Insecticide Resistance and Resistance Management

OXFORD

Bifenthrin Baseline Susceptibility and Evaluation of Simulated Aerial Applications in *Striacosta albicosta* (Lepidoptera: Noctuidae)

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Subject Editor: Aaron Gassmann

Abstract

Striacosta albicosta (Smith) is a maize pest that has recently expanded its geographical range into the eastern United States and southeastern Canada. Aerial application of pyrethroids, such as bifenthrin, has been a major practice adopted to manage this pest. Reports of field failure of pyrethroids have increased since 2013. *Striacosta albicosta* populations were collected in 2016 and 2017 from maize fields in Nebraska, Kansas, and Canada and screened with bifenthrin active ingredient in larval contact dose-response bioassays. Resistance ratios estimated were generally low in 2016 (1.04- to 1.32-fold) with the highest LC_{50} in North Platte, NE (66.10 ng/cm^2) and lowest in Scottsbluff, NE (50.10 ng/cm^2). In 2017, O'Neill, NE showed the highest LC_{50} (100.66 ng/cm^2) and Delhi, Canada exhibited the lowest (6.33 ng/cm^2), resulting in a resistance ratio variation of 6.02- to 15.90-fold. Implications of bifenthrin resistance levels were further investigated by aerial application simulations. Experiments were conducted with a spray chamber where representative *S. albicosta* populations were exposed to labeled rates of a commercial bifenthrin formulation. Experiments resulted in 100% mortality for all populations, instars, insecticide rates, and carrier volumes, suggesting that levels of resistance estimated for bifenthrin active ingredient did not seem to impact the efficacy of the correspondent commercial product under controlled conditions. Results obtained from this research indicate that control failures reported in Nebraska could be associated with factors other than insecticide resistance, such as issues with the application technique, environmental conditions during and/or after application, or the insect's natural behavior. Data generated will assist future *S. albicosta* resistance management programs.

Key words: baseline susceptibility, bifenthrin, spray chamber, pyrethroids, resistance management

Striacosta albicosta (Smith), commonly referred to as western bean cutworm, is a significant pest of maize, *Zea mays* (L.), and dry edible bean, *Phaseolus vulgaris* (L.). First identified in Arizona in 1887 (Smith 1887), *S. albicosta* is native to the southwestern region of the United States. Reports of economic damage caused by larval feeding started in the late 1950s, and were only common in Colorado, Idaho, and Nebraska (Hoerner 1948; Douglass et al. 1957; Hagen 1962, 1963). However, by late 1999, *S. albicosta* had begun to expand eastward. Since then, *S. albicosta* has caused economic damage as far east as Pennsylvania, New York, and Quebec, Canada (Baute 2009,

Tooker and Fleischer 2010, Ingerson-Mahar 2012, Whalen 2012, Smith et al. 2018a). Furthermore, there have been reports of damage to maize and dry bean in northeastern Mexico (Sánchez-Peña et al. 2016).

In maize, *S. albicosta* larvae first feed on tassel and pollen until reaching the third to the fourth instar, when most feeding concentrates directly on developing kernels at the ear tip or sides of the ear (Michel et al. 2010, Paula-Moraes et al. 2013). Kernel feeding can damage up to 40% of the ear and introduce secondary fungal infections (Hagen 1962, Catangui and Berg 2006, Parker et al. 2016,

Smith et al. 2018b). Reports of yield losses in maize vary, ranging from 248.83 kg/ha (Seymour et al. 2010) to 1,013.47 kg/ha (Paula-Moraes et al. 2013).

Only two transgenic *Bacillus thuringiensis* (Bt) proteins have shown any efficacy against *S. albicosta* (Eichenseer et al. 2008). With recent development of resistance to the Cry1F protein (Ostrem et al. 2016, Smith et al. 2017), the only remaining effective protein is VIP3A (Bowers et al. 2014, Farhan et al. 2017). Therefore, insecticide application is the most routinely employed, and critically important, method for managing this insect, with the majority of early research on *S. albicosta* control addressing this strategy (Hoerner 1948; Hagen 1962, 1963; Hanstbarger 1969; Hirnyck 1983; Archibald et al. 2017; Montezano et al. 2017; Swoboda-Bhattarai et al. 2018). An understanding of *S. albicosta* biology is critical to the effective application of chemical control. Because of *S. albicosta*'s instar-specific feeding behavior (starting on developing tassel tissue within the whorl during early instars and moving to the ear zone during later instars), larvae are vulnerable to chemical control for a short period. Therefore, correct timing of chemical treatment is critical and should not be initiated before the pest population is active and exposed or after ear damage has begun (Higley and Peterson 1994, Paula-Moraes et al. 2012). In Nebraska, the most common threshold recommended by extension entomologists and crop consultants is 5–8% of plants with an egg mass or larvae (Paula-Moraes et al. 2013). However, for regions where *Fusarium graminearum* (Schwabe) (Hypocreales: Nectriaceae) infection is more prevalent, the 5% threshold may be too high, and repeated scouting of the same field starting in mid-July may be necessary to make control decisions based on region-specific action thresholds (OMAFRA 2017, Smith et al. 2018b).

Multiple classes of insecticides have been identified as effective against *S. albicosta*, including carbamates, organophosphates, pyrethroids, spinosyns, Bt, diacylhydrazines, and diamides. In Nebraska, the most commonly used class of insecticides is pyrethroids, with bifenthrin being the most common active ingredient (Archibald et al. 2017). Pyrethroids accounted for 81% of all insecticide applications targeting *S. albicosta* in Nebraska between 2014 and 2016, and rarely included rotation of the mode of action (Archibald et al. 2017). The most common commercial products used were Brigade (bifenthrin), Hero (bifenthrin + zeta-cypermethrin), Mustang Maxx (zeta-cypermethrin), Capture (bifenthrin), and Warrior (lambda-cyhalothrin) (Archibald et al. 2017). For Kansas and Canada there is no information available for the percentage of the current use of pyrethroids, but it is registered every year for use to manage *S. albicosta* (Farhan et al. 2017). Pyrethroid insecticides have been used for more than 40 yr and along with organophosphate insecticides account for the vast majority of applied insecticides in terms of volume and acres (Perry and Moschini 2019).

Despite the frequent use of pyrethroids against *S. albicosta*, growers and crop consultants from the western U.S. Corn Belt have been reporting inadequate control since approximately 2013. A recent survey performed in Nebraska indicated that 41.1% of respondents reported a decrease in insecticide efficacy against *S. albicosta* (Archibald et al. 2017). While there are no cases of *S. albicosta* pyrethroid resistance reported in the literature, there have been more than 100 reported cases of resistance to first-generation pyrethroid insecticides among Noctuidae pests since the early 1980s (e.g., Pietrantonio et al. 2007, Whalen 2012, Malaquias et al. 2015, Qayyum et al. 2015, Saleem et al. 2016). The frequent use of pyrethroids in the western Corn Belt could be selecting *S. albicosta* and other maize pests for resistance. In fact, development of pyrethroid resistance has already been confirmed in this region for the western

corn rootworm *Diabrotica virgifera virgifera* LeConte (Pereira et al. 2015, 2017; Souza et al. 2019).

With limited control for *S. albicosta* from Bt toxins expressed in transgenic maize (Ostrem et al. 2016, Smith et al. 2017) and the market increase in inexpensive pyrethroid generic formulations (Dewar 2016), it is expected that growers will continue or even increase use of these insecticides. A baseline study of *S. albicosta* is therefore critical for the development of an appropriate resistance-monitoring plan and insect resistance management (IRM) program supporting the early detection of insecticide resistance. However, levels of bifenthrin susceptibility have never been formally evaluated in *S. albicosta* populations, nor the decrease in pyrethroid efficacy reported in the U.S. Corn Belt. Thus, the objective of this project was to determine the current baseline susceptibility of field-collected populations of *S. albicosta* to the pyrethroid bifenthrin using residual exposure overlay bioassays. Considering that insect resistance levels found in the laboratory for pesticide active ingredients do not always correlate to in-field control failure (Siegfried et al. 2007; Tabashnik et al. 2009, 2013; Luttrell and Jackson 2012; Souza et al. 2019), we also evaluated the performance of a commercial bifenthrin formulation by simulated aerial applications.

Materials and Methods

Insect Collections

Bioassays were conducted on neonate larvae hatched from field-collected egg masses or from egg masses laid by field-collected adults. In 2016, five field populations from Nebraska were tested: Scottsbluff, Brule, Benkelman, Grand Island, and North Platte (Fig. 1). In 2017, four additional populations from Nebraska (Kearney North, Kearney South, Grant, and O'Neill), one from Colby, KS, and one from Delhi, ON, Canada (Fig. 1) were included. Field-collected egg masses were cut from maize leaves, placed into plastic containers, and transported in coolers to the laboratory where they were transferred to moistened filter paper inside Petri dishes. Collected eggs were held in growth chambers at 26.6°C, 70–80% RH, 16:8 (L:D) h photoperiod and monitored daily for hatching. Adults were collected from black light traps (Montezano et al. 2019) placed on the outer field edge of each sampling location, taken to the laboratory, and transferred to rearing cages (63.5 × 63.5 × 63.5 cm) containing pots of late vegetative stage pinto bean plants (*P. vulgaris*) for oviposition. Adult diet consisted of a 5% sucrose and 0.2% ascorbic acid solution provided in a 150 mm × 15 mm sponge inside a Petri dish. Maintenance of moths and eggs followed the methods described by Dyer et al. (2013). Egg masses laid on bean plants were collected daily, transferred to growth chamber conditions as previously described, and monitored daily for hatching.

Baseline Susceptibility With Bifenthrin Active Ingredient

The susceptibility of *S. albicosta* populations to bifenthrin was determined in contact dose-response bioassays (Magalhaes et al. 2007) where neonates (<36 h after hatching) were exposed to six to eight concentrations of the insecticide active ingredient (bifenthrin 98%, Chem Service, Inc., West Chester, PA) applied to filter paper discs (Whatman No. 1001 042, Sigma-Aldrich, St. Louis, MO). A bifenthrin stock solution (1 µg a.i./µl) was prepared in acetone and further diluted in distilled water to desired exposure concentrations in the range of 4–256 ng/cm². Filter papers were placed into Petri dishes (4.7 cm in diameter × 0.7 cm height, Pall Corporation, Port Washington, NY) and each received 150 µl of the
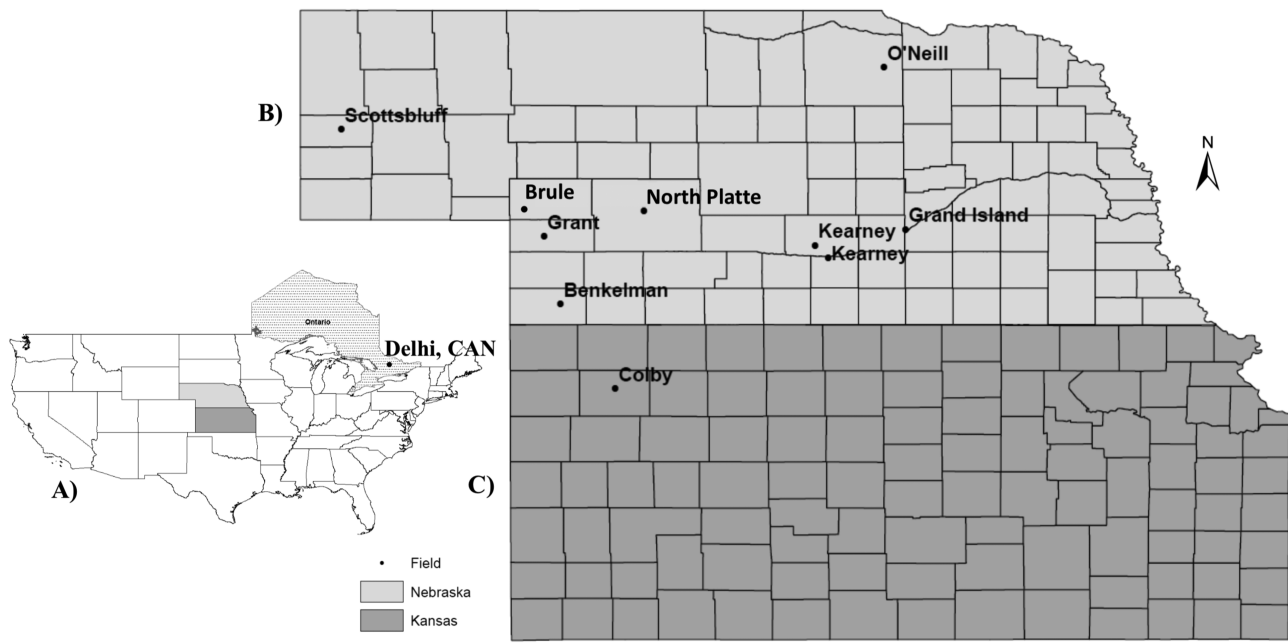
Fig. 1. (A) Areas in the United States and Canada where *S. albicosta* populations were collected. (B) Sites in Nebraska. (C) Site in Kansas.

corresponding bifenthrin concentration. There were three replicates per concentration and treatments with distilled water-only represented the controls. After the filter papers were allowed to dry for 5–10 min, 20 neonates were transferred to each Petri dish using a fine camel-hair paintbrush (size 2). Three Petri dishes were used per treatment per population for a total of 60 neonates per treatment per population. Petri dishes were maintained at 23°C, 70–80% RH, and 24 h scotophase. Mortality was recorded 16 h after larval transfer. Larvae that did not move for at least the length of their body after gentle prodding using a fine camel-hair paintbrush were considered dead.

Efficacy of Bifenthrin Commercial Formulation

Aerial application simulations were performed in the laboratory to investigate the efficacy of a commercial bifenthrin formulation on field populations of *S. albicosta*. Brigade 2EC (bifenthrin 25.1%, FMC Corporation, Philadelphia, PA) was tested at the lowest (36.8 g a.i./ha; 2.1 fl oz per acre) and highest (112.1 g a.i./ha; 6.4 fl oz per acre) label rates recommended for *S. albicosta* control. Insecticide solutions were prepared in tap water at two carrier volumes recommended for aerial applications (18.7 and 46.8 liters per ha; 2 and 5 gallons per acre) and applied in a research track spray chamber (DeVries, Hollandale, MN) at the Pesticide Application Technology Laboratory (PAT-Lab, University of Nebraska–Lincoln, West Central Research and Extension Center, North Platte, NE). Spray chamber calibration was completed as described in Souza et al. (2019) using two TT110015 ground spray nozzles (Teejet Technologies, Spraying Systems Co., Wheaton, IL) to reproduce the aerial spray deposition pattern obtained in a cornfield at mid-canopy leaves. The spray deposition data collected at mid-canopy would represent an average exposure that *S. albicosta* larvae would receive within the top half of the maize canopy, including the exposure on leaves near maize ears. Bottoms and lids of Petri dishes (9.0 mm height × 50.0 mm diameter, Pall Corporation, Port Washington, NY) were prelabeled and evenly distributed on the center of the spray chamber table to receive the insecticide applications. Four Petri dishes were sprayed for each combination of bifenthrin rate, carrier volume, and insect population.

Individual applications were performed for each treatment replication. Untreated dishes were used as controls. Petri dishes were left open for 30 min after treatment to guarantee complete drying and then taken to the Agroecosystems Entomology Lab (University of Nebraska–Lincoln, West Central Research and Extension Center, North Platte, NE) for insect infestation. Neonates (<36 h old), second-instar, and third-instar larvae from three field-collected populations (Grand Island, Kearney North, and Kearney South) were infested separately. A group of 20 larvae were transferred to each Petri dish using a fine camel-hair paintbrush. Mortality was recorded at 16 h after infestation, larvae that did not move for at least the length of their body after gentle prodding were considered dead.

The experiment had a factorial treatment design with bifenthrin rates, application rates, and *S. albicosta* populations as factors in a complete randomized design. The experiment was replicated once with 60 neonates (20 per Petri dish), and 60 second-instar larvae in the first experimental run, and 60 third-instar larvae in the second experimental run.

Statistical Analysis

The bifenthrin dose-response data were analyzed with a probit regression (Finney 1971) using PoloPlus-PC software (LeOra Software LCC 1987) where LC_{50}s with their corresponding 95% confidence intervals (CIs), regression slopes, and the Pearson goodness-of-fit chi-square value (χ^2) were obtained. Resistance ratios (RR_{50}s) along with the correspondent 95% CIs were also generated with PoloPlus-PC software as described by Robertson et al. (2007). RR_{50}s are usually calculated by dividing the LC_{50} of a resistant population by the LC_{50} of the susceptible population. However, since *S. albicosta* bifenthrin-resistant or laboratory colonies not previously exposed to insecticides do not exist, RR_{50}s were calculated by dividing the LC_{50} of each population by the estimated LC_{50} of the population with lowest LC_{50} collected each year (Pereira et al. 2015), and nonoverlapping CIs determined significant differences between populations. In each year, the population with the lowest LC_{50} was used as reference. Scottsbluff, NE and Delhi, Canada were used as reference populations for 2016 and 2017, respectively.

Nonoverlapping 95% CI of RR_{50}s determined significant differences between populations (Robertson et al. 2007).

An additional likelihood ratio test for equality and parallelism of probit regressions was performed in PoloPlus-PC at the significance level α = 0.05 to compare the 2016 and 2017 susceptibility of populations collected in similar locations. This test provided an indication of qualitative and quantitative differences in potential year-to-year changes in susceptibility (Robertson and Rappaport 1979, Robertson et al. 2007) with three possible outcomes: 1) lines were equal if both the slopes and intercepts of the probit regressions were statistically the same, suggesting no difference in susceptibility between years; 2) lines were unequal but parallel if only the slopes of the probit lines were statistically the same, indicating quantitative differences in insecticide susceptibility; and 3) lines were not parallel and unequal if both slopes and intercepts were significantly different, suggesting that both quantitative and qualitative genetic variation might be affecting insecticide susceptibility.

Results

Baseline Susceptibility With Bifenthrin Active Ingredient

The bifenthrin LC_{50}s estimated in 2016 for *S. albicosta* populations ranged from 50.10 ng/cm² (Scottsbluff) to 66.10 ng/cm² (North Platte) (Table 1). RR_{50}s were calculated relative to the LC_{50} of the most susceptible population (Scottsbluff) and ranged from 1.04- to 1.32-fold (Table 1). Overlapping 95% CI of RR_{50}s indicated that there were no statistically significant differences among populations tested in 2016.

In 2017, the bifenthrin LC_{50}s estimated ranged between 6.33 ng/cm² (Delhi, Canada) and 100.66 ng/cm² (O'Neill, NE) (Table 2). RR_{50}s were calculated relative to the most susceptible population (Delhi, Canada) and ranged between 6.33- and 15.90-fold (Table 2) with most 95% CI overlapping each other (Table 2). Considering the fact that a known susceptible population could not be obtained,

resistance ratios presented here are likely an underestimate (Payton et al. 2003).

Among the five populations collected in Nebraska in both 2016 and 2017, only Scottsbluff had statistically similar susceptibility to bifenthrin in both years (Fig. 2A), where probit regression lines were found to be both equal ($χ^2$ = 0.19; df = 2; P > 0.05) and parallel ($χ^2$ = 0.02; df = 1; P > 0.05). In 2017, Brule was found to be significantly less susceptible to bifenthrin (Fig. 2B) with both hypotheses of equality ($χ^2$ = 39.89; df = 2; P < 0.05) and parallelism ($χ^2$ = 13.02; df = 1; P < 0.05) rejected. In fact, there was a 1.75-fold increase in LC_{50} estimated for Brule between 2016 (Table 1) and 2017 (Table 2). The probit regression lines estimated for the Grand Island population (Fig. 2C) were also found to be significantly unequal ($χ^2$ = 18.63; df = 2; P < 0.05) and not parallel ($χ^2$ = 11.01; df = 1; P < 0.05). However, Grand Island seemed to be more susceptible to bifenthrin in 2017 (Table 2) than in 2016 (Table 1) with a 1.14-fold decrease in LC_{50}.

The hypothesis of equality was rejected for Benkelman ($χ^2$ = 14.47; df = 2; P < 0.05) (Fig. 2D) and North Platte ($χ^2$ = 15.14; df = 2; P < 0.05) (Fig. 2E) indicating significant differences in bifenthrin susceptibility between 2016 and 2017 populations. Since the hypothesis of parallelism was accepted for the same populations ($χ^2$ = 0.05; df = 2; P > 0.05 and $χ^2$ = 3.35; df = 1; P < 0.05, respectively), variability differences are likely to be quantitative rather than qualitative. In 2017, Benkelman showed a 1.41-fold decrease in bifenthrin LC_{50}, whereas North Platte presented a 1.38-fold increase.

Efficacy of Bifenthrin Commercial Formulation

In the aerial application simulation with bifenthrin commercial insecticide, *S. albicosta* exhibited 100% mortality for all combinations of insecticide rates (36.8 and 112.1 g a.i./ha), carrier volumes (18.70 and 46.80 liters per ha), insect populations (Grand Island, Kearney South, and Kearney North), and instars (neonates, second, and third) tested, while 100% survival was observed in all correspondent control treatments.

Table 1. Baseline susceptibility of *Striacosta albicosta* field populations collected in 2016 to bifenthrin estimated from contact dose-response bioassays with neonates

Population	N	Slope (±SE)	LC_{50} (95% CI) ng/cm²	$χ^2$ (df)	RR_{50} (95% CI)
Scottsbluff, NE	243	4.08 (0.43)	50.10 (42.41–57.53)	0.81 (2)	–
Brule, NE	239	5.12 (0.63)	52.02 (46.62–58.53)	1.30 (2)	1.04 (0.86–1.25)
Benkelman, NE	240	3.10 (0.37)	56.39 (33.73–77.65)	2.10 (2)	1.13 (0.90–1.39)
Grand Island, NE	239	2.92 (0.31)	62.86 (53.84–73.50)	1.01 (2)	1.26 (1.02–1.60)
North Platte, NE	239	3.93 (0.58)	66.10 (45.59–93.12)	2.44 (2)	1.32 (1.08–1.61)

Table 2. Baseline susceptibility of *Striacosta albicosta* field populations collected in 2017 to bifenthrin estimated from contact dose-response bioassays with neonates

| Population	N	Slope (±SE)	LC_{50} (95% CI) ng/cm²	$χ^2$ (df)	RR_{50} (95% CI)
Delhi, Canada	360	3.50 (0.50)	6.33 (3.10–8.34)	5.65 (3)	–
Benkelman, NE	471	3.19 (0.28)	40.05 (32.95–47.00)	6.02 (5)	6.33 (5.17–7.73)
Scottsbluff, NE	421	4.16 (0.60)	52.26 (35.60–63.80)	4.40 (4)	8.25 (6.53–10.44)
Grand Island, NE	409	5.10 (0.48)	55.18 (41.01–69.00)	9.87 (4)	8.72 (7.20–10.56)
Colby, KS	537	2.83 (0.23)	62.22 (50.90–74.80)	10.87 (6)	9.83 (8.08–11.94)
Grant, NE	300	3.65 (0.36)	63.64 (31.20–95.10)	3.39 (2)	10.05 (8.02–12.60)
Kearney, NE (North)	370	2.86 (0.24)	74.04 (63.27–86.52)	5.00 (5)	11.70 (9.58–14.27)
Kearney, NE (South)	410	3.03 (0.28)	75.51 (66.94–84.63)	3.72 (4)	11.93 (9.78–14.53)
Brule, NE	358	2.90 (0.30)	91.09 (78.99–107.02)	1.22 (3)	14.39 (11.54–17.92)
North Platte, NE	360	4.47 (0.46)	91.32 (82.20–99.87)	2.76 (3)	14.42 (11.97–17.38)
O'Neill, NE	420	3.36 (0.31)	100.66 (86.45–119.17)	4.28 (4)	15.90 (13.12–19.26)
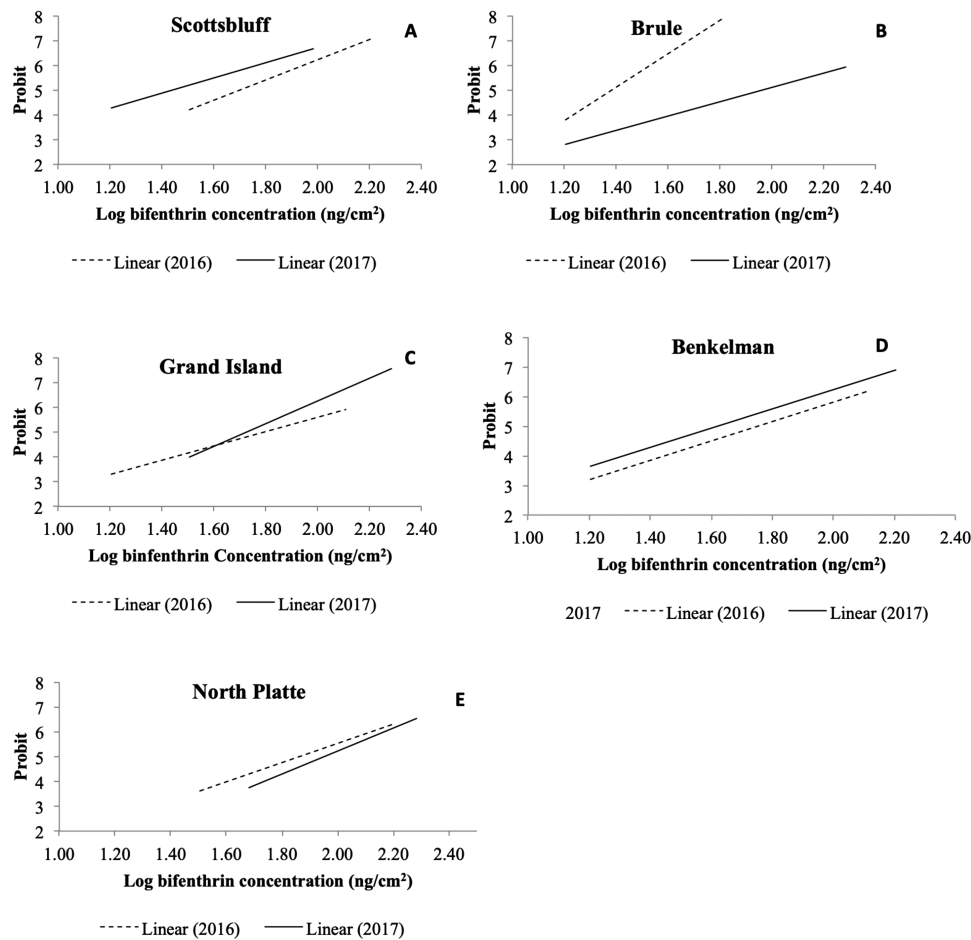
Fig. 2. Probit linear regressions tested for equality and parallelism of slopes and intercepts at the significance level α = 0.05. Comparing 2016 (dashed) and 2017 (line) estimations within western bean cutworm population, lines were: both equal and parallel for (A) Scottsbluff, NE. Unequal and not parallel for (B) Brule, NE, and (C) Grand Island, NE. Unequal but parallel for (D) Benkelman, NE, and (E) North Platte, NE.

Discussion

Based on this study, the most susceptible field population of *S. albicosta* in Nebraska in 2016 was from Scottsbluff, which was not significantly different from the least susceptible population from North Platte, and with only a 1.32-fold of resistance ratio between these populations (Table 1). The earliest reports of complaints about decreased efficacy of pyrethroids in Nebraska were from the southwestern region (J. A. Peterson, personal communication); therefore, Benkelman, NE was considered to be a 'problem field' population. Updated field reports from 2017 indicated that the Kearney, NE sites also had failures in controlling *S. albicosta* using pyrethroids. 'Nonproblem field' populations were classified as areas where application failures of pyrethroids had not been reported (e.g., Scottsbluff, Brule, Grand Island, and North Platte, NE). However, for all 2016 collections in Nebraska, the 95% CIs of estimated resistance ratios overlapped, indicating that there were no significant differences in susceptibility among these populations. Our data show that although Kearney, NE sites had higher bifenthrin LC_{50}s compared to the geographically nearest site (Grand Island, NE), their RR_{50} levels were not significantly different. This suggests that reported failures were not necessarily associated with a relative difference in insecticide susceptibility as measured by contact dose-response bioassays. This finding may be explained by the fact that *S. albicosta* are mobile. Adults may move freely between sprayed and nonsprayed fields and it is possible that there is high gene flow

among *S. albicosta* populations, diluting potential resistant alleles and generating a similar pattern of susceptibility between the populations in Nebraska. Consequently, it can be expected that, if there has been an increase in resistance alleles in recent years, it is widespread among Nebraska populations.

RR_{50}s ≥ 10 has been used to determine cases of resistance (Mota-Sanchez et al. 2002, Tabashnik et al. 2014), whereas lower magnitudes often indicate natural variation among populations (Robertson et al. 1995). However, because a susceptible laboratory population could not be obtained for reference, resistance ratios found in this study were likely underestimated (Payton et al. 2003). Overall, the LC_{50}s among Nebraska field populations were similar in 2016 and 2017 (Tables 1 and 2), and the aerial application simulation with bifenthrin commercial insecticide exhibited 100% mortality for the conditions evaluated, suggesting that any changes in LC_{50}s between the 2 yr were due to natural variation among the populations (Robertson et al. 1995). However, when the Delhi, ON, Canada population was used as a reference in 2017, an approximately 15-fold difference in susceptibility was detected for Brule, North Platte, and O'Neill, NE locations. The lower bifenthrin LC_{50} of Delhi, Canada detected in 2017 was somewhat expected. The expansion of *S. albicosta* from the western U.S. Corn Belt to southeastern Canada likely started around 2008 when the pest was first reported in the province of Ontario (Smith et al. 2018a). Since that was before initial reports of pyrethroid failures in Nebraska had begun, it

would be expected that founder *S. albicosta* populations settling in Canada were still considerably susceptible to pyrethroids and that without further selection pressure, resistance alleles remained at low frequency (Roush and Daly 1990). In addition, if there have been *S. albicosta* populations migrating into Canada more recently, there may have been reversion toward susceptibility after a few generations without intense selection pressure (Mascarenhas et al. 1998, Sial and Brunner 2012).

The region of O'Neill, located in north central Nebraska, is known for high production of non-Bt popcorn and non-Bt edible white maize, therefore relying significantly on pyrethroid applications to control pests such as *Ostrinia nubilalis* (Hübner) and *Helicoverpa zea* (Boddie), in addition to *S. albicosta*. Aerial applications of pyrethroids are also common in Bt maize around Brule and North Platte to complement *D. v. virgifera* control strategies (Pereira et al. 2015, 2017; Souza et al. 2019). The timing of these insecticide aerial applications often overlaps with *S. albicosta* oviposition and larval feeding activities, providing considerable pyrethroid exposure and selection pressure on this pest. These agronomic practices have led to high selection pressure for resistance to pyrethroids in these regions and are likely to explain the higher resistance ratios observed in 2017 for these populations.

Results from the spray chamber experiment indicate that the levels of bifenthrin susceptibility estimated for *S. albicosta* populations in the contact dose-response bioassays might not be high enough to impact the performance of a correspondent commercial formulation under controlled conditions. These results were not only found for neonates, but also for second- and third-instar larvae, suggesting that the reduced efficacy of the pyrethroid bifenthrin reported locally might have occurred due to factors other than decrease in susceptibility to insecticide active ingredients, such as chemical application techniques. Aerial applications often provide inconsistent insecticide coverage that can result in reduced control due to sublethal exposure (Bynum et al. 1991, Souza et al. 2019). Such features of aerial application, combined with the short period during which *S. albicosta* is exposed to chemical applications, and high temperatures in the U.S. Corn Belt during aerial applications, might be critical factors leading to reports of low pyrethroid efficacy. Further studies of operational factors influencing pyrethroid field efficacy against *S. albicosta* may help to improve the efficiency of chemical management practices adopted for this pest.

Although *S. albicosta* pyrethroid resistance was not confirmed in the U.S. western Corn Belt, a significant increase in bifenthrin LC_{50}s estimated for Brule and North Platte, NE populations occurred between 2016 and 2017. Results from the likelihood ratio test for equality and parallelism of probit regression lines suggest that both quantitative and qualitative genetic variations may be affecting the shift in bifenthrin susceptibility observed. Multiple mechanisms of pyrethroid resistance have been found in insect species, which includes not only different genes and mutations carried by resistant populations, but also change in expression of detoxification enzymes (Li et al. 2007). Biological characteristics of *S. albicosta*, such as high fecundity and ability to disperse long distances (Michel et al. 2010), may contribute to a rapid resistance evolution and spreading of pyrethroid resistance alleles under selection pressure (Georghiou and Taylor 1977).

The best period for the establishment of baseline susceptibility of a target pest to a specific chemical or new plant-incorporated protectant (PIP) should be prior to the extensive marketable use of such product, and most importantly, prior to the development of resistance among field populations (Wu 2014). Such data are necessary for determining susceptibility changes related to the exposure to the chemical, monitoring of the evolution of resistance, and the development of adequate IRM strategies (Roush and Miller 1986). Changes in *S. albicosta* susceptibility to pyrethroids might have occurred in the U.S. western Corn Belt in the last 20 yr of use of this insecticide class. However, no baseline susceptibility was previously developed for this pest. The bifenthrin baseline susceptibility data generated in this study represent the first step in the development of a pyrethroid resistance-monitoring program for *S. albicosta* field populations. With the imminent establishment of *S. albicosta* as a primary pest beyond its original range (Smith et al. 2018a), adoption of informed IRM practices within integrated pest management programs will be critical to delay the evolution of *S. albicosta* resistance to pyrethroids and to prolong the efficacy of technologies currently available to control this pest.

Acknowledgments

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