Lethal, Sublethal, and Behavioral Effects of Sulfur-Containing Products in Bioassays of Three Species of Orchard Mites

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ABSTRACT The effects of three sulfur products (calcium polysulfide [= lime sulfur], dry flowable sulfur, and ammonium thiosulfate, a plant nutrient), were tested in bioassays against a predatory mite, *Galandromus occidentalis* (Nesbitt), and two species of tetranychid (pest) mites, twospotted spider mite (*Tetranychus urticae* Koch) and European red mite [*Panonychus ulmi* (Koch)]. Calcium polysulfide and ammonium thiosulfate were acutely toxic on contact to adult females of all three mite species, causing 58–100% mortality in 48 h. Dry flowable sulfur, in contrast, was nontoxic to adults of all three species. Fresh residues of the sulfur products were essentially nontoxic to females of *G. occidentalis* and *T. urticae*. *Galandromus occidentalis* consumed 8.2 and 4.0× fewer prey contaminated with residues of calcium polysulfide and ammonium thiosulfate; dry flowable sulfur had no effect on prey consumption. Higher posttreatment temperatures (32 versus 18°C) did not affect the toxicity of dry flowable sulfur to *G. occidentalis* and *T. urticae*. The toxic effect of the sulfur products was not related to the concentration of elemental S but rather to some intrinsic characteristic of the compound itself. There were substantial differences in the responses of different stages of *G. occidentalis*. Residues that were nontoxic to adult females were highly toxic to hatching larvae, including those of dry flowable sulfur. In addition, all three products were highly repellent to adult female *G. occidentalis*. The lethal effect of calcium polysulfide on larvae was still present when the laboratory-aged residues on bean leaves were 8–9 d old. Field-aged residues on apple (*Malus* spp.) leaves were highly toxic (89% mortality) after 7 d, but mortality declined to 50 and 17% after 14 and 22 d, respectively. The increasing use of sulfur-containing products is detrimental to predatory mites and may play a role in the diminishing effectiveness of integrated mite control in Washington apple orchards.

KEY WORDS *Galandromus occidentalis*, *Tetranychus urticae*, *Panonychus ulmi*, sulfur, lime sulfur

Sulfur is one of the oldest known pesticides, its fumigant and insecticidal properties having been recognized and exploited since Homeric times (Shepard 1951). It has been used in deciduous tree fruit pest management in Washington state since the industry began in the 1880s. Sulfur is a broadly toxic pesticide, exhibiting fungicidal, acaricidal, and insecticidal properties. In addition, sulfur is an essential element for plant nutrition, and is sometimes applied in combination with other nutrients. Although the use of sulfur as a pesticide has been largely displaced by modern synthetic materials, it has been recommended for use in Washington tree fruit industry since the first spray schedules were printed in 1912 (Beattie and Melander 1912), and it remains recommended and used today (NASS 2006, Smith et al. 2007).

A variety of sulfur-based pesticides have been used over the years. One early refinement to sulfur use was the addition of quicklime (CaO), creating a complex mixture of calcium polysulfides (commonly known as lime sulfur). The addition of CaO was found not only to improve the insecticidal properties of the sulfur but also to make it less phytotoxic, a chronic problem with the use of wettable sulfurs. The high ambient temperatures found to improve the activity of sulfur (Shepard 1951) also proved to cause greater phytotoxicity.

Currently, the use of sulfur products in Washington's apple (*Malus* spp.) production programs is increasing, particularly in two use niches. First, calcium polysulfide has been developed as a blossom thinner (McArtney et al. 2006, Smith et al. 2007). Although other materials are available at later stages for thinning fruitlets, blossom thinning is considered critical to crop load regulation. Ammonium thiosulfate is also applied during this period of bloom as a nutrient spray. Second, fungicidal use of sulfur is increasing, particularly in organic apple production; in Washington, certified organic production is ≈4.6% of the apple acreage (Granatstein and Kirby 2008). Additionally, although disease pressure is generally lower in the arid growing districts of eastern Washington than in other areas of the United States, recent plantings of mildew-susceptible cultivars have made some level of fungi-

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cidal protection imperative. Although sulfur is one of the few organically approved fungicides, its use is also beneficial in conventional production, providing an alternative mode of action to synthetic fungicides in resistance management (FRAC 2008).

In contrast to its important beneficial roles, sulfur-containing pesticides have long been identified as disruptive to integrated mite control (Garman and Townsend 1938, Cutright 1944, Lord 1949, MacPhee and Sanford 1954, Collyer and Kirby 1955, Hoyt 1965). In most cases, elimination of a phytoseiid predator is cited as the cause of disruption; however, Hoyt et al. (1970) considered that there was little direct effect on the predator, and the negative effects were due to the elimination of the alternate prey, apple rust mite, *Aculus schlechtendali* (Nalepa). In Washington, the deleterious effects were managed by restricting most of the use of sulfur products to the prebloom period (Smith et al. 2007), with limited use of sulfur fungicides in the postbloom period. Over the past 15 yr, however, the use of calcium polysulfide and sulfur fungicides has increased from three and 6%, respectively, in 1991 (NASS 1992) to 33 and 47% of the apple acreage treated in 2005 (NASS 2006).

Although the gross negative effects of sulfur applications on integrated mite management in apple have been widely recognized, there have been few detailed laboratory studies quantifying the effects of sulfur-containing products. Auger et al. (2003) provided detailed measurements concerning the effects of temperature and humidity on the toxic effects of micronized sulfur on a laboratory strain of *T. urticae.* Watve and Lienk (1975) showed that wettable sulfur had little effect on two species of phytoseiids in a slide-dip bioassay of adults. Hoy and Standow (1982) documented high levels of resistance to several sulfur products in populations of *Metaseiulus* [=*Galandromus*=*Typhlodromus*] *occidentalis* Nesbitt from California vineyards, but they noted that other populations were susceptible, including one from apple in Washington. However, there are no contemporary data from Washington orchards, and the effects of nutrient sprays containing sulfur have not been explored. These materials are not labeled or used as pesticides and are therefore presumed to have no effect on arthropods.

After decades of successful integrated mite management programs in Washington state apple orchards, acaricide use has increased in recent years (NASS 1992, 2006). During the same period, there have been many changes in apple pest management systems that may be affecting the stability of integrated mite management, including the use of lime sulfur as a blossom thinner. Increasing restrictions on the use of organophosphate insecticides have caused a shift in the insecticides used for control of codling moth, *Cydia pomonella* L., the key pest of apple in Washington. The most extensively used class of replacement pesticides are the neonicotinoids (Brunner et al. 2005), which have been associated with disruption of integrated mite control (Beers et al. 2005). Other potentially disruptive materials currently in use include novaluron (E.H.B. and L.M.-R., unpublished data), kaolin particle films (Knight et al. 2001), carbaryl and formetanate hydrochloride (Smith et al. 2007), and spinosad (Villanueva and Walgenbach 2005).

The following series of experiments were designed to examine in greater detail the lethal and sublethal effects of some commonly used sulfur-containing products on the predatory mite, *Galandromus occidentalis* (Nesbitt) (Acari: Phytoseiidae), to determine their potential role in disruption of integrated mite control. This species is the key predator in Washington apple. Additionally, the effects of sulfur products were examined on their primary prey, twospotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), and the European red mite, *Panonychus ulmi* (Koch) (Acari: Tetranychidae).

Materials and Methods

Three sulfur products commonly used by the Washington tree fruit industry were chosen for use in the bioassays. Calcium polysulfide (Rex Lime Sulfur, OrCal Inc., Junction City, OR) has been used increasingly as a thinning agent during the bloom period, in addition to its use as a fungicide. Ammonium thiosulfate (Thio-Sul, Tessenderlo Kerley, Phoenix, AZ) is a plant nutrient applied during the bloom period; its sulfur content is similar to that of calcium polysulfide. Dry flowable sulfur (Kumulus 80 DF, Micro-Flo, Memphis, TN) is used primarily as a postbloom fungicide for apple powdery mildew.

Contact and Residual Bioassays with Adults. An initial series of bioassays was done on *G. occidentalis*, *T. urticae*, and *P. ulmi* to determine the appropriate length of the evaluation period for mortality and fecundity. In addition, these bioassays examined the effects of using synchronous cohorts of females versus females of unknown age.

For a given species, the adults of unknown age were from the same source as those reared in synchronous cohorts. Collections of *G. occidentalis* (synchronous and unknown age) and *P. ulmi* (synchronous only) were taken from commercial apple orchards. *T. urticae* (synchronous and unknown age) were taken from a greenhouse colony started from a population in a commercial pear orchard in May 2007. The *T. urticae* colony was maintained on lima bean, *Phaseolus vulgaris* 'Henderson Bush', plants.

Mites (all species) used for the synchronous cohort bioassays were reared on apple leaf disks 'Delicious' at 22°C. Females were allowed to oviposit for 48 h and then removed. The resulting eggs were reared to the adult stage (7–10 d, depending on the species), and these adults were used in the bioassay. For the bioassays using mites of unknown age, adult mites used in the bioassays were taken either directly from a commercial orchard (*G. occidentalis*) or from the greenhouse colony (*T. urticae*). A mixture of *T. urticae* stages from a greenhouse colony was provided as prey for *G. occidentalis.*

The bioassay arena for both synchronous and unknown age mites was an apple leaf disk 2.2 cm in diameter. Disks were placed with the lower surface facing up on a pad of moist cotton in a plastic cup. Adult female mites (20 *T. urticae;* 10 *G. occidentalis*, or *P. ulmi*) were transferred to the disk surface using a camel's-hair brush.

Leaf disks containing mites were treated with a Potter Precision Laboratory Spray Tower (Burkard Mfg., Rickmansworth, United Kingdom) at 6.5 psi by using 2 ml of spray solution. The rates chosen simulated those used by the industry (see tables). Treatments in all bioassays had five replicate disks. The disks and mites were held after treatment at 22°C with a photoperiod of 16:8 (L:D) h. Mortality and fecundity (number of eggs deposited) were evaluated at 24, 48, 72, 96, and 120 h after treatment.

In addition to the contact bioassays via topical application on adult mites, *G. occidentalis* and *T. urticae* were exposed to 2-h aged residues. The same application methods described above were used, with the exception that sprays were allowed to dry for 2 h before adult female mites were transferred to the disk surface. For *G. occidentalis* bioassays, assessment of prey consumption was included in addition to mortality and fecundity. A larger disk arena (3.5 cm in diameter) and reduced numbers of females (five per disk) were used to allow more space for prey items (the eggs of *T. urticae*). To provide prey, 20–30 *T. urticae* females were transferred to the disks, allowed to oviposit for 24–48 h, and removed. The position of each *T. urticae* egg was marked with a felt-tip pen, and the numbers of eggs were counted and recorded. Each disk contained 50–80 *T. urticae* eggs, such that prey was not limiting during the course of the bioassay; replicates where no prey eggs were found at the time of evaluation (48 h) were discarded. Two rates of the three sulfur products (in addition to a distilled water check) were used in each bioassay (see tables). Mortality, fecundity, and prey consumption were evaluated after 48 h.

For the *T. urticae* bioassays, the larger disk arena was also used. Twenty adult female mites were transferred to disks with 2-h-old residues. A single rate of each of the three sulfur products was used. Mortality and fecundity were evaluated after 48 h.

Effect of Temperature on Dry Flowable Sulfur. The unexpected low toxicity of dry flowable sulfur in contact bioassays was further explored in bioassays on *G. occidentalis* and *T. urticae* held at two temperatures posttreatment. Increased activity for sulfur products at higher temperatures has been noted in previous work (Shepard 1951, Auger et al. 2003). Bioassay arenas and application methods were as outlined above for residual bioassays, except that the treatments were contact, and arenas were held at either 18 or 32°C. Mortality, fecundity, and prey consumption (*G. occidentalis* only) were assessed after 48 h.

Effect of Rate on Sulfur Products. Two bioassays using *G. occidentalis* were conducted exploring the effect of rate of sulfur products. The first bioassay, using adult females in a contact bioassay, looked specifically at the rate response to calcium polysulfide to determine whether there was a rate that was nontoxic or if sublethal effects occurred at lower rates. This bioassay was conducted on 3.5-cm disks and measured mortality, fecundity, and prey consumption after 48 h. The second bioassay held the rate of sulfur content across the three products constant (presuming sulfur was the active ingredient), as opposed to varying the rate with industry practice. Adult female *G. occidentalis* were bioassayed using the contact bioassay method described above, except that females were exposed to 2-h-old residues.

Effect of Sulfur Products on Eggs and Larvae of *G. occidentalis*. We also examined the effects of the three sulfur products on hatching of *G. occidentalis* eggs and mortality of the newly eclosed larvae. Adult female *T. urticae* were allowed to oviposit for 48 h on 3.5-cm bean leaf disks to provide an abundant food supply for the *G. occidentalis* females. Predatory mites were then allowed to oviposit for 24 h, at which time the females were removed. Predatory mite egg locations were marked and recorded and then treated by contact with the three sulfur solutions. Egg hatch was evaluated 24, 48, and 72 h after treatment, and larval mortality was evaluated after completion of egg hatch (72 h).

Repellency of Sulfur Products to *G. occidentalis*. The effect of sulfur product residues on the behavior of adult female *G. occidentalis* was examined in a repellency bioassay. Bean disks (3.5 cm in diameter) were cut so that they were bisected by the midvein. One half was marked with a felt-tip pen, and this half of the leaf disk was dipped into the sulfur solution. The other half of the leaf disk was untreated. The residues were allowed to dry for 2 h, and then 10 female *G. occidentalis* were placed on the midvein. The positions of the females on the leaf disk (treated or untreated half) were recorded three times at 2–3-h intervals on the day of treatment.

Effect of Aged Residues on *G. occidentalis* Larvae. Two bioassays examined the effect of aged residues on mortality of *G. occidentalis* larvae. The first was conducted using 3.5-cm bean leaf disks held at ambient temperatures in the laboratory (22 ± 2°C). A cohort of *G. occidentalis* eggs (laid in a 24-h period on bean leaf disks) were stored at 10°C until needed. A second set of bean leaf disks was either treated with an 8% (vol:vol) rate of calcium polysulfide in a Potter Spray Tower or left untreated as a check. After a period of residue aging, female *T. urticae* were then transferred to the leaf disks to oviposit for 24 h to provide food and then removed. Ten *G. occidentalis* eggs were then taken from cold storage and transferred to the treated and untreated leaf disks. Evaluations of egg hatch and larval mortality were made at 24-h intervals until egg hatch was completed. Residue age at the completion of egg hatch was 5, 7, and 9 d after treatment. Bioassays were discontinued after this point because of the high levels of phytotoxicity caused by calcium polysulfide on the treated leaf disks.

The second bioassay looked at larval mortality caused by field-aged residues on apple leaves. Applications of calcium polysulfide (8%, vol:vol) were made

Table 1. Effect of sulfur-containing products on mortality and fecundity of *G. occidentalis* in apple leaf disk bioassays

Treatment	Rate (vol:vol) or form. prod./liter	Hours after treatment				
		24 h	48 h	72 h	96 h	120 h
		Synchronous cohorts—% mortality				
Calcium polysulfide	8%	36 ± 6.0ab	58 ± 7.3a	74 ± 7.3a	82 ± 2.0a	88 ± 2.0a
Ammonium thiosulfate	3.3%	54 ± 10.3a	66 ± 4.0a	72 ± 4.0a	84 ± 4.0a	86 ± 5.1a
Sulfur (dry flowable)	14.4 g	8 ± 8.0b	16 ± 6.8b	22 ± 6.8b	32 ± 8.6b	36 ± 9.3b
Check		14 ± 5.1b	24 ± 6.8b	24 ± 6.8b	26 ± 6.8b	30 ± 5.5b
F, P		7.68, 0.002	15.05, <0.001	20.87, <0.001	27.96, <0.001	26.81, <0.001
		Synchronous cohorts—eggs/female-day				
Calcium polysulfide	8%	1.5 ± 0.2a	1.2 ± 0.1a	1.1 ± 0.1a	0.9 ± 0.1a	0.9 ± 0.1a
Ammonium thiosulfate	3.3%	1.3 ± 0.2a	1.2 ± 0.1a	1.0 ± 0.2a	1.0 ± 0.2a	1.0 ± 0.2a
Sulfur (dry flowable)	14.4 g	1.3 ± 0.2a	1.4 ± 0.1a	1.3 ± 0.1a	1.4 ± 0.1a	1.4 ± 0.1a
Check		1.1 ± 0.1a	1.3 ± 0.2a	1.3 ± 0.1a	1.3 ± 0.1a	1.2 ± 0.1a
F, P		0.91, 0.457	0.53, 0.668	1.58, 0.232	2.44, 0.102	2.57, 0.090
		Field collected—% mortality				
Calcium polysulfide	8%	50 ± 3.2a	82 ± 3.7a	94 ± 4.0a	96 ± 2.4a	96 ± 2.4a
Ammonium thiosulfate	3.3%	56 ± 6.8a	60 ± 8.9a	66 ± 8.7b	74 ± 6.8a	82 ± 3.7a
Sulfur (dry flowable)	14.4 g	6 ± 4.0b	12 ± 3.7b	20 ± 3.2c	34 ± 7.5b	46 ± 9.8b
Check		6 ± 4.0b	10 ± 6.3b	24 ± 5.1c	38 ± 8.6b	50 ± 11.0b
F, P		33.74, <0.001	34.63, <0.001	39.21, <0.001	19.42, <0.001	10.10, <0.001
		Field collected—eggs/female-day				
Calcium polysulfide	8%	0.9 ± 0.2a	0.9 ± 0.2a	0.8 ± 0.2a	0.8 ± 0.2a	0.8 ± 0.2a
Ammonium thiosulfate	3.3%	0.7 ± 0.2ab	0.5 ± 0.1a	0.6 ± 0.2a	0.7 ± 0.2a	0.8 ± 0.2a
Sulfur (dry flowable)	14.4 g	0.3 ± 0.0b	0.6 ± 0.1a	0.8 ± 0.0a	1.0 ± 0.1a	1.2 ± 0.1a
Check		0.3 ± 0.1b	0.6 ± 0.0a	0.8 ± 0.1a	1.0 ± 0.1a	1.1 ± 0.1a
F, P		4.03, 0.026	2.09, 0.142	0.57, 0.641	1.15, 0.360	1.65, 0.217

Means within columns and bioassays not followed by the same letter are significantly different ($P \leq 0.05$; Tukey's HSD). For all analyses, df = 3, 19.

to a block of 'Fuji' apples in the Washington State University Tree Fruit Research & Extension Center research orchard. The applications were made on two and 5 May (coinciding with 20 and 80% bloom, the recommended timing for blossom thinning using this material) by using an airblast sprayer calibrated to deliver 200 gpa. Leaves were collected 7, 14, and 22 d after the last application (12, 19, and 27 May); check leaves were collected from an untreated section of the same block. Only mature leaves present at the time of application were used in the bioassays; those from the treated trees had visible residues. Precipitation during the course of the experiment was negligible (<5 mm). Leaf disks 3.5 cm in diameter were cut from the leaves and placed in plastic portion cups as described above. Fifteen to 20 adult female *T. urticae* were transferred to the disks (to provide food); immediately thereafter 10–12 female *G. occidentalis* were added. Motile forms of both species were removed 24 h later. Positions of *G. occidentalis* eggs were marked with a felt-tip pen, and larval survival was evaluated after completion of egg hatch (4–6 d after collection from field).

Data Analysis. Percentage mortality of adult mites was calculated as [100-((live/initial transferred) × 100)]. Fecundity was calculated as the number of eggs deposited per female-day, where a female-day was the running total of live females at each evaluation period (thus, five live females at 24 h and three live females at 48 h produced eight female-days at 48 h). The overall contribution to the succeeding generation, combining mortality and fecundity, was measured by the total number of eggs laid. Prey consumption was recorded as the eggs remaining at the time of evaluation subtracted from the initial number before *G. occidentalis* females were introduced. Total prey consumed and prey consumed per female-day are reported. The experimental design for experiments measuring only mortality and fecundity was a completely randomized design; experiments that measured prey consumption were a randomized complete block, with the experimental units blocked on the initial numbers of *T. urticae* eggs. All experiments had five replicates (leaf disks). Data were analyzed using analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) mean separation procedure (SAS Institute 1988). Levene's test (Levene 1960) for nonhomogeneity of variances was used to determine whether data required transformation; if so indicated, data were transformed [$\log(x + 0.5)$] for prey consumption and fecundity and arcsine(sqrt(x/100)) for percentage mortality. Bioassays examining the effect of repellency were analyzed with a chi-square goodness-of-fit test comparing the treated and untreated disk halves. Bioassays examining the effect of temperature were analyzed as a 2 by 2 factorial; main effect means were separated using Tukey's HSD procedure, unless the interaction term was significant; in this case, mean separation was conducted on individual treatments.

Results

Contact and Residual Bioassays with Adults. The three mite species responded similarly to the three

Table 2. Effect of sulfur-containing products on mortality and fecundity of *T. urticae* in apple leaf disk bioassays

Treatment	Rate (vol:vol) or form. prod./liter	Hours after treatment				
		24 h	48 h	72 h	96 h	120 h
		Synchronous cohorts—% mortality				
Calcium polysulfide	8%	44 ± 7.0b	60 ± 8.9a	76 ± 5.3a	79 ± 4.3a	81 ± 4.3a
Ammonium thiosulfate	3.3%	64 ± 6.6a	70 ± 6.5a	73 ± 5.4a	79 ± 3.3a	81 ± 2.9a
Sulfur (dry flowable)	14.4 g	3 ± 2.0c	4 ± 2.9b	16 ± 2.4b	31 ± 4.6b	44 ± 4.0b
Check		0 ± 0.0c	3 ± 2.0b	12 ± 3.4b	27 ± 3.7b	48 ± 5.8b
F, P		41.12, <0.001	37.85, <0.001	65.29, <0.001	51.84, <0.001	21.35, <0.001
		Synchronous cohorts—eggs/female-day				
Calcium polysulfide	8%	2.2 ± 0.5a	1.4 ± 0.3a	1.3 ± 0.3a	1.1 ± 0.2a	1.1 ± 0.2a
Ammonium thiosulfate	3.3%	1.7 ± 0.5a	1.1 ± 0.3a	1.0 ± 0.3a	1.0 ± 0.2a	1.0 ± 0.2a
Sulfur (dry flowable)	14.4 g	2.7 ± 0.3a	2.1 ± 0.2a	1.8 ± 0.2a	1.7 ± 0.2a	1.5 ± 0.1a
Check		2.8 ± 0.2a	2.1 ± 0.2a	1.7 ± 0.2a	1.6 ± 0.2a	1.5 ± 0.1a
F, P		1.79, 0.190	3.99, 0.027	2.60, 0.088	2.69, 0.081	2.24, 0.123
		Field collected—% mortality				
Calcium polysulfide	8%	64 ± 10.3a	70 ± 10.7a	75 ± 9.4a	84 ± 7.6a	84 ± 7.6ab
Ammonium thiosulfate	3.3%	69 ± 6.6a	76 ± 4.0a	80 ± 3.5a	87 ± 3.4a	90 ± 2.7a
Sulfur (dry flowable)	14.4 g	9 ± 3.7b	27 ± 3.4b	42 ± 4.4b	60 ± 4.7b	71 ± 1.9bc
Check		7 ± 2.5b	19 ± 4.3b	31 ± 4.3b	49 ± 3.7b	58 ± 1.2c
F, P		27.03, <0.001	21.12, <0.001	17.01, <0.001	12.91, <0.001	11.43, <0.001
		Field collected—eggs/female-day				
Calcium polysulfide	8%	3.6 ± 1.4a	2.8 ± 1.0a	2.3 ± 0.8a	2.3 ± 0.8a	2.3 ± 0.8a
Ammonium thiosulfate	3.3%	2.7 ± 0.4a	2.2 ± 0.2a	1.9 ± 0.2a	1.9 ± 0.3a	1.8 ± 0.3a
Sulfur (dry flowable)	14.4 g	2.0 ± 0.1a	1.4 ± 0.2a	1.1 ± 0.1a	1.1 ± 0.1a	1.0 ± 0.1a
Check		2.8 ± 0.2a	1.8 ± 0.1a	1.4 ± 0.1a	1.2 ± 0.1a	1.1 ± 0.1a
F, P		0.80, 0.511	1.24, 0.328	1.55, 0.240	1.69, 0.209	1.79, 0.189

Means within columns and bioassays not followed by the same letter are significantly different ($P \leq 0.05$; Tukey's HSD). For all analyses, df = 3, 19.

sulfur products. Calcium polysulfide and ammonium thiosulfate were moderately to highly toxic on contact to females of all species (Tables 1–3). Although differences among mite species were not compared statistically, of the three species tested, *P. ulmi* seemed to be the most sensitive. The females that survived, however, were able to reproduce normally (no significant differences in eggs per female-day).

There were some absolute differences between synchronous and nonsynchronous cohorts of *G. occidentalis* and *T. urticae* in terms of fecundity; the synchronous cohorts, where all females were ≤48 h old, tended to lay more eggs than those of unknown age. However, the relative effect of the treatments was not different between the two bioassay types nor were there consistent differences in mortality. Given the greater amount of time and labor required to produce synchronous cohorts, females of unknown age were used in subsequent bioassays.

The 120-h bioassays indicated that most of the mortality from these particular products occurred in the first 48–72 h, with little increase in mortality thereafter. The higher levels of mortality in the treatments were weighed against increasing mortality in the checks. Overall, the latter was acceptable at 48 h but tended to be too high at 72 h (Abbott 1925). There

Table 3. Effect of sulfur-containing products on mortality and fecundity of *P. ulmi* in apple leaf disk bioassays

Treatment	Rate (vol:vol) or form. prod./liter	Hours after treatment				
		24 h	48 h	72 h	96 h	120 h
		Synchronous cohorts—% mortality				
Calcium polysulfide	8%	88 ± 5.8a	96 ± 2.4a	98 ± 2.0a	98 ± 2.0a	100 ± 0.0a
Ammonium thiosulfate	3.3%	100 ± 0.0a	100 ± 0.0a	100 ± 0.0a	100 ± 0.0a	100 ± 0.0a
Sulfur (dry flowable)	14.4 g	36 ± 4.0b	46 ± 6.0b	52 ± 5.8b	72 ± 3.7b	80 ± 3.2b
Check		22 ± 4.9b	26 ± 5.1c	28 ± 3.7c	38 ± 2.0c	44 ± 4.0c
F, P		79.19, <0.001	79.45, <0.001	96.69, <0.001	152.48, <0.001	107.28, <0.001
		Synchronous cohorts—eggs/female-day				
Calcium polysulfide	8%	1.8 ± 0.2a	1.5 ± 0.3a	1.5 ± 0.5a	1.4 ± 0.5a	1.4 ± 0.5a
Ammonium thiosulfate	3.3%					
Sulfur (dry flowable)	14.4 g	2.2 ± 0.3a	1.8 ± 0.2a	1.6 ± 0.2a	1.6 ± 0.2a	1.5 ± 0.2a
Check		1.3 ± 0.2a	1.3 ± 0.2a	1.3 ± 0.1a	1.2 ± 0.1a	1.1 ± 0.1a
F, P		3.72, 0.062	2.01, 0.185	0.71, 0.514	0.62, 0.558	0.71, 0.516

Means within columns and bioassays not followed by the same letter are significantly different ($P \leq 0.05$; Tukey's HSD). For all analyses, df = 3, 19.

Table 4. Mortality and prey consumption by *G. occidentalis* exposed to residues of three sulfur-containing products on apple leaf disks (mean ± SEM)

Treatment	Rate (vol:vol)	*G. occidentalis* % mortality	*T. urticae* eggs consumed	
			Total[a]	Per female-day
Calcium polysulfide	8%	40 ± 8.9a	4.6 ± 1.9b	0.8 ± 0.3b
Calcium polysulfide	4%	44 ± 7.5a	7.4 ± 2.3b	1.2 ± 0.4b
Check		32 ± 4.9a	37.6 ± 3.7a	5.0 ± 0.4a
F, P		0.70, 0.516	9.97, 0.003	37.89, <0.001
Ammonium thiosulfate	2%	20 ± 6.3a	7.2 ± 2.7b	0.9 ± 0.3b
Ammonium thiosulfate	1%	8 ± 8.0a	11.6 ± 1.7ab	1.3 ± 0.2b
Check		0 ± 0.0a	28.8 ± 5.6a	2.9 ± 0.6a
F, P		2.92, 0.092	9.88, 0.003	6.94, 0.010
Sulfur (dry flowable)	24 g	0 ± 0.0a	37.2 ± 3.2a	3.7 ± 0.3a
Sulfur (dry flowable)	12 g	8 ± 8.0a	29.6 ± 4.6a	3.3 ± 0.5a
Check		0 ± 0.0a	30.8 ± 3.8a	3.1 ± 0.4a
F, P		1.00, 0.397	1.13, 0.356	0.64, 0.542

Means within columns not followed by the same letter are significantly different ($P \leq 0.05$; Tukey's HSD). For all analyses, df = 2, 14.
[a] Data transformed $\log(x + 0.5)$ due to unequal variances.

were few changes in the relative statistical results after 48 h; therefore, subsequent bioassays were standardized on 48 h.

In contrast to the contact bioassays, exposure to 2-h-old residues caused no mortality of *G. occidentalis* for any of the three sulfur products (Table 4). Consumption of contaminated prey (*T. urticae* eggs), however, was dramatically reduced by residues of calcium polysulfide and ammonium thiosulfate. Predatory mites consumed ≈8× and 4× fewer contaminated eggs for the high rate of calcium polysulfide and ammonium thiosulfate, respectively, in relation to the check. Dry flowable sulfur had no effect on prey consumption.

There was no measurable mortality in *T. urticae* caused by 2-h-old residues (Table 5). There were no effects on fecundity or total eggs produced by any of the three sulfur products tested.

Effect of Temperature on Dry Flowable Sulfur. Increasing temperature increased prey consumption and fecundity of *G. occidentalis*, but the effect of the sulfur spray solution was nonsignificant for these parameters (Table 6). There was a significant effect on mortality, however, but because the interaction term was also significant, no conclusion can be drawn about the main effects of temperature and treatment. The percentage of mortality in the sulfur-treated disk held at 32°C was significantly higher than the other treatments, indicating the potential for toxicity being dependent on higher temperatures; however, the level of mortality found in this treatment was low (16%) relative to other bioassays, and well within the range of overall check mortality. Thus, it is difficult to determine whether there were differences in mortality of *G. occidentalis* associated with an interaction between treatment and temperature.

Neither treatment nor temperature affected the percentage of mortality of *T. urticae* adult females (Table 7). The higher temperature regime produced significantly higher numbers of eggs laid after 48 h (both total eggs and eggs per female-day), but the effect of treatment with dry flowable sulfur was not significant.

Effect of Rate of Sulfur Products. Mortality in the rate range bioassay with calcium polysulfide was high relative to other bioassays with this product (100% in the 4%, vol:vol, rate) (Table 8). The only rate that was not significantly different than the check was the lowest rate tested (0.5%, vol:vol). Total prey consumption was reduced by the three highest rates, although this was due to the higher levels of mortality in these treatments, rather than the prey consumption rate of the surviving females. Fecundity, either total eggs or eggs per female-day, was not affected by the treat-

Table 5. Effect of three sulfur-containing products on mortality and fecundity of *T. urticae* exposed to residues on bean leaf disks (mean ± SEM)

Treatment	Rate (vol:vol or form. prod./liter)	Mortality	*T. urticae* eggs laid	
			Total	Per female-day
Calcium polysulfide	8%	4.0 ± 1.9a	129.2 ± 7.9a	3.3 ± 0.2a
Ammonium thiosulfate	2%	1.0 ± 1.0a	123.8 ± 9.5a	3.1 ± 0.3a
Sulfur (dry flowable)	24 g	1.0 ± 1.0a	135.8 ± 20.0a	3.4 ± 0.5a
Check		0.0 ± 0.0a	163.6 ± 9.3a	4.1 ± 0.2a
F, P		2.23, 0.124	1.96, 0.160	1.57, 0.237

Means within columns followed by the same letter are not significantly different ($P \leq 0.05$; Tukey's HSD). For all analyses, df = 3, 19.

Table 6. Effect of posttreatment temperature on mortality, prey consumption, and fecundity of *G. occidentalis* females exposed by contact to dry flowable sulfur

Effect	Factor	df	*F*	*P*	Mean ± SEM
Mortality	Sulfur	1, 19	16.00	0.001	
	Sulfur (dry flowable)				8 ± 3.3
	Check				0 ± 0.0
	Temp	1, 19	16.00	0.001	
	18°C				0 ± 0.0
	32°C				8 ± 3.3
	Sulfur × temp	1, 19	16.00	0.001	
	Check, 18°C				0 ± 0.0b
	Sulfur (dry flowable), 18°C				0 ± 0.0b
	Check, 32°C				0 ± 0.0b
	Sulfur (dry flowable) 32°C				16 ± 4.0a
Total *G. occidentalis* eggs laid	Sulfur	1, 19	0.84	0.373	
	Sulfur (dry flowable)				1.6 ± 0.6a
	Check				1.0 ± 0.3a
	Temp	1, 19	3.35	0.086	
	18°C				0.7 ± 0.4a
	32°C				1.9 ± 0.5a
	Sulfur × temp	1, 19	0.37	0.550	
	Check, 18°C				0.6 ± 0.4
	Sulfur (dry flowable), 18°C				0.8 ± 0.8
	Check, 32°C				1.4 ± 0.5
	Sulfur (dry flowable) 32°C				2.4 ± 0.8
G. occidentalis eggs/female-day	Sulfur	1, 19	1.05	0.320	
	Sulfur (dry flowable)				0.2 ± 0.1a
	Check				0.1 ± 0.0a
	Temp	1, 19	3.68	0.073	
	18°C				0.1 ± 0.0a
	32°C				0.2 ± 0.1a
	Sulfur × temp	1, 19			
	Check, 18°C		0.53	0.477	0.1 ± 0.0
	Sulfur (dry flowable), 18°C				0.1 ± 0.1
	Check, 32°C				0.1 ± 0.1
	Sulfur (dry flowable) 32°C				0.3 ± 0.1
Total *T. urticae* eggs consumed	Sulfur	1, 19			
	Sulfur (dry flowable)		4.45	0.051	27.0 ± 4.5a
	Check				32.8 ± 5.4a
	Temp	1, 19			
	18°C		100.76	<0.001	16.1 ± 2.0b
	32°C				43.7 ± 2.4a
	Sulfur × temp	1, 19			
	Check, 18°C		2.12	0.165	17.0 ± 2.1
	Sulfur (dry flowable), 18°C				15.2 ± 3.6
	Check, 32°C				48.6 ± 2.0
	Sulfur (dry flowable) 32°C				38.8 ± 3.0
T. urticae eggs consumed/female-day	Sulfur	1, 19	2.42	0.140	
	Sulfur (dry flowable)				2.9 ± 0.5a
	Check				3.3 ± 0.5a
	Temp	1, 19	119.04	<0.001	
	18°C				1.6 ± 0.2b
	32°C				4.5 ± 0.2a
	Sulfur × temp	1, 19	0.78	0.390	
	Check, 18°C				1.7 ± 0.2
	Sulfur (dry flowable), 18°C				1.5 ± 0.4
	Check, 32°C				4.9 ± 0.2
	Sulfur (dry flowable) 32°C				4.2 ± 0.3

ments. The former is unexpected given the high levels of mortality, which would be expected to result in lower total numbers of eggs deposited.

Where the rate of elemental sulfur was held constant across the three products, there were no significant differences in mortality when exposed to residues (Table 9). As in previous bioassays, prey contaminated by calcium polysulfide and ammonium thiosulfate were consumed at much lower rates than the uncontaminated prey; prey consumption in the dry flowable sulfur treatment was not significantly different than the check. There were significant reductions in fecundity in this bioassay in the calcium polysulfide and ammonium thiosulfate treatments, whereas the fecundity in the dry flowable sulfur treatment was not different than the check.

Stage Susceptibility to Sulfur Products. The three sulfur products tested delayed *G. occidentalis* egg hatch in the first evaluation (1 DAT [days after treatment]), but by three DAT, 100% of the eggs had hatched in all treatments (Table 10). Larval survival, however, was greatly reduced by all three products,

Table 7. Effect of posttreatment temperature on mortality and fecundity of *T. urticae* females exposed by contact to dry flowable sulfur

Effect	Factor	df	*F*	*P*	Mean ± SEM
Mortality	Sulfur	1, 19	0.00	1.000	
	Sulfur (dry flowable)				3.0 ± 1.3a
	Check				3.0 ± 1.1a
	Temp	1, 19	0.36	0.555	
	18°C				2.5 ± 1.1a
	32°C				3.5 ± 1.3a
	Sulfur × temp	1, 19	3.27	0.089	
	Check, 18°C				4.0 ± 1.9
	Sulfur (dry flowable), 18°C				1.0 ± 1.0
	Check, 32°C				2.0 ± 2.0
	Sulfur (dry flowable) 32°C				5.0 ± 1.6
Total *T. urticae* eggs laid	Sulfur	1, 19	0.89	0.359	
	Sulfur (dry flowable)				118.2 ± 27.1a
	Check				104.8 ± 24.8a
	Temp	1, 19	104.35	<0.001	
	18°C				39.1 ± 4.7b
	32°C				183.9 ± 13.0a
	Sulfur × temp	1, 19	0.13	0.719	
	Check, 18°C				43.2 ± 7.4
	Sulfur (dry flowable), 18°C				35.0 ± 6.0
	Check, 32°C				193.2 ± 20.7
	Sulfur (dry flowable) 32°C				174.6 ± 16.9
T. urticae eggs laid/female-day	Sulfur	1, 19	0.71	0.413	
	Sulfur (dry flowable)				3.0 ± 0.7a
	Check				2.7 ± 0.6a
	Temp	1, 19	125.28	<0.001	
	18°C				1.0 ± 0.1b
	32°C				4.7 ± 0.3a
	Sulfur × temp	1, 19	0.03	0.863	
	Check, 18°C				1.1 ± 0.2
	Sulfur (dry flowable), 18°C				0.9 ± 0.1
	Check, 32°C				4.9 ± 0.5
	Sulfur (dry flowable) 32°C				4.5 ± 0.3

with calcium polysulfide nearly eliminating hatching larvae. This is one of the few bioassays in which dry flowable sulfur caused a significant reduction in comparison to the check, with ≈70% lower survival. The high mortality rate of larvae exposed to residues is in contrast to adults exposed to residues, where no measurable mortality occurred.

Repellency Bioassay. Residues of all three sulfur products were repellent to adult *G. occidentalis* at all three evaluations (Fig. 1). Overall, there were 4.2×, 6.3×, and 4.3× more females found on the untreated halves of the leaf disks in comparison to the halves treated with calcium polysulfide, ammonium thiosulfate, and dry flowable sulfur, respectively.

Effect of Aged Residues on *G. occidentalis* Larvae. There was high mortality of *G. occidentalis* larvae on aged residues of calcium polysulfide held under laboratory conditions on bean disks. Mortality was 100% on 5- and 7-d-old residues, and 98% on 9-d-old residues (Fig. 2). Check mortality ranged from 6 to 18%. Mortality in the calcium polysulfide treated disks after 9 d was essentially the same as that on fresh residues.

There was 89% mortality of *G. occidentalis* larvae on calcium polysulfide residues on apple leaves aged 7 d

Table 8. Effect of four rates of calcium polysulfide on mortality, prey consumption, and fecundity of *G. occidentalis* exposed by contact (mean ± SEM)

Treatment	Rate (vol:vol)	% mortality[a]	*T. urticae* eggs		*G. occidentalis* eggs	
			Total consumed[b]	Eggs/female-day[b]	Total laid[b]	Eggs/female-day[b]
Calcium polysulfide	4%	100 ± 0.0a	9.8 ± 1.6b	7.0 ± 2.9a	2.6 ± 0.2a	1.4 ± 0.6a
Calcium polysulfide	2%	92 ± 4.9a	12.4 ± 2.3b	5.3 ± 1.5a	3.4 ± 1.1a	1.1 ± 0.6a
Calcium polysulfide	1%	76 ± 9.8a	29.6 ± 3.4a	5.8 ± 0.7a	5.0 ± 0.8a	1.0 ± 0.1a
Calcium polysulfide	0.50%	24 ± 11.7b	35.2 ± 5.3a	3.9 ± 0.4a	6.6 ± 0.9a	0.7 ± 0.1a
Check		24 ± 7.5b	40.8 ± 5.3a	4.9 ± 0.4a	6.4 ± 2.1a	0.8 ± 0.2a
F, P		7.49, <0.001	10.00, <0.001	0.67, 0.714	1.45, 0.249	0.45, 0.890

Means within columns not followed by the same letter are not significantly different ($P < 0.05$; Tukey's HSD).
[a] Data transformed due to unequal variances arcsine(sqrt(x/100)). For all analyses, df = 8, 24.
[b] Data transformed due to unequal variances $\log(x + 0.5)$.

Table 9. Effect of three sulfur-containing products on mortality, prey consumption, and fecundity of *G. occidentalis* exposed to residues on bean leaf disks (mean ± SEM)

Treatment	Rate (vol:vol or form. prod./liter)	% mortality[a]	*T. urticae* eggs		*G. occidentalis* eggs	
			Total consumed[b]	Eggs/female-day[b]	Total laid[b]	Eggs/female-day[b]
Calcium polysulfide	8.4%	4 ± 4.0a	0.0 ± 0.0b	0.0 ± 0.0c	0.6 ± 0.4b	0.1 ± 0.0b
Ammonium thiosulfate	5.6%	20 ± 6.3a	4.2 ± 1.9c	0.5 ± 0.2b	0.8 ± 0.5b	0.1 ± 0.1b
Sulfur (dry flowable)	24 g	8 ± 4.9a	47.0 ± 1.7a	5.0 ± 0.2a	8.6 ± 1.2a	0.9 ± 0.1a
Check		12 ± 8.0a	53.8 ± 1.9a	6.4 ± 0.9a	10.2 ± 1.7a	1.2 ± 0.2a
F, P		1.28, 0.338	120.16, <0.001	106.60, <0.001	18.83, <0.001	28.11, <0.001

Rates of formulated materials are equivalent to 19 g sulfur/liter spray solution. Means within columns not followed by the same letter are not significantly different ($P < 0.05$; Tukey's HSD). For all analyses, df = 7, 19.

[a] Data transformed due to unequal variances arcsine(sqrt(x/100)).

[b] Data transformed due to unequal variances $\log(x + 0.5)$.

in the field (residues were 11 d old at the completion of hatch) compared with 8% mortality on the untreated check leaves (Fig. 3). Mortality dropped to 50% on 14-d-old residues (20 d at completion of hatch) and to 17% on 22-d-old residues (26 d at completion of hatch).

Discussion

Calcium polysulfide and ammonium thiosulfate were nonselective to adult female mites when applied topically, causing mortality to both predator and pest, whereas dry flowable sulfur was generally lower in toxicity than the other two products. In general, toxicities of calcium polysulfide and ammonium thiosulfate were acute in nature; topical applications caused mortality, whereas even fresh residues had little or no toxicity to adults.

Although lethal effects of residues on *G. occidentalis* adult females were minimal for all materials tested, larvae were much more affected. Larval mortality was nearly 100% from both fresh and aged residues of calcium polysulfide. The differential responses of the two stages is in agreement with the findings of Hoy and Standow (1982), which documented high levels of larval mortality in *G. occidentalis* strains that had little or no adult mortality when exposed to sulfur residues. Larval mortality was one of the few cases where dry flowable sulfur had a significant effect; the other case was repellency to females, where all sulfur-containing compounds had repellent effects.

Several sublethal effects on *G. occidentalis* were documented by these bioassays in addition to acute topical toxicity. Prey consumption was consistently reduced by calcium polysulfide and ammonium thiosulfate. Only one test showed a reduction in fecundity of the surviving females but eventually reduced feeding would have a negative effect on egg production (Sabelis 1985); the relatively short duration of these bioassays would likely mask this effect. Nevertheless, the primary loss in contribution to the succeeding generation is through contact mortality to adults and larval mortality from contact or residues.

The consistent differences among the three sulfur-containing materials are difficult to explain. The toxic action is thought to be due to elemental sulfur in vapor form (Shepard 1951). Two volatile breakdown products, hydrogen sulfide and sulfur dioxide, are also thought to play a role in toxicity. In our bioassays, however, when the amount of elemental sulfur was held constant in the rates of the three compounds, the much lower toxicity of dry flowable sulfur on adult forms was still apparent. In addition, higher temperatures, which should increase the rate of sulfur volatilization, did not result in increased mortality in *T. urticae;* the effect on *G. occidentalis* was statistically significant, but extremely small. The effect of increasing temperature on mortality of *T. urticae* exposed to sulfur was demonstrated by Auger et al. (2003); this work also noted that high relative humidity was important for the expression of mortality. However, the higher levels of relative humidity (e.g., 75 and 90%) combined with high temperatures (27.5 and 35°C) used in the latter study do not occur in the arid growing districts of eastern Washington and may explain

Table 10. Effect of sulfur-containing products on egg hatch and larval survival of *G. occidentalis* (mean ± SEM)

Treatment	Rate (vol:vol or form. prod./liter)	Proportion egg hatch			% mortality (larvae)
		1 DAT	2 DAT	3 DAT	
Calcium polysulfide	8%	0.33 ± 0.05b	0.82 ± 0.04a	1.00 ± 0.00a	97.6 ± 1.8c
Ammonium thiosulfate	2%	0.38 ± 0.05b	0.75 ± 0.03a	1.00 ± 0.00a	84.7 ± 5.9bc
Sulfur (dry flowable)	24 g	0.48 ± 0.03b	0.89 ± 0.03a	1.00 ± 0.00a	74.2 ± 3.1b
Check		0.79 ± 0.05a	0.85 ± 0.05a	1.00 ± 0.00a	3.1 ± 1.8a
F, P		11.78, <0.001	1.04, 0.456		45.86, <0.001

Means within columns not followed by the same letter are significantly different (Tukey's HSD, $P \leq 0.05$). For all analyses, df = 7, 18. Data transformed arcsine(sqrt(y)) due to unequal variances.

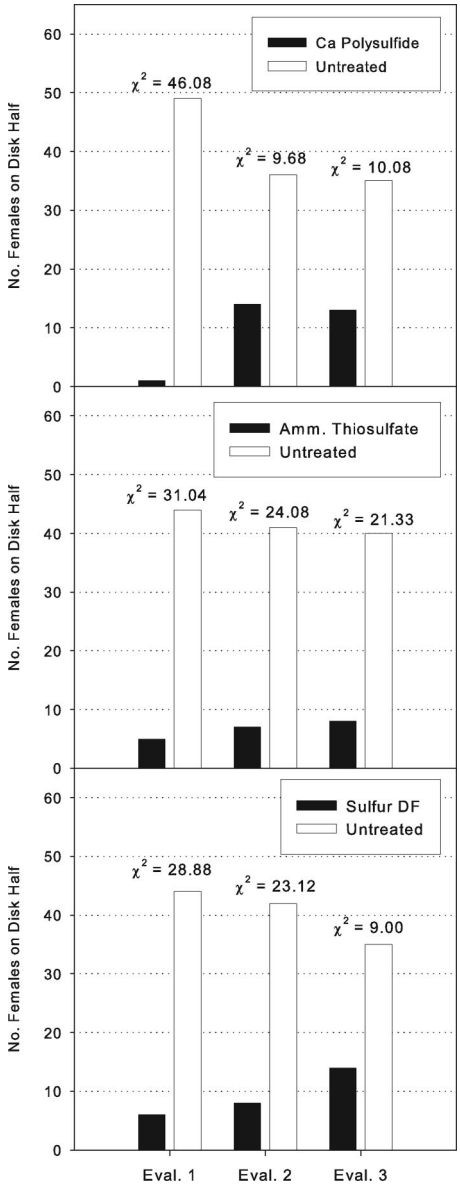

Fig. 1. Repellency of calcium polysulfide, ammonium thiosulfate, and dry flowable sulfur to adult female *G. occidentalis*. Critical χ^2 value ($\alpha = 0.05$, df = 1) is 3.84.

why the toxicity of sulfur varies among growing regions.

The toxic effect of residues in the field persisted much longer than expected. There was still measurable toxicity after 22 d in the field after a typical application pattern. In addition to the persistence of toxic residues, the timing of some of these materials may be critical in the population development of *G. occidentalis*. Calcium polysulfide and ammonium thiosulfate are applied during bloom when *G. occidentalis* adult females have emerged from overwintering sites and are dispersing throughout the tree canopy and starting to reproduce (Hoyt et al. 1970). Although

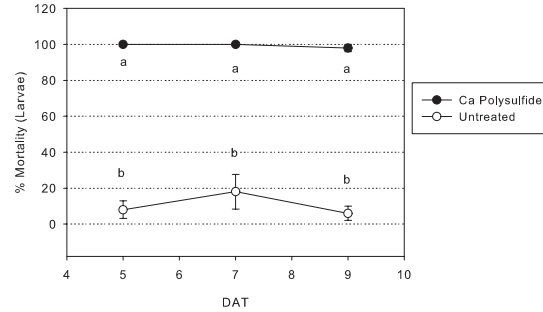

Fig. 2. Effect of aged residues of laboratory-applied calcium polysulfide on bean disks on mortality of *G. occidentalis* larvae. Residue age 5 d, $F = 352.67$, $P < 0.001$; residue age 7 d, $F = 71.53$, $P < 0.001$; residue age 9 d, $F = 423.20$, $P < 0.001$; for all analyses, df = 1, 9.

Hoyt (1969a) showed little negative effect on the predator from prebloom sprays of lime-sulfur, the slightly later timing currently used in Washington apple production may expose the predatory mite to a much greater extent via contact and residues. Multiple applications, typically required for blossom thinning, likely increase the detriment to the predator.

An additional effect of sulfur products on integrated mite management is their toxicity to rust mites; these products are usually labeled for this use. Rust mites are the primary alternate prey of *G. occidentalis* (Hoyt 1969b), and maintaining a moderate population is considered essential for success. Elimination of the rust mites as a food source, either during or after bloom, negatively impacts predator survival. Although elimination of alternate prey is most often cited as a problem for integrated mite management, damage from feeding by rust mites causes a reduction in nutritional quality of leaves. Thus, reducing rust mite populations by sulfur sprays used for thinning or pathogen control may not only remove prey but also reduce competitive displacement of the more damaging tetranychid species (Croft and Hoying 1977).

There has been a renewed interest in the nontarget effects of sulfur products in recent years (James et al. 2002, Prischmann et al. 2005, Costello 2007). Overall,

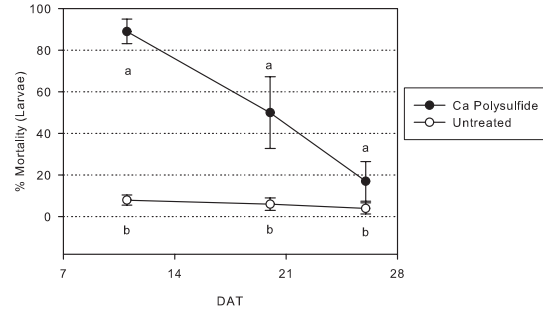

Fig. 3. Effect of aged residues of field-applied calcium polysulfide on apple disks on mortality of *G. occidentalis* larvae. Residue age 7 d, $F = 161.24$, $P < 0.001$; residue age 14 d, $F = 6.25$, $P = 0.037$; residue age 22 d, $F = 6.69$, $P = 0.036$; for all analyses, df = 1, 9.

the results of our research are consistent with the findings of these field studies (either increased spider mite densities, or decreased phytoseiid mite densities associated with the use of multiple sulfur applications). The studies were in vineyards, which tend to be more intensively sprayed with sulfur fungicides, but subtle changes in timing and materials may enhance the impact in orchard systems.

This study elucidates specific mechanisms by which sulfur products may contribute to disruption of integrated mite control. Many of these uses occur early in the season, before the period when high mite populations usually occur (July and August), but destabilizing the components of integrated mite control early in the year may have significant long-term effects. It is unlikely, however, that the use of sulfur products is the sole cause of the recent increased mite outbreaks. With materials such as the pyrethroids, the cause of disruption was easily identified; phytoseiid populations were decimated for long periods, and spider mites were released from biological control (Hoyt et al. 1978). The Washington apple industry has avoided the use of pyrethroids in its apple pest management programs (NASS 2006) to avoid disruption of biological control in general, and the highly successful integrated mite control program in particular (Croft and Hoyt 1978). In contrast, the current situation seems not to be related to a single compound or group of compounds. The additive effects of many slightly or moderately harmful applications, including the sulfur products in this study, are likely responsible for the increased mite outbreaks experienced by the Washington apple industry.

Acknowledgments

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