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Research

Acaricide efficacy and resistance in South Carolina tomato populations of twospotted spider mite

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Abstract

Twospotted spider mite, *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) is a key pest of vegetable crops in the southeastern US. Spider mites can cause significant yield loss in tomato due to reduced photosynthetic capacity and direct feeding damage. Use of acaricides is the primary control method, but acaricide resistance is a serious concern. We sought to characterize efficacy of acaricides registered for use on tomato by conducting 2 field trials in South Carolina in 2015 and 2016. The most effective treatments were abamectin, fenpyroximate, and cyflumetofen. Bifenazate and bifenthrin had lower efficacy than other products, and acaricide resistance was a suspected cause. Therefore, 3 spider mite populations were collected from grower fields in 2017, subjected to concentration-response screening, and compared to a known-susceptible population. Probit analysis revealed that all populations were resistant to bifenthrin at levels that would likely result in field failure. All populations were resistant to abamectin, with the LC_{50} of 1 population above field rate. Resistance to acequinocyl and spiromesifen also was present in all populations, but LC_{50} values were well below field rate. Based on our results and known nontarget effects of bifenthrin and abamectin on predatory mites, growers should avoid using these products for spider mite management. Poor performance of bifenazate in the efficacy study could not be attributed to resistance, although it is possible that the populations from the efficacy study were resistant and those screened for resistance were not. Many acaricides registered in tomato appear to be effective for mite management in South Carolina.

Key Words: *Tetranychus urticae*; bifenthrin; abamectin; bifenazate; miticide; probit

Resumen

La araña roja de dos manchas, *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) es una plaga clave de los cultivos de hortalizas en el sureste de los Estados Unidos. Los ácaros pueden causar una pérdida significativa de rendimiento en el tomate debido a la reducción de la capacidad fotosintética y al daño de la alimentación directa. El uso de acaricidas es el método de control principal, pero la resistencia a dichos acaricidas es una preocupación seria. Buscamos caracterizar la eficacia de los acaricidas registrados para su uso en tomate mediante la realización de 2 ensayos de campo en Carolina del Sur del 2015 a 2016. Los tratamientos más efectivos fueron abamectina, fenpiroximato y ciflumetofeno. El bifenazato y la bifentrina tuvieron menor eficacia que otros productos y se sospechaba que la resistencia a los acaricidas fue la causa. Por lo tanto, se recolectaron 3 poblaciones de ácaros de los campos de cultivo en el 2017, se sometieron a un examen de concentración-respuesta y se compararon con una población susceptible conocida. El análisis probit reveló que todas las poblaciones fueron resistentes a la bifentrina en niveles que probablemente resultarían en fallas de campo. Todas las poblaciones fueron resistentes a la abamectina, con una CL_{50} de 1 población por encima de la tasa de campo. La resistencia al acequinocilo y al espiromesifeno también estuvo presente en todas las poblaciones, pero los valores de CL_{50} estuvieron muy por debajo de la tasa de campo. Según nuestros resultados y los efectos de no-objetivo conocidos de la bifentrina y la abamectina en los ácaros depredadores, los productores deben evitar el uso de estos productos para el control de la araña roja. El rendimiento deficiente del bifenazato en el estudio de eficacia no se pudo atribuir a la resistencia, aunque es posible que las poblaciones del estudio de eficacia fueran resistentes y las que se sometieron a cribado de resistencia no. Muchos de los acaricidas registrados en tomate parecen ser efectivos para el manejo de ácaros en la Carolina del Sur.

Palabras Clave: *Tetranychus urticae*; bifentrina; abamectina; bifenazate; acaricida; probit

South Carolina tomato (*Solanum lycopersicum* L.; Solanaceae) production is a $32 million industry consisting of about 607 ha (1,500 acres), comprising nearly a quarter of the vegetable industry of the state (CAED 2016). Twospotted spider mite, *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae), is an important pest of fruiting vegetables throughout much of the southeastern US. In tomato, spider mites affect yields directly by feeding on fruit and causing damage known as gold fleck (Meck et al. 2012) and indirectly by feeding on foliage (Meck et al. 2013). Tomatoes that are not treated for mites may result in more than 90% of the fruit with gold fleck, compared to 0 to 5% if preventative weekly applications are made (Meck et al. 2013). Defoliation and chlorophyll loss due to foliar feeding may reduce tomato yields by more than 50% (Jayasinghe & Mallik 2010; Meck et al. 2013), primarily through reduced numbers of fruit produced (Meck et al. 2013).

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Biological control of spider mites is poor on tomatoes due to the effects of glandular trichomes on mortality and searching efficacy of predators (Gillespie & Quiring 1994; Cedola et al. 2001; Simmons & Gurr 2005). The predatory mite *Phytoseiulus persimilis* Athias-Henriot (Mesostigmata: Phytoseiidae) is released for spider mite control in greenhouse tomato production (Lange & Bronson 1981; Gerson & Weintraub 2012) and populations also are found in areas where they have not been recently released (Ditillo et al. 2016). However, high pressure from other pests such as caterpillars and viral and fungal pathogens also creates the need for foliar pesticide applications (Lange & Bronson 1981; Kennedy et al. 1983), some of which are harmful to predatory mites like *P. persimilis* (Ditillo et al. 2016), disrupting biological control. Therefore, spider mites on tomato are primarily managed by acaricide applications.

Heavy reliance on acaricides for mite management creates a high risk for resistance development. Biologically, pesticide resistance involves increase in tolerance to a pesticide within a population of arthropods over time, which results in increased population fitness (Onstad 2014). From the perspective of stakeholders, populations are described as resistant or not (as opposed to a continuum), and resistance typically is described as a decrease in susceptibility that increases the probability of a control failure (Onstad 2014). Twospotted spider mite is considered "the most resistant pest"; resistance to 96 different active ingredients has been documented (Van Leeuwen et al. 2010; Arthropod Pesticide Resistance Database 2020). The ability of *T. urticae* to develop resistance so rapidly is attributed to its short life cycle, high fecundity, arrhenotokous reproduction, and tendency to inbreed (Van Leeuwen et al. 2009). It also has an exceptionally wide host range, increasing the risk that populations will be exposed to multiple applications of various pesticides as spider mites move between crops. Polyphagy also pre-adapts *T. urticae* for pesticide detoxification by co-opting the same mechanisms used to detoxify plant defense compounds (Grbic et al. 2011; Dermauw et al. 2012).

Given the extreme risk of resistance development, resistance management strategies are critical. Acaricides labelled on tomato limit applications to 1 to 3 per season, depending on the product (Kemble et al. 2019). Keeping spider mite populations at low levels may require up to 9 acaricide applications to a single crop (Meck et al. 2013). Growers need products with high levels of efficacy to limit application costs and to remain within label restrictions. Therefore, knowledge of field efficacy and potential resistance issues is crucial. Bifenthrin, abamectin, acequinocyl, bifenazate, fenpyroximate, spiromesifen, and cyflumetofen are registered for spider mite control on tomato. Of these, spiromesifen primarily causes mortality in eggs and juveniles and reduces fecundity of females (Marcic 2012). The other active ingredients are effective primarily on motile stages (Marcic 2012). Acequinocyl, bifenazate, and cyflumetofen are specific acaricides, while the other products are also labelled for control of some insects (Marcic 2012). As a pyrethroid, bifenthrin has broad-spectrum activity.

Because of the importance of acaricide-based spider mite management in southeast tomato, our first goal was to compare various products for field efficacy against *T. urticae*. In some cases, certain active ingredients performed more poorly than expected, leading us to suspect issues with pesticide resistance. Our second goal was to quantify resistance levels in *T. urticae* populations collected from South Carolina tomato fields to both detect resistance and collect near-baseline susceptibility data for newer products.

Materials and Methods

FIELD EFFICACY TEST

Two trials were conducted on commercial tomato farms in Wadmalaw Island, South Carolina, USA (32.6783909°N, 80.1403297°W) in 2015 and Edisto Island, South Carolina, USA (32.5722150°N, 80.2954228°W) in 2016, which are 19 km apart. Individual plots were single rows 6.7 m in length and contained about 13 staked grape tomato plants, cultivar 'BHN1022' in 2015 and 'Sweet Zen' in 2016. Both growers maintained the field containing the plots with standard practices, including fungicide (copper hydroxide + pencozeb) and insecticide (chlorantraniliprole) applications for caterpillar management. The experiments consisted of evaluating 7 acaricides and a water control (Table 1), with 3 replications (3 rows) in a randomized complete block design. Spacing between rows was 1.8 m from center to center. Plants were about 90 d old at the time of the first acaricide application.

A backpack sprayer (Stihl SR 450, Virginia Beach, Virginia, USA, without nozzles) was calibrated to deliver a spray volume of 636 liter per ha (68 gallons per acre) when both sides of a row were treated. Individual plots received about 0.25 L of mixed solution. Each acaricide was mixed at the highest label rate at the equivalent of 935 liter per ha (100 gallons per acre) (Table 1). Acaricides were mixed with the appropriate adjuvant (Table 1) as indicated by the label. Induce and Kinetic were mixed at a rate of 1.25- and 0.94-mL adjuvant per liter solution, respectively. Adjuvant was not added to the water control. Each acaricide was sprayed twice, with applications about 2 wk apart, except for bifenazate which was sprayed only once on the first application date due to label restrictions. Applications were made on 26 Jun and 10 Jul 2015 and 8 Jun and 23 Jun 2016.

Mite counts were taken by randomly selecting 5 leaflets from each plot and counting all motile *T. urticae* using a dissecting microscope (SMZ168B, Motic Microscopes, Schertz, Texas, USA). Counts were taken immediately prior to each application and 3 d after treatment. In 2015, an additional count occurred on 15 Jun, 11 d prior to the first

Table 1. Acaricides used in 2015 and 2016 field trials.

AI	Product	AI per product	Product use rate (g AI per ha)	Product mix amount (per 1.89 L solution)	Aduvant
bifenthrin	Brigade 2 EC[a]	240 g per L	91.2	0.77 mL	Induce[g]
abamectin	Agri-Mek 0.15 EC[b]	84 g per L	98.3	2.37 mL	Induce
acequinocyl	Kanemite 15 SC[c]	150 g per L	340.5	4.58 mL	none
bifenazate	Acramite 50 WS[c]	50%	560.0	2.27 g	Induce
fenpyroximate	Portal XLO[d]	48 g per L	112.3	4.73 mL	Induce
spiromesifen	Oberon 2 SC[e]	240 g per L	148.8	1.26 mL	Induce
cyflumetofen	Nealta[f]	200 g per L	200	2.03 mL	Kinetic[g]

[a]FMC Corporation, Philadelphia, Pennsylvania, USA; [b]Syngenta Crop Protection, Inc., Greensboro, North Carolina, USA; [c]Arysta LifeScience North America, LLC, Cary, North Carolina, USA; [d]Nichino America, Inc., Wilmington, Delaware, USA; [e]Bayer CropScience LP, Research Triangle Park, North Carolina, USA; [f]BASF Corporation, Research Triangle Park, North Carolina, USA; [g]Helena Agri-Enterprises, LLC, Collierville, Tennessee, USA.

application. In 2016, plots were rated at 3 d after treatment after each application for mite damage levels on a scale of 1 to 10, with 1 indicating no damage and 10 complete necrosis. To account for the cumulative effects of mite damage over time, we calculated cumulative mite d (Beers & Hoyt 1993) for each of 3 sampling dates following the first treatment.

RESISTANCE SCREENING

Tetranychus urticae were collected from 3 commercial tomato farms in South Carolina, located in Wadmalaw Island (32.6802212°N, 80.1322898°W), St. Helena Island (32.396560°N, 80.568510°W), and Mount Pleasant (32.8488840°N, 79.8147364°W). Collection dates were 2 May 2017, 7 Jul 2017, and 19 Oct 2017, respectively. Mites were collected by removing infested tomato foliage from the field. Then, individual mites ($n \geq 50$) were removed from the infested leaves and placed onto lima bean (*Phaseolus lunatis* L.; Fabaceae) plants var. 'Henderson Bush.' Colonies were maintained at about 22 °C, in isolated rooms with supplemental lighting provided by plant growth lights (16:8 h L:D photoperiod). A known-susceptible colony of *T. urticae* was subcultured from a colony maintained by Cornell University (Geneva, New York, USA), which has been in culture for more than 20 yr.

Concentration response assays were conducted within 3 mo of collection. Assays were conducted on arenas consisting of lima bean leaf disks (2.2 cm diam) placed abaxial side up on water-soaked cotton inside of a plastic cup (96.1 mL) (Solo, Publix, Lakeland, Florida, USA). For adulticidal products, 20 female *T. urticae* were added to each leaf disk and then immediately treated. For spiromesifen (which is ovicidal), about 10 female *T. urticae* were added to each disk and allowed to oviposit overnight. Then, the females were removed from the disks and egg numbers were adjusted to 20 per disk. The position of each egg was marked with a felt pen and then each disk was treated.

For each concentration response assay, we tested 6 concentrations of each product and a water control. Concentration ranges (mg AI per L) tested for the field-collected populations were: bifenthrin (5–4,000), abamectin (0.175–70), acequinocyl (0.025–100), bifenazate (0.0075–30), fenpyroximate (0.05–10), spiromesifen (0.1–50), and cyflumetofen (0.2–80). Treatments were made by mixing the correct amount of formulated product with water to create a 1 L solution, then serially diluting this solution to obtain lower concentrations. Initial concentrations tested were based on prior work with other *T. urticae* populations (Schmidt-Jeffris, unpublished) and adjusted as needed to obtain mortality gradients necessary to calculate LC_{50} (lethal concentration 50%) values (described below). Treatments were applied using a Potter Spray Tower (Burkard Scientific, London, United Kingdom) at about 35 kPa to spray 2 mL of a solution on each disk. Each concentration and the water control was replicated 5 times and replications for each population × AI combination were conducted simultaneously. Assays were held in a growth chamber (23.18 ± 0.04 °C, 52.52 ± 0.10% RH, 16:8 h L:D photoperiod) and evaluated at 24 h after treatment (adulticides) or until about 100% of eggs in the water control hatched (spiromesifen, 4–6 d). Spider mite females that could not move a full body length forward after being gently prodded with a brush were considered dead.

DATA ANALYSIS

Field efficacy data were analyzed using SAS version 9.3 (SAS Institute, Cary, North Carolina, USA) software. Data were analyzed separately by date within year. Mean mites per leaflet and cumulative mite d were compared for each date using a generalized linear mixed model (PROC GLIMMIX), with acaricide as the fixed effect and replicate as a random effect, specifying a negative binomial distribution. Treatment means were compared using least-squares means multiple *t*-tests at $P < 0.05$. Friedman's chi-square test was conducted to determine if there were differences in damage rating scores between treatments while controlling for replicate (PROC FREQ).

The LC_{50} values, their associated 95% confidence intervals, and the probit regression parameters (slope, intercept, and natural response) were calculated for each acaricide × location combination using PoloPC (Leora Software LLC, Parma, Missouri, USA). The LC_{50} was used to calculate the resistance ratio (LC_{50} field population divided by LC_{50} susceptible population). Additionally, we used the regression parameters to predict the percent mortality of each population if treated with the maximum labeled field rate of each product. Resistance ratio and comparison of LC_{50} to field rate was used to determine likely resistance in lieu of monitoring susceptibility changes over time. There are no baseline data available for these spider mite populations to allow for a "true" resistance monitoring survey.

Results

FIELD EFFICACY TEST

In 2015, mite counts did not differ between treatments on either of the pre-treatment dates (Table 2). Mite counts were significantly different on 26 Jun and 13 Jul (3 d after treatment after the first and second application) but not on the d of the second application (10 Jul, 11 d after treatment after the first application). On 29 Jun 2015 (3 d after treatment, first application), mite counts were higher in the bifenazate treatment relative to all other treatments except for bifenthrin (Fig. 1). On 13 Jul 2015 (3 d after treatment, second application), bifenazate and spiromesifen did not differ from the control. Based on mite counts, the most effective treatments were abamectin, fenpyroximate, and cyflumetofen; bifenthrin was intermediate (Fig. 1). Cumulative mite d were not significantly different on any of the sampling d in 2015 (Table 2). Numerically, bifenthrin and bifenazate accumulated more cumulative mite d than the control (Fig. 2).

Spider mite pressure was higher in the 2016 trial. Here, mite counts differed on every sample date except for the pre-treatment count (Table 1). On 13 Jun 2016 (3 d after treatment after the first application), bifenthrin mite counts did not differ from the control (Fig. 1). Abamectin, acequinocyl, fenpyroximate, spiromesifen, and cyflumetofen had the lowest mite counts, with bifenazate intermediate. Prior to the second application (23 Jun, 15 d after treatment after the first application), mite counts did not differ between bifenthrin and control treatments. Abamectin, acequinocyl, fenpyroximate, spiromesifen, and cyflumetofen had the lowest mite counts on this date, with bifenazate intermediate (Fig. 1). On the final sampling date, bifenthrin and bifenazate mite counts did not differ from the control. Spiromesifen mite counts were intermediate, while abamectin, acequinocyl, fenpyroximate, and cyflumetofen had the lowest mite counts (Fig. 1).

Cumulative mite d differed on 23 and 27 Jun in 2016 (Table 2). On 23 Jun, the bifenthrin and the control did not differ in cumulative mite d (Fig. 2). Abamectin, acequinocyl, fenpyroximate, and cyfluthrin had the lowest cumulative mite d; bifenazate and spiromesifen were intermediate. On the final d of sampling, cumulative mite d did not differ between bifenthrin and the control, and bifenazate was intermediate to this group and the remaining treatments (Fig. 2).

Damage ratings differed on both dates that they were estimated ($\chi^2 = 5.51$; $P = 0.0189$; $\chi^2 = 7.99$; $P = 0.0047$). For both dates, the overall median damage rating across all samples was 6. At the first rating, bifenthrin, bifenazate, and fenpyroximate had higher damage ratings than the overall median rating (Fig. 3). On 27 Jun 2016, bifenthrin, bifenazate, and the control had higher damage ratings than the overall median.

Table 2. Statistical results for overall models analyzing data from acaricide field trials. First value is d after first treatment, second value is d after second treatment. Pre-treatment dates are indicated with negative numbers.

Variable	Date	D after treatment	*F*	df	*P*
mites per leaflet	15 Jun 2015	−11, −25	0.68	7, 14	0.6837
	26 Jun 2015	0, −14	1.41	7, 14	0.2762
	29 Jun 2015	3, −11	4.04	7, 14	0.0126
	10 Jul 2015	14, 0	1.57	7, 13	0.2301
	13 Jul 2015	21, 7	3.73	7, 13	0.0195
	08 Jun 2016	0, −15	0.50	7, 14	0.8199
	13 Jun 2016	5, −10	7.24	7, 14	0.0009
	23 Jun 2016	15, 0	9.33	7, 14	0.0002
	27 Jun 2016	19, 4	12.93	7, 14	< 0.0001
Cumulative mite d	26 Jun 2015	0, −14	1.21	7, 14	0.3572
	29 Jun 2015	3, −11	1.38	7, 14	0.2860
	10 Jul 2015	14, 0	1.61	7, 13	0.2175
	13 Jul 2015	21, 7	1.60	7, 13	0.2203
	13 Jun 2016	5, −10	0.42	7, 14	0.8752
	23 Jun 2016	15, 0	4.76	7, 14	0.0064
	27 Jun 2016	19, 4	7.07	7, 14	0.0010

RESISTANCE SCREENING

The LC_{50} values for each population × AI are presented in Figure 4. For all 7 acaricides, the lab colony had lower LC_{50}'s (or very similar, as in bifenazate for the Mt. Pleasant population) than the 3 field-collected populations (Fig. 4). Bifenthrin resistance was present in all 3 populations, with the resistance ratio showing a 250 to 350-fold decrease in susceptibility (Fig. 4). This resulted in LC_{50} values at or near field rate. Using the regression parameters (Table 3), we predicted that the field rate of bifenthrin would cause only 48 to 62% mortality in our field-collected populations. Abamectin resistance also was observed in the St. Helena population, with a 2,800-fold decrease in susceptibility and a LC_{50} well above field rate. The resistance ratio of the Wadmalaw population was 208. The field rate of abamectin was predicted to kill 31 and 85% of the St. Helena and Wadmalaw populations, respectively. The Mt. Pleasant population also shows some resistance to cyflumetofen, with a resistance ratio of 14 and a LC_{50} that is 21% of the field rate. However, expected mortality at the field rate remained above 97% for all populations tested.

Discussion

In general, the most effective treatments were abamectin, fenpyroximate, and cyflumetofen. However, although abamectin was one of the best performing products in our field trials, we were able to detect resistance to it in all 3 *T. urticae* populations tested. The St. Helena population was highly resistant, with a resistance ratio of nearly 3,000 and LC_{50} well above the field rate. Abamectin can be highly effective against *T. urticae* in tomato (Hall & Shelton 1998; Kuhar et al. 2007; Walgenbach & Schoof 2010, 2017), but resistance to it has been reported in many crops (Marcic 2012; Arthropod Pesticide Resistance Database 2020). This may be due to the long period this product has been available and its use for control of multiple pests. Therefore, ab-

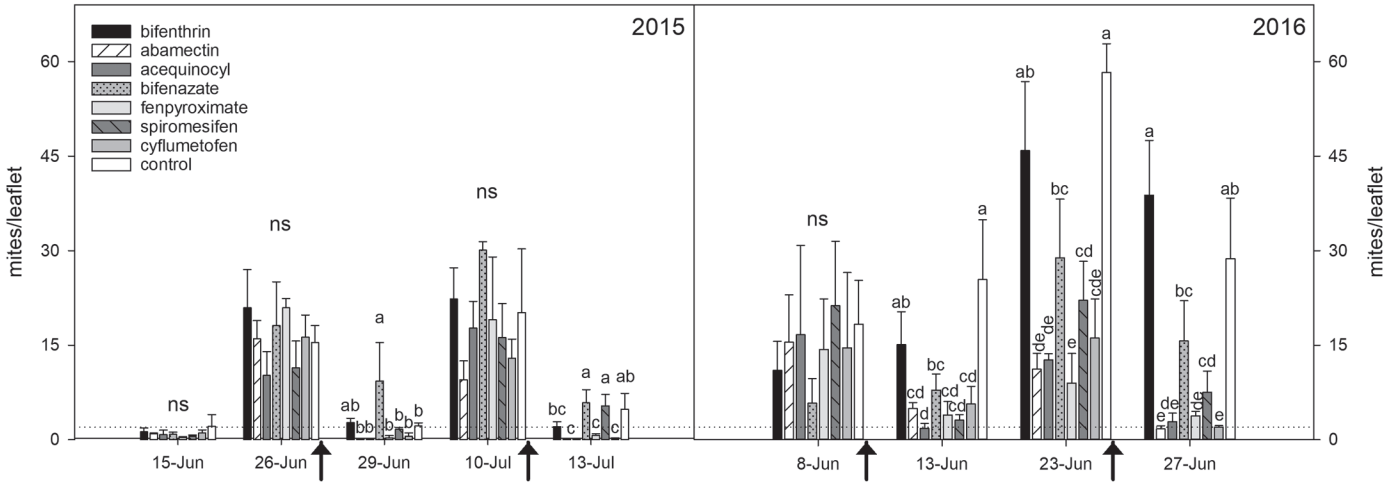

Fig. 1. Mean (± SE) spider mite (*Tetranychus urticae*) counts per tomato leaflet in a 2015 and 2016 acaricide efficacy trial conducted in South Carolina, USA. Arrows indicate dates of acaricide applications. Treatments with the same letter within a date are not statistically different (lsmeans $P > 0.05$). "ns" indicates that the overall model was not significant. The dotted line represents the action threshold for spider mites in tomato (2 per leaflet).

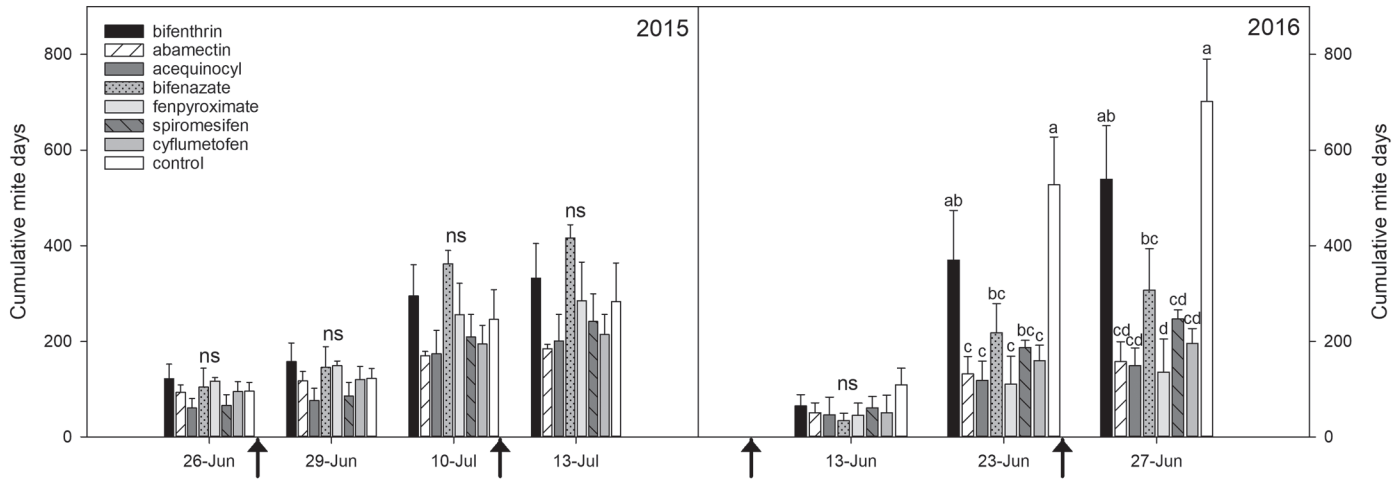

Fig. 2. Mean (± SE) cumulative mite d of *Tetranychus urticae* in a 2015 and 2016 acaricide efficacy trial conducted in South Carolina, USA. Arrows indicate dates of acaricide applications. Treatments with the same letter within a date are not statistically different (lsmeans $P > 0.05$). "ns" indicates that the overall model was not significant.

amectin use should be limited because of potential resistance issues coupled with non-target effects on key predatory mites (Bergeron & Schmidt-Jeffris 2020).

Bifenthrin was the poorest performing product in the efficacy trials, followed by bifenazate. The action threshold for spider mites on tomato is 2 mites per leaflet (Kemble et al. 2019). Following the first 2015 application, bifenazate was the only treatment that greatly exceeded this level. The final 2015 cumulative mite d values were highest numerically for bifenazate and bifenthrin. This trend was stronger in 2016 when these 2 treatments were the only ones with mite levels dramatically higher than the action threshold.

In the case of bifenthrin, poor field performance is likely due to the resistance that was detected in all 3 tested populations, 1 of which was collected from the same farm on which the 2015 trial was conducted. Pyrethroid resistance is well-documented in spider mites (Arthropod Pesticide Resistance Database 2020). Pyrethroids also are known for causing spider mite flare-ups due to increased reproduction (hormoligosis), non-target effects on natural enemies, and potentially, physiological impacts on treated host plants, such as altered rates of transpiration and photosynthesis (Gerson & Cohen 1989). Of these, non-target effects on natural enemies are the best described (Croft 1990; Ditillo et al. 2016; Bergeron & Schmidt-Jeffris 2020). This is particularly problematic when the spider mite population is resistant, leading to a situation that highly is favorable to the pest and unfavorable to the predator (Schmidt-Jeffris & Beers 2018; Bergeron & Schmidt-Jeffris 2020). Despite some activity against susceptible populations of spider mites, bifenthrin should not be used for their management.

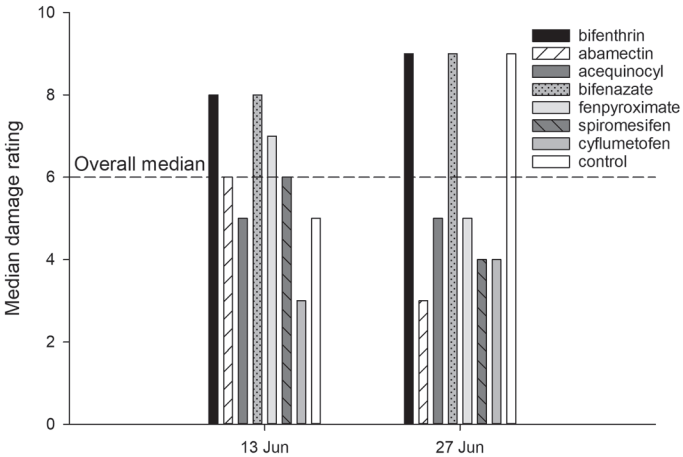

Fig. 3. Median plot damage ratings in a 2016 acaricide efficacy trial conducted in South Carolina, USA. The dashed line indicates the overall median across treatments. Plots were rated on a 1 to 10 scale, with "1" indicating no damage and "10" indicating complete leaf necrosis.

Bifenazate was the next most ineffective acaricide examined. Unlike the other products tested, this acaricide only can be used on a tomato crop once. This may account for the higher levels of *T. urticae* in this treatment for the final counts, when all other treatments had been applied twice. However, it also had relatively higher spider mite populations than other treatments after the first application. Prior research found bifenazate to highly be effective for spider mite control in tomato (Kuhar et al. 2007; Walgenbach & Schoof 2007, 2009, 2010, 2013, 2016, 2017). These trials found bifenazate to be more effective than spiromesifen (Walgenbach & Schoof 2007, 2010, 2013), fenpyroximate (Walgenbach & Schoof 2010), and cyflumetofen (Walgenbach & Schoof 2016, 2017). Among the acaricides, it typically has the fastest knockdown and longest residuals (Walgenbach & Schoof 2013, 2016). One study even found a single application of bifenazate to be twice as effective as 2 applications of cyflumetofen (Walgenbach & Schoof 2016).

The poor performance of bifenazate in our study relative to past efficacy led us to suspect that resistance may have developed. However, all 3 populations tested had LC_{50} values that were comparable to the control and well below field rate. It is possible that the populations of *T. urticae* in the 2015 and 2016 field trials were resistant to bifenazate, and those that we collected to screen for resistance were not. Additional screening will be required to determine if bifenazate resistance is present in South Carolina populations of *T. urticae*, but the present study does not indicate that this is occurring. Growers that experience field failures should first confirm that other issues, such as inadequate coverage or calibration errors, are not to blame for poor acaricide performance.

Neither LC_{50} values or field efficacy indicated potential field-relevant resistance issues with acequinocyl, fenpyroximate, spiromesifen, or cyflumetofen. However, the resistance ratio for acequinocyl and spiromesifen were very high (> 100) for all 3 populations tested. This is due to the very low LC_{50}'s for the susceptible population. While it

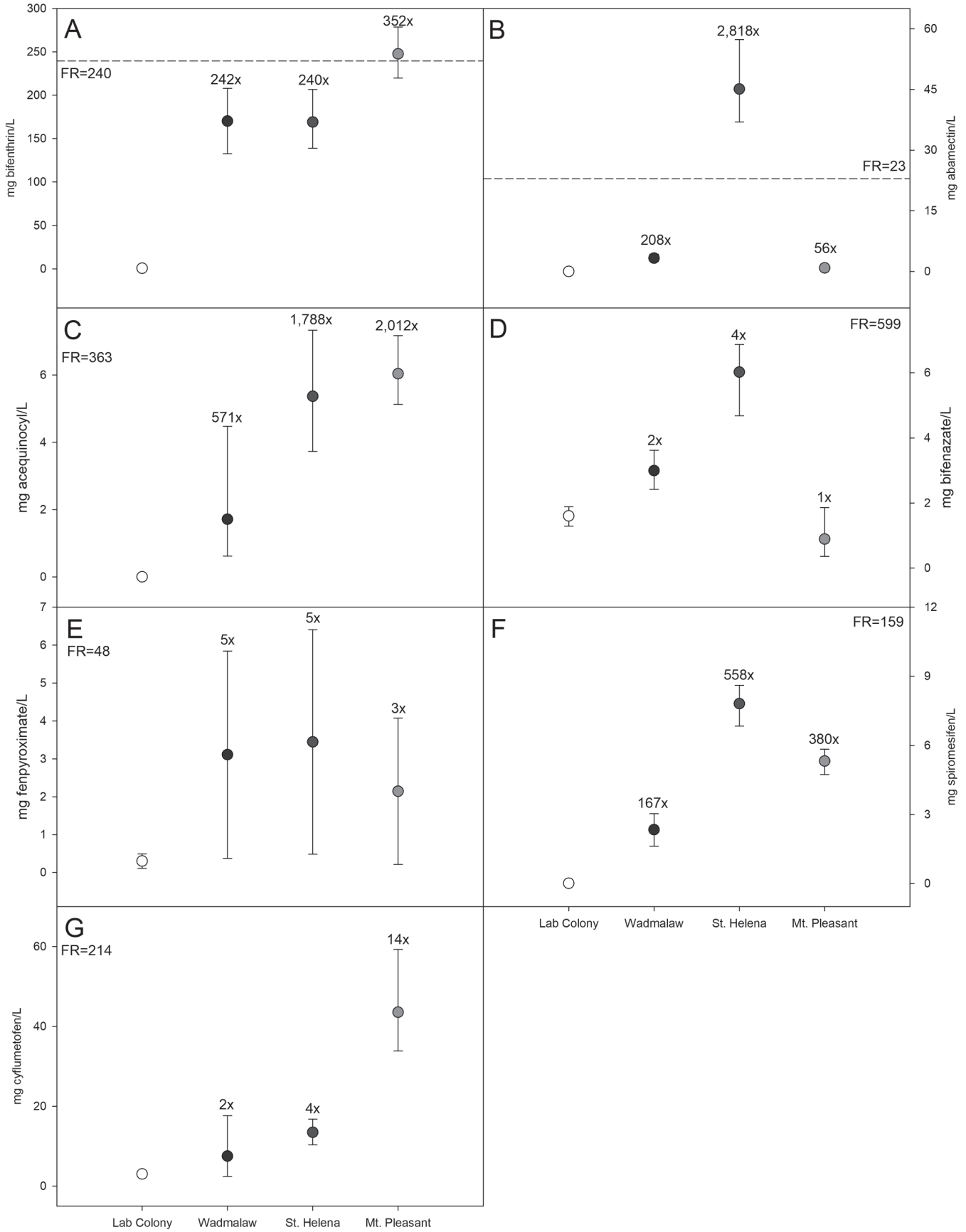

Fig. 4. LC_{50} values (± 95% confidence interval) for 7 AIs screened against a known-susceptible lab colony and 3 field-collected populations of *Tetranychus urticae*. When present, the dashed line indicates the amount of AI in the maximum labelled field rate. This value also is indicated in each graph by "FR=". The resistance ratio of each AI × population is written above each data point.

Table 3. Model results (± SE) for probit assays screening for acaricide resistance in 3 field populations and a susceptible laboratory population of *Tetranychus urticae*.

	AI	Slope	Intercept	Natural response
Wadamalaw	bifenthrin	2.022 ± 0.173	−4.510 ± 0.437	0.010 ± 0.010
	abamectin	1.245 ± 0.078	−0.651 ± 0.092	0 ± 0
	acequinocyl	1.981 ± 0.170	−0.463 ± 0.113	0 ± 0
	bifenazate	3.157 ± 0.272	−1.503 ± 0.221	0 ± 0
	fenpyroximate	3.033 ± 0.216	−1.494 ± 0.126	0 ± 0
	spiromesifen	4.670 ± 0.522	−1.725 ± 0.332	0.051 ± 0.012
	cyflumetofen	1.371 ± 0.098	−1.201 ± 0.127	0 ± 0
St. Helena	bifenthrin	2.069 ± 0.173	−4.609 ± 0.389	0.003 ± 0.003
	abamectin	1.725 ± 0.204	−2.854 ± 0.315	0 ± 0
	acequinocyl	2.335 ± 0.213	−1.703 ± 0.220	0.017 ± 0.008
	bifenazate	5.184 ± 1.026	−4.041 ± 0.958	0 ± 0
	fenpyroximate	4.130 ± 0.336	−2.219 ± 0.211	0.015 ± 0.007
	spiromesifen	9.077 ± 1.185	−8.104 ± 1.129	0.032 ± 0.008
	cyflumetofen	3.126 ± 0.255	−3.530 ± 0.323	0 ± 0
Mt. Pleasant	bifenthrin	3.247 ± 0.318	−7.774 ± 0.769	0.009 ± 0.005
	abamectin	2.460 ± 0.251	0.122 ± 0.119	0.004 ± 0.004
	acequinocyl	2.082 ± 0.146	−1.626 ± 0.121	0 ± 0
	bifenazate	1.642 ± 0.118	0.081 ± 0.130	0 ± 0
	fenpyroximate	2.980 ± 0.198	−0.986 ± 0.100	0 ± 0
	spiromesifen	6.178 ± 0.908	−4.484 ± 0.723	0.117 ± 0.019
	cyflumetofen	2.757 ± 0.256	−4.518 ± 0.408	0 ± 0
Susceptible	bifenthrin	0.759 ± 0.070	0.116 ± 0.086	0.042 ± 0.024
	abamectin	2.266 ± 0.324	4.078 ± 0.578	0.010 ± 0.010
	acequinocyl	0.829 ± 0.111	2.058 ± 0.161	0.010 ± 0.010
	bifenazate	3.390 ± 0.396	−0.696 ± 0.165	0.077 ± 0.016
	fenpyroximate	2.992 ± 0.313	0.560 ± 0.084	0 ± 0
	spiromesifen	0.795 ± 0.078	1.462 ± 0.098	0.031 ± 0.018
	cyflumetofen	3.049 ± 0.311	−1.467 ± 0.208	0.058 ± 0.018

may indicate that some resistance has developed to these products in South Carolina populations of *T. urticae*, field failure is highly unlikely. These results stress the need to account for how LC_{50}'s compare to field rate when assessing resistance, because this better accounts for how resistance is defined by stakeholders (Onstad 2014).

Most acaricides continue to be effective tools for managing spider mites in South Carolina tomato. Growers should continue to use scouting and action thresholds, and rotate between the available modes of action to maintain product efficacy. Improvement of management programs to reduce use of broad-spectrum insecticides for managing other pests will allow for higher populations of spider mite natural enemies and decreased reliance on acaricides, extending the efficacy of these products. Of the most effective products in this study, cyflumetofen is the least harmful to the predator *P. persimilis* (Bergeron & Schmidt-Jeffris 2020). Bifenazate also is selective (Bergeron & Schmidt-Jeffris 2020) and should be considered if local *T. urticae* populations are known to be susceptible.

Table 4. Predicted percent mortality of each *Tetranychus urticae* population at the highest labeled field rate for each active ingredient.

	Wadmalaw	St. Helena	Mt. Pleasant	Susceptible
bifenthrin	62.23	62.45	48.46	97.52
abamectin	85.15	30.60	99.97	100
acequinocyl	100	100	99.99	100
bifenazate	100	100	100	100
fenpyroximate	99.99	100	100	100
spiromesifen	100	100	100	99.94
cyflumetofen	97.70	99.99	97.18	100

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