisture as well as temperatures >27°C promoted twospotted spider mite development. A similar trend was observed in a field study with low soil moisture promoting twospotted spider mite reproduction during the early season (11 November–8 December). Irrespective of moisture levels, a significantly higher incidence of *X. fragaria* was recorded in treatments with drip/overhead irrigation systems compared with drip irrigation. Implications for management of soil moisture levels are discussed with respect to the abundance of twospotted spider mite and *X. fragaria* in strawberries.

KEY WORDS soil moisture, temperature, twospotted spider mite, irrigation, strawberries

STRAWBERRIES ARE AN IMPORTANT small fruit crop in Florida with a farm gate value of ≈$152 million annually (National Agricultural Statistics Service 2004). Current production is threatened by high populations of twospotted spider mite, *Tetranychus urticae* Koch, the key arthropod pest during strawberry production season (Jepson et al. 1975, Hochmuth 1988). In the past, twospotted spider mite has been controlled with several applications of acaricides. However, high fecundity and problems associated with resistance to acaricides (Trumble and Morse 1993) have made the management of twospotted spider mite a major problem for strawberry growers in Florida.

Predatory mite releases, including *Phytoseiulus persimilis* Athias-Henriot, have had moderate success in suppressing twospotted spider mite activity, especially in southern Florida where rainfall patterns and temperatures are more consistent than the northern regions of the state (Decou 1994). However, growers in northern Florida as well as other strawberry-producing areas in the southeast have not had much success in managing twospotted spider mite populations with augmentative releases of predatory mites (Liburd et al. 2003). Differences in environmental conditions between southern and northern Florida may account for the high populations of twospotted spider mite usually recorded in north central Florida during the early spring growing season when rainfall patterns and temperatures are irregular. A better understanding of the reproductive response of twospotted spider mite under varying environmental conditions may help to explain why strawberry growers in north central Florida and other areas of the southeast experience high populations during the spring growing season.

Soil moisture and irrigation have been shown to influence mite feeding in almonds (Hoy 1985) as well as fruit size and yield in strawberries (Dwyer et al. 1987). Blatt (1984) evaluated irrigation and planting methods to determine their effects on fruit size and yield in strawberries. He found that application of water before plants became water stressed significantly increased the number and size of berries as well as overall marketable yield. Similarly, Dwyer et al. (1987) monitored the response of 1-, 2-, and 3-yr-old strawberry plants to irrigation schedules by using three criteria: daily rainfall, leaf water potential, and soil moisture. They found that all irrigated plots had significantly higher yields compared with nonirrigated strawberry plots. In addition, fruit weight was found to be higher in all irrigated plots.

In addition to soil moisture, several studies have documented the effects of temperatures on twospotted spider mite reproduction (Ferro and Chapman 1979, Ho and Lo 1979). Ferro and Chapman (1979)

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recorded a higher percentage of twospotted spider mite egg hatch at 35°C compared with a temperature of 25°C. Similarly, Ho and Lo (1979) recorded lower reproductive rates of twospotted spider mite in soybean, *Glycine max* (L.) Merr., at low temperatures (<20°C).

Our hypothesis is that in addition to fruit size and marketable yields, soil moisture and temperature affect the reproduction and development of twospotted spider mite as well as the incidence of diseases in strawberries. Our research goals were to study environmental conditions; specifically soil moisture and temperature, to determine how these factors influence the reproduction and development of twospotted spider mite. Effects of soil moisture and temperature were examined in the laboratory in a controlled environment and then in the field under varying conditions. Furthermore, irrigation systems were studied in the field to determine how watering techniques (drip versus overhead irrigation) may affect growth and reproduction of twospotted spider mite and the incidence of angular leaf spot, *Xanthomonas fragaria* Kennedy & King disease.

Materials and Methods

Laboratory. Laboratory experiments were conducted at the University of Florida, Fruit and Vegetable Integrated Pest Management (IPM) Laboratory in Gainesville, FL.

Soil Moisture. Twelve potted 'Sweet Charlie' strawberry plants were randomly selected from our greenhouse nursery stock. Plants were pruned to six leaf-trifoliates and placed into 20-cm pot saucers before they were examined using a 2× circular illuminated magnifier (Cole Parmer, Vernon Hills, IL) to ensure that all plants were free from mites. Soil moisture levels in each pot were tested using a 9-in. soil moisture meter (tensiometer) (Lincoln Irrigation Company, Lincoln, NE), which measures moisture levels and translates the results to a scale of 0–10 (with 0 being completely dry soil and 10 being entirely saturated). The soil containing potted plants was then allowed to air-dry to conform to the required soil moisture levels according to each experimental treatment.

Three treatments were evaluated: 1) a low soil moisture (representing 1–3 on the soil moisture meter), 2) a moderate soil moisture ([control] 4–6 on the soil moisture meter), and 3) a high soil moisture (7–9 on the soil moisture meter). Experimental design was a completely randomized block with four replicates per treatment. Ten twospotted spider mite (adults) were placed onto each plant subjected to the various soil moisture treatments (low, moderate, and high moisture levels). The duration of the experiment was 9 d.

Temperature. Three environmental rearing chambers (Percival Environmental Chambers, Boone, IA) were used for this experiment. Each chamber was set for a photoperiod of 16:8 (L:D) h with 70% RH. During the 8-h dark period, the temperature was set at 15°C in all rearing chambers. Three treatments were evaluated: 1) a low daytime temperature 18°C, 2) a moderate daytime temperature 27°C (control), and 3) a high daytime temperature 35°C.

By using a similar protocol described for the soil moisture experiment, 12 plants were selected at random from the greenhouse and screened using a 2× circular illuminated magnifier to ensure that plants were mite free. Each plant was pruned to six leaf-trifoliate, and 10 twospotted spider mites were placed onto each plant. Experimental design was completely randomized block with four replicates. The experiment ran for 9 d.

Sampling. Every third day, all mites (motiles) and unhatched eggs on each plant in both soil moisture and temperature experiments were counted using a 40× adjustable stereomicroscope. All twospotted spider mite life stages (excluding eggs) were lumped and referred to as motiles.

Statistical Analysis. Data from the soil moisture and temperature experiments were analyzed using repeated measures analysis of variance (ANOVA) with mean separation using least significant differences (LSDs) to show treatment differences (PROC MIXED, SAS Institute 2002). Data were considered significant when P values were < 0.05.

Field Trial. The field experiment was located at the University of Florida, Plant Science Research and Education Unit, in Citra, FL. 'Sweet Charlie' strawberry transplants were planted into 24 plots on the 7 October 2002, and the experiment was continued until 15 April 2003. Plot size was 7.3 by 6 m with a 10-m buffer between each plot. Rows were 1.2 m in width, and plants were spaced ≈30 cm apart. Approximately 240 plants were planted in each plot. Overhead sprinklers were installed on all plots for frost protection (when needed).

Experimental design was a completely randomized block with four replicates. Six treatments (watering program) were evaluated. The program for each treatment was split into two 15-min watering cycles at 730 and 1000 hours, during the specific days when the treatment was administered. Treatments included 1) watering every day by using drip irrigation (high moisture level), 2) watering every day by using drip and overhead irrigation (high moisture level), 3) watering every other day by using drip irrigation ([moderate] control), 4) watering every other day by using drip and overhead irrigation ([moderate] control), 5) watering every third day by using drip irrigation (low moisture level), and 6) watering every third day by using drip and overhead irrigation (low moisture level). The duration of this experiment was from 7 October 2002 to 3 April 2003.

Sampling. Twenty leaves were collected randomly in each plot (80 leaves per treatment). Leaves were collected from the lower strata of the plant and examined for twospotted spider mite under a 40× stereomicroscope. Similar to the laboratory experiment, all twospotted spider mite life stages (excluding eggs) were lumped together and referred to as motiles. The number of motiles and eggs were counted and recorded.

Table 1. Mean ± SEM twospotted spider mite egg and motile populations on strawberries grown under different soil moisture levels in the greenhouse

Treatment[a]	Days after initial twospotted spider mite transfer					
	3 d		6 d		9 d	
	Eggs	Motiles	Eggs	Motiles	Eggs	Motiles
Low soil moisture	451.5 ± 69.2a	27.3 ± 5.7ab	454.0 ± 138.2a	375.8 ± 100.8a	953.0 ± 287.5a	487.5 ± 99.0a
Moderate soil moisture	490.3 ± 67.4a	37.3 ± 3.3a	215.8 ± 56.6a	202.5 ± 66.4a	863.0 ± 136.9a	524.8 ± 112.6a
High soil moisture	195.5 ± 12.8b	16.8 ± 1.3b	87.0 ± 23.3b	89.5 ± 48.4b	260.0 ± 63.4b	147.3 ± 15.4b

Means followed by the same letter are not significantly different ($P = 0.05$, LSD test).

For 3 d eggs, $F = 17.8$; df = 2, 6; $P = < 0.01$; for 3 d motiles, $F = 5.3$; df = 2, 6; $P = 0.05$; for 6 d eggs, $F = 6.2$; df = 2, 6; $P = 0.04$; for 6 d motiles, $F = 4.4$; df = 2, 6; $P = 0.07$; for 9 d eggs, $F = 6.0$; df = 2, 6; $P = 0.04$; and for 9 d motiles, $F = 12.8$; df = 2, 6; $P < 0.01$.

[a] Low soil moisture represents 1–3 on the soil moisture meter, 4–6 for moderate soil moisture, and 7–9 for high soil moisture.

At the end of the season, 20 plants in each plot were chosen randomly and examined for angular leaf spot. We used two parameters to determine the presence of the disease. First, if >5% of the upper surface of the leaves on each plant displayed irregular reddish brown necrotic spots, the plant was diagnosed as having angular leaf spot. Second, if water-soaked areas were present on >5% of the lower surface of the leaves on each plant, it was diagnosed as displaying angular leaf spot. Positive identification of angular leaf spot was determined by Richard E. Cullen (Plant Disease Clinic, University of Florida, Gainesville, FL). Plants selected from the various treatments were classified into two categories: 1) presence of disease and 2) absence of disease.

Statistical Analysis. Because the production season for this experiment lasted for >6 mo, data were initially pooled to determine overall trends and then separated into three categories: early (11 November–8 December), mid (22 February–11 March), and late (18 March–15 April) season to follow the trends throughout the season.

Poisson Regression with PROC GENMOD (SAS Institute 2002) was used to determine the effects of drip versus drip/overhead irrigation on populations of twospotted spider mite. Data were considered significant when the P values were ≤0.05. Binomial coefficients were used to estimate disease incidence.

Results

Laboratory. *Soil Moisture.* There were significantly higher numbers of twospotted spider mite eggs in the low and moderate soil moisture treatments compared with the high soil moisture treatment after 3, 6, and 9 d (Table 1). Overall, the low soil moisture treatment averaged 2.3, 5.2, and 3.6 times as many eggs compared with the high soil moisture treatment for 3, 6, and 9 d, respectively. Similarly, there were significantly higher populations of twospotted spider mite motiles in the low and moderate soil moisture treatments compared with the high soil moisture treatment after 6 and 9 d (Table 1). Treatments were significant over time for both the eggs ($F = 10.2$; df = 6, 18; $P < 0.01$) and motiles ($F = 5.1$; df = 6, 18; $P < 0.01$).

Temperature. There were significantly higher populations of twospotted spider mite eggs in the high temperature (35°C) treatment compared with the low temperature (18°C) treatment after 3, 6, and 9 d (Table 2). After 9 d, twospotted spider mite egg numbers at all three temperatures (low, moderate, and high) were significantly different. Similarly, significantly higher populations of twospotted spider mite motiles were recorded in the high temperature treatment compared with the low temperature treatment after 6 and 9 d, respectively (Table 2). Significantly different numbers of twospotted spider mite motiles were present in all three temperature treatments after 6 and 9 d. Treatments were significant over time for both the eggs ($F = 16.7$; df = 6, 18; $P < 0.01$) and motiles ($F = 2.8$; df = 6, 18; $P = 0.04$).

Field Trial. Comparison of different moisture levels under drip irrigation revealed that there were significantly higher populations of twospotted spider mite in low soil moisture plots compared with high soil moisture plots during the early season (11 November–8 December; Fig. 1). There were no significant differences in the population of twospotted spider mite among soil moisture treatments during mid- and late seasons for drip and drip/overhead irrigation.

Table 2. Mean ± SEM twospotted spider mite egg and motile populations on strawberries grown at different temperatures

Treatment	Days after initial twospotted spider mite transfer					
	3 d		6 d		9 d	
	Eggs	Motiles	Eggs	Motiles	Eggs	Motiles
Low temp (18°C)	25.5 ± 8.3b	6.3 ± 1.7a	41.0 ± 5.3b	6.8 ± 2.5c	43.0 ± 10.1c	4.8 ± 1.8c
Moderate temp (27°C)	70.3 ± 13.6a	10.5 ± 1.9a	152.8 ± 34.4a	40.8 ± 14.4b	99.0 ± 12.2b	91.3 ± 16.4b
High temp (35°C)	115.0 ± 12.4a	8.5 ± 0.9a	149.3 ± 29.0a	137.5 ± 22.2a	203.0 ± 32.3a	204.3 ± 36.2a

Means followed by the same letter are not significantly different ($P = 0.05$, LSD test).

For 3 d eggs, $F = 10.9$; df = 2, 6; $P = 0.01$; for 3 d motiles, $F = 1.9$; df = 2, 6; $P = 0.24$; for 6 d eggs, $F = 8.6$; df = 2, 6; $P = 0.02$; for 6 d motiles, $F = 31.9$; df = 2, 6; $P = <0.01$; for 9 d eggs, $F = 17.4$; df = 2, 6; $P = <0.01$; and for 9 d motiles, $F = 68.4$; df = 2, 6; $P = <0.01$.

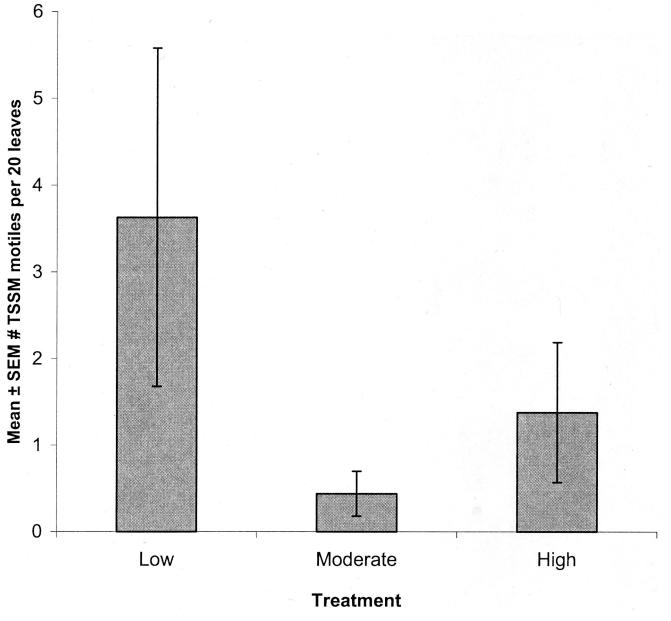

Fig. 1. Comparison of low, moderate and high soil moistures under drip irrigation during the early season (11 November–8 December) by using χ^2 analysis (χ^2 = 4.84; df = 1, 18; P = 0.03). Vertical bars represent mean ± SEM. Poisson regression SAS version 9.0 with PROC GENMOD to estimate parameters (SAS Institute 2002).

Comparison of drip versus drip/overhead irrigation across all treatments indicated that there was a significantly higher population of twospotted spider mite motiles under drip/overhead irrigation during the early and late season (18 March–15 April) as well as over the course of the entire season (Table 3). Overall, the drip/overhead irrigation treatments averaged 5.1, 6.2, and 5.5 times as many twospotted spider mite motiles compared with drip irrigation treatments in the early, late, and entire season, respectively. Finally, the probability of getting symptoms of angular leaf spot for treatments with drip/overhead was 80% in contrast with only a 30% probability for treatments with drip irrigation.

Discussion

Our results demonstrate that low soil moisture and high temperature increase twospotted spider mite reproduction in strawberries, with nearly 3 times as many eggs and motiles on plants exposed to low or moderate soil moistures compared with high soil moisture. Similar results were recorded for plants exposed to high temperatures (35°C) when they were 4 times as many twospotted spider mite motiles as opposed to plants exposed to lower temperatures (18°C). The mechanism(s) of temperature and soil moisture effects on twospotted spider mite physiology is unknown at present and requires further research. However, previous work has shown that when plants (soybean) are deprived of water, the sugars inside the leaves become more concentrated (White 1984), increasing the feeding of twospotted spider mite and promoting outbreaks (English-Loeb 1989). Another possibility is that when soil moisture is a limiting factor, more water is retained in the leaves of plants, which decreases the humidity around the leaves. This limits the amount of water that twospotted spider mite excretes, allowing the mite to spend more energy on reproduction (Boudreaux 1958).

In the field experiment, low soil moisture promoted twospotted spider mite reproduction. Temperatures during early season averaged 27°C with low levels of rainfall. These conditions were similar to those created in the laboratory where low soil moisture also increased twospotted spider mite reproduction. After 8 December, temperatures in north central Florida fell below 18°C, and mite populations fell significantly. Observations during the laboratory experiments indicated that a temperature of ≤18°C caused a cessation in twospotted spider mite reproduction. The period between 8 December and 15 February was characterized by low numbers of twospotted spider mite in the field. After 15 February, temperatures exceeded

Table 3. Effects of drip versus drip/overhead irrigation on populations of twospotted spider mite motiles on strawberries

Season	Mean ± SEM no. of twospotted spider mite motiles/20 leaves		χ^2 value	P
	Drip	Drip/overhead		
Early	0.4 ± 0.3	2.3 ± 1.7	8.63	0.0033
Mid	4.7 ± 2.1	13.6 ± 7.9	0.70	0.4032
Late	17.8 ± 7.0	110.1 ± 41.8	7.74	0.0054
Entire	7.7 ± 2.6	42.0 ± 15.6	5.64	0.0175

Poisson regression SAS version 9.0 with PROC GENMOD to estimate parameters (SAS Institute 2002).

18°C, increasing reproduction and development of twospotted spider mite populations.

Unseasonably high levels of precipitation occurred from 15 February to 1 March, which interfered with our soil moisture treatments during mid-season and may have accounted for some of the insignificant differences recorded during that period. Strawberry plants exposed to drip/overhead irrigation had a much higher incidence of angular leaf spot than plants under drip irrigation only. We suggest that the severity of this disease was magnified in all treatments because of the mid-season rains coupled with nighttime irrigation to prevent frost injury.

Higher populations of twospotted spider mite also were recorded in our drip/overhead irrigation compared with drip (across treatments) at the beginning and the end of the season. The reason for the higher numbers of twospotted spider mite under drip/overhead irrigation is unknown and needs further investigation. As in our soil moisture field experiment, we suggest that the reason why treatment differences were not significant during mid-season in our irrigation studies was due to the excessive amount of rain during that time.

Our work indicates that soil moisture management is critical when addressing arthropod (twospotted spider mite) and disease problems in strawberries. Earlier work showed that soil moisture is also important in increasing berry size and overall marketable yields (Blatt 1984, Dwyer et al. 1987). Strawberry growers involved in IPM programs should take precautions to ensure plants do not become water stressed or are not overwatered because these practices increase the potential for mite and disease problems, which ultimately affects overall marketable yields. The use of drip irrigation during the production season seems to be an important tool in managing soil moisture levels. The amount of water and frequency of irrigation a strawberry crop should receive depends on the grower's locality, soil type, and crop stage of development.

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