Journal of Economic Entomology, 109(2), 2016, 676–683
doi: 10.1093/jee/tov392
Advance Access Publication Date: 30 December 2015
Research article

Field and Forage Crops

Captures of Boll Weevils (Coleoptera: Curculionidae) in Relation to Trap Orientation and Distance From Brush Lines

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Received 26 October 2015; Accepted 4 December 2015

Abstract

Eradication programs for the boll weevil (*Anthonomus grandis grandis* Boheman) rely on pheromone-baited traps to trigger insecticide treatments and monitor program progress. A key objective of monitoring in these programs is the timely detection of incipient weevil populations to limit or prevent re-infestation. Therefore, improvements in the effectiveness of trapping would enhance efforts to achieve and maintain eradication. Association of pheromone traps with woodlots and other prominent vegetation are reported to increase captures of weevils, but the spatial scale over which this effect occurs is unknown. The influences of trap distance (0, 10, and 20 m) and orientation (leeward or windward) to brush lines on boll weevil captures were examined during three noncropping seasons (October to February) in the Rio Grande Valley of Texas. Differences in numbers of captured weevils and in the probability of capture between traps at 10 or 20 m from brush, although often statistically significant, were generally small and variable. Variations in boll weevil population levels, wind directions, and wind speeds apparently contributed to this variability. In contrast, traps closely associated with brush (0 m) generally captured larger numbers of weevils, and offered a higher probability of weevil capture compared with traps away from brush. These increases in the probability of weevil capture were as high as 30%. Such increases in the ability of traps to detect low-level boll weevil populations indicate trap placement with respect to prominent vegetation is an important consideration in maximizing the effectiveness of trap-based monitoring for the boll weevil.

Key words: boll weevil, *Anthonomus grandis*, pheromone, trapping

During the past two decades, crop losses and insect control costs in cotton (*Gossypium hirsutum* L.) dramatically decreased from about US$1.68 billion in 1995 (Williams 1996) to an estimated US$657 million in 2013 (Williams 2015). A major contributor to these decreases has been eradication efforts directed against the boll weevil (*Anthonomus grandis grandis* Boheman). However, maintaining the successes associated with boll weevil eradication will require effective methods to rapidly and accurately detect incipient infestations of weevils in eradication zones and migrants from nearby infested areas.

Boll weevil eradication programs rely heavily on pheromone-baited traps to trigger in-season insecticide treatments and to assess program progress. In the later stages of eradication, the role of pheromone trapping shifts from providing a population index to detection of low-level or localized weevil populations. Delayed detection of these populations can result in field infestations and increased control costs and effort. Therefore, implementation of trapping protocols that maximize trap captures and the probability of weevil detection could reduce costs and enhance progress of eradication programs.

Association of pheromone traps with woodlots and similar vegetational features reportedly increase captures of boll weevils compared with captures in other settings (Hardee et al. 1972, Roach et al. 1972), but reports to the contrary also exist (Leggett 1984). Where observed increases in weevil captures were reported, they were attributed to the role of woodlots as boll weevil overwintering habitat (Roach et al. 1972, Rummel et al. 1980). However, Spurgeon and Raulston (2006) found increased captures of boll weevils in pheromone traps that were closely associated with a variety of vegetation types. Specifically, captures were increased by close trap association with relatively tall, dense, and erect vegetation with a well-defined edge (brush lines, dense woods, citrus orchards,

Published by Oxford University Press on behalf of Entomological Society of America 2015.

mid- and late-season sugarcane) compared with trap association with fallow areas or low-growing or sparse vegetation (grassy areas, early-season sugarcane, unimproved pasture with sparse brush). Spurgeon and Raulston (2006) referred to the former vegetational features as "prominent" vegetation. Furthermore, some of the prominent vegetation types associated with high trap captures are not considered overwintering habitat for the weevil (e.g., sugarcane, citrus). Sappington and Spurgeon (2000) attributed at least part of the increased captures associated with prominent vegetation to moderation of wind speed around the traps. In the study by Spurgeon and Raulston (2006), traps exhibiting increased boll weevil captures were immediately adjacent to the prominent vegetation whereas traps with lower captures were generally well distanced from prominent vegetation. No study has examined the spatial scale over which this vegetational effect occurs. The objective of the research reported herein was to examine the relationship between boll weevil pheromone trap captures and distance of the trap from prominent vegetation.

Materials and Methods

Experimental Design and Study Arena

A 3-yr study was conducted on the Russell Plantation near San Benito, TX. The plantation occupies ≈1,500 ha of pasture and cropland and features an extensive system of drainage canals that are lined with brush (primarily mesquite, *Prosopis* spp., and Acacia, *Acacia* spp.). Experimental treatments included trap orientation to the brush lines (leeward or windward, expecting a prevailing southeasterly wind direction) and distance from the brush (0, 10, and 20 m). In October 2004, a total of 10 trapping sites were selected, each featuring six traps arranged in a line. All sites fit the classification of "heavy brush" (traps were not visible from the opposite side of the canal) as described by Sappington and Spurgeon (2000). Each trapping site was >200 m from any other trapping site. Sappington (2002) demonstrated intertrap interference when wind directions were close to parallel to a line of traps compared with wind directions that were close to perpendicular to a line of traps. Therefore, sites were selected such that orientation of the brush line was less than 20° from magnetic North, permitting the orientation of each line of traps from the Northeast (45 ± 5° from magnetic North) to the Southwest. Traps were arranged with consistent intertrap spacing within a site but variable spacing among sites to maintain the overall orientation of the trap line as well as the desired distance from the brush (Fig. 1). Thus, distances between traps within sites (measuring down the margin of the brush line) increased with deviation of brush line orientation from magnetic North from about 10 m (sites 4–6) to about 27 m (sites 7–10). Eight of the trapping sites were maintained throughout the three years of study. Sites 9 and 10 used during October 2004 to February 2005 were replaced after the first year of study because the brush was cleared from the canal banks during the summer of 2005.

Each position defined by the combination of trapping site, orientation, and distance from brush was occupied by a standard boll weevil pheromone trap (Southeastern Eradication Foundation trap, Technical Precision Plastics, Mebane, NC). Each trap was supported about 1 m above ground level on a section of metal conduit. Traps placed at the brush line interface (0 m) were located in areas 1–1.5-m diameter which were maintained free of grass and other vegetation for the duration of the trapping period. Traps placed at 10 or 20 m from brush were in fallow fields. Each trap was baited with a standard 10-mg pheromone lure (Scentry Biologicals, Billings, MT)

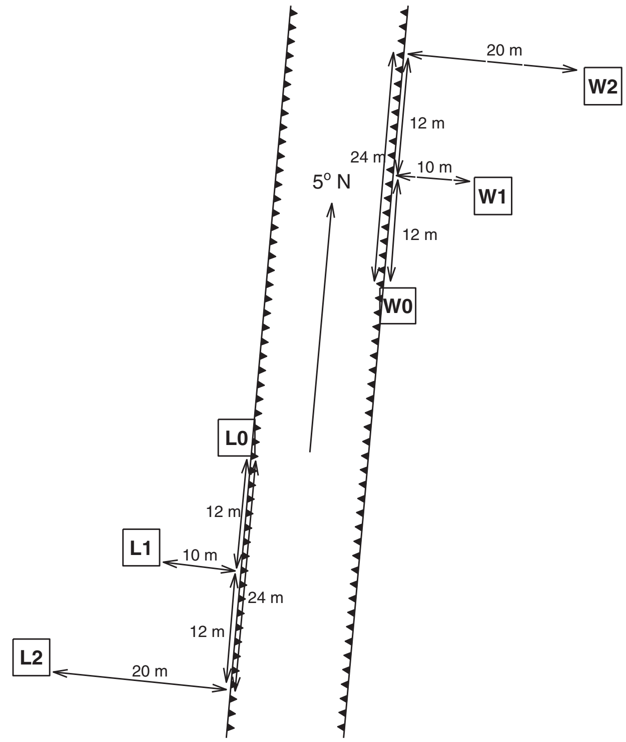

Fig. 1. Schematic of boll weevil trap arrangement within trapping sites 1–3 representing treatment combinations of orientation (leeward, L0-2; windward, W0-2) and distance (0, 0 m; 1, 10 m; 2, 20 m) from brush-lined canals. Intertrap distances (measured down the brush line) ranged from about 10 m (sites 4–6) to about 27 m (sites 7–10), depending on deviation of the brush line orientation from magnetic North.

that was replaced weekly. Each year (2004, 2005, 2006) traps were established in mid-October and were maintained weekly for 16 wk except for in early 2007, when inclement weather prohibited access to the study and caused the loss of data for 2 wk. Each week, captured weevils were transferred from the traps to individual vials of 70% isopropanol, and were subsequently counted in the laboratory. Traps were also inspected for weevil legs and heads indicative of predation, and were cleared of spiders and webs. Data were excluded from analysis for traps that were obstructed by spider webbing, showed signs of predation on weevils, or that were dislodged by weather or farming operations. Besides the 2 wks of observations lost to inclement weather in year 3, about 4.5% of observations were excluded ranging from 50 out of 960 (year 1) to 35 out of 780 observations (year 3). The majority of these exclusions were caused by apparent insect or spider predation on trapped weevils.

Weather Records

Daily (24-h) weather summaries were obtained for the South Padre Island International Airport, Brownsville, TX, from the Global Historical Climatology Network (Menne et al. 2012a, b). Standard weather parameters of interest included direction of the fastest 2-min wind speed (°), daily maximum temperature (°C), and average daily wind speed (m s^{-1}). Although hourly weather records were available, the additional resolution provided by these data is not useful because weevil captures were recorded weekly and the times of capture each day were unknown. Weekly medians of daily maximum temperature and average daily wind speed were calculated for each week of trapping. In addition, the reciprocal of the median weekly wind speed was calculated so that correlations with weekly weevil captures would be positive and visual interpretation of trends would be simplified. The direction of the fastest 2-min wind speed each day was standardized as the absolute deviation from 135° (southeasterly) before the weekly median deviation was calculated.

Relationships among weather parameters and captures of boll weevils were not examined statistically because of autocorrelations and limited representation of interactions among weather parameters, confounding seasonal declines in the boll weevil population, and the low temporal resolution of the trapping data. Instead, weather and trapping data were plotted graphically to aid in characterizing environmental conditions during the trapping periods, and to assist in interpretation of the trapping data. Regarding wind direction, deviations ≤60° from 135° magnetic North were considered to represent prevailing southeasterly winds. Deviations between 60 and 120° represented winds roughly parallel to the lines of traps, and deviations >120° were opposite prevailing winds.

Although Jones and Sterling (1979) reported the threshold for boll weevil flight was below 15.6°C, other observations based on sticky-trap captures suggest a higher temperature threshold for substantial flight activity. Fenton and Dunnam (1928) concluded that most weevil flight occurs when the daily maximum temperature is above 15.6°C, but also reported the lowest temperature at which flight was observed was 19.4°C. Gaines (1936) likewise reported that >97% of weevil captures occurred at temperatures above 18.3°C. Based on these latter reports it was assumed that response to traps would be low during weeks when the median daily high temperature was <18.3°C.

Wind speed is known to influence boll weevil response to pheromone traps (Hardee et al. 1969, Ridgway et al. 1976, Rummel and Bottrell 1976, Sappington and Spurgeon 2000, Sappington 2002), but detailed knowledge of the relationship between wind speed and trap response is lacking. Based on flight mill studies, McKibben et al. (1991) estimated normal flight speed of the boll weevil was <1.33 m s^{-1}. Hardee et al. (1969) reported flight of weevils was deterred at wind speeds above 7 km h^{-1} (1.9 m s^{-1}). However, Sappington (2002) observed effects of trap interference (increased capture by the upwind-most trap) when wind speeds were between 10 and 20 km h^{-1} (2.8–5.6 m s^{-1}), acknowledging that some captures may have occurred during temporary lulls. In addition, Spurgeon et al. (1999) and Spurgeon (2001) observed weevil response to bait sticks so long as wind speeds were below about 16 km h^{-1} (4.4 m s^{-1}). Therefore, it appears that boll weevil flight speeds are underestimated in flight mill studies. Considering the uncertainty of the effects of wind speed variation within and among days, an arbitrary value of 4 m s^{-1} (or 0.25 s m^{-1}) was selected as a reference for visually interpreting boll weevil captures in traps, assuming that average daily wind speeds in excess of this value would be associated with low weevil response to traps.

Statistical Analyses

The trap captures from the first year of study (2004–2005) were analyzed using a generalized linear mixed model with Laplace approximation and a negative binomial distribution (PROC GLIMMIX, SAS Institute 2012). The negative binomial was used because initial analyses indicated variances were too large to be modeled using the Poisson distribution (Pearson χ^2/df >2; Stroup 2013). The model contained fixed effects of trap distance from the brush lines (0, 10, 20 m), trap orientation to the brush (leeward, windward) and their interaction. Although interpretation of seasonal sampling or trapping data would usually focus on interactions of main effects with date, traps for monitoring boll weevils are not normally relocated in anticipation of short-term changes in weather conditions. Therefore, trap orientation in the statistical models was maintained as originally assigned even during weeks when winds were not from the prevailing direction. Also, because in practice each trap is typically set and remains at or near a single location, the marginal effects across dates were of more interest than were differences among dates *per se*. For these reasons, date was considered a random factor. Also considered random were trapping site × date (site nested within date; a blocking effect), and the orientation × site × date interaction which served as the error term for testing the effect of trap orientation. Residual was used as the error term for testing effects of trap distance and the orientation × distance interaction. Significant interactions of main effects were explored by examining the corresponding simple effects using the SLICE option of the LSMEANS statement. Where tests of the simple effects were significant, pair-wise comparisons of the means were made using the SLICEDIFF option adjusting for multiplicity with the ADJUST = SIMULATE option. Estimated means and standard errors on the data scale were obtained from estimates on the model scale using the ILINK option. Inverse-linked estimates obtained from model-scale means correspond to medians on the data scale because means are poor measures of central tendency for asymmetrical non-Gaussian distributions (Stroup 2013).

The second trapping year (2005–2006) was initiated following the first full year of a renewed boll weevil eradication program. Therefore, boll weevil numbers, and trap captures, were generally lower and with more zero counts than during the first year of the trapping study. Captures of weevils in traps were analyzed using the same statistical model as for the first year data, except the Poisson distribution was used based on the Pearson χ^2/df (0.86). In addition, the probability of capturing one or more weevils was estimated, again using the same linear mixed model, but assuming a binomial distribution. Captures by pheromone traps in the third year of the study were analyzed exactly as described for the second year of the study.

Results

Year 1 (2004–2005)

Winds were generally from the prevailing southeasterly direction during 10 of the 16 trapping weeks (Fig. 2a). Trap orientations (leeward, windward) were functionally reversed because of northwesterly winds during only two of the weekly periods, both of which corresponded with low weevil response to the traps (Fig. 2a and d). Temperatures were high enough to allow substantial response to traps during all but a single week in late December (Fig. 2b), but wind speeds were low enough to facilitate capture of large numbers of weevils during only five of the 16 wk (Fig. 2c).

Analyses of numbers of captured weevils indicated a significant influence of trap distance on boll weevil capture ($F = 126.8$; df = 2, 586; $P < 0.01$) but no effect of trap orientation to the brush ($F = 2.06$; df = 1, 159; $P = 0.15$). However, the significant orientation × distance interaction ($F = 9.82$; df = 2, 586; $P < 0.01$) indicated the effects of trap distance varied with trap orientation. Tests of simple effects of trap orientation within each distance indicated traps on the leeward sides of brush lines captured more weevils than traps on the windward sides when traps were 10 m from the brush ($F = 15.40$; df = 1, 586; $P < 0.01$; Table 1). Differences corresponding to trap orientation were not demonstrated when traps were either directly on the brush line (0 m, $F = 3.08$; df = 1, 586; $P = 0.08$; Table 1) or 20 m from the brush ($F = 0.13$; df = 1, 586; $P = 0.72$; Table 1). Tests of simple effects indicated significant differences

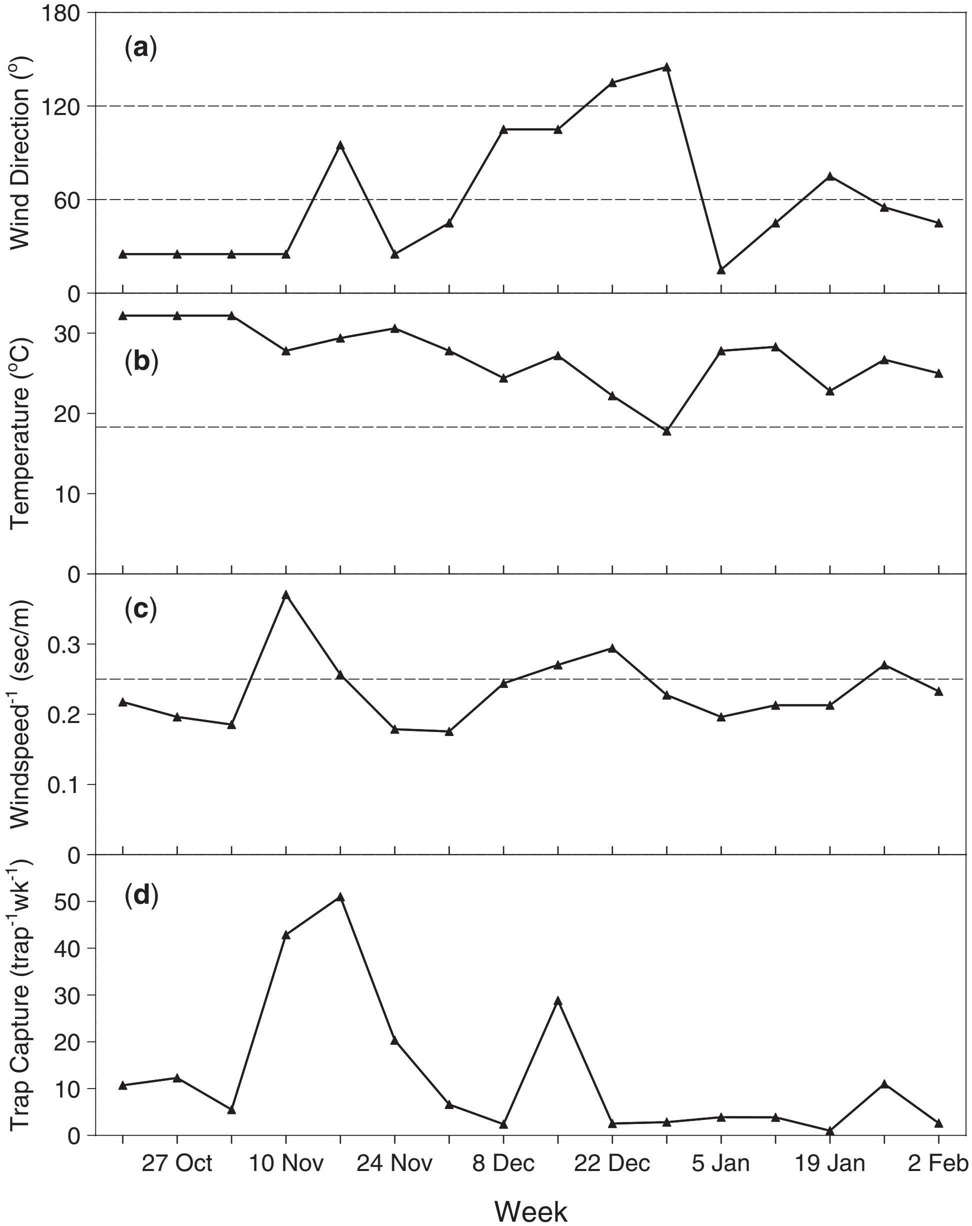

Fig. 2. Weekly medians of daily weather measurements and mean captures of boll weevils in pheromone traps, San Benito, TX, 2004–2005. (**a**) Wind direction is the absolute deviation from 135° magnetic north of the fastest 2-min wind speed; (**b**) temperature is the observed daily maximum; (**c**) windspeed^{-1} is the reciprocal of the average daily wind speed; and (**d**) trap capture is the model-estimated (inverse-linked least-squares mean) number of boll weevils captured per trap. Reference lines (60 and 120° for wind direction, 18.3°C for temperature, 0.25 s m^{-1} for wind speed) are provided as interpretive aids.

among trap distances within both trap orientations (leeward, $F = 42.52$; df = 2, 586; $P < 0.01$; windward, $F = 96.75$; df = 2, 586; $P < 0.01$). For leeward traps, captures diminished with increasing distance from the brush (Table 1), although differences in captures at 10 and 20 m were modest. For traps established on the windward side, captures were highest at 0 m and lower at 10 and 20 m from the brush (Table 1).

Second Year (2005–2006) Trap Captures

Winds were classified as from the prevailing southeasterly direction during nine of the 16 trapping periods, and were reversed (northwesterly) during only 2 wk, both of which corresponded to relatively low captures of weevils (Fig. 3a and d). Three of the four apparent peaks in trap captures were associated with periods characterized by prevailing winds. As during the previous year, temperatures approached levels too low to permit substantial response to traps during only a single week (21 December; Fig. 3b). Relatively low wind speeds were associated with the weeks of highest trap response (Fig. 3c and d), but wind speeds were also low during 5 wk when trap response was low.

Analyses of boll weevil captures failed to indicate a significant effect of trap orientation ($F = 0.27$; df = 1, 159; $P = 0.61$). However, both trap distance ($F = 38.34$; df = 2, 600; $P < 0.01$) and the orientation × distance interaction ($F = 20.56$; df = 2, 600; $P < 0.01$) were significant. Tests of simple effects within each trap distance indicated significant differences between trap orientations at 0 ($F = 12.64$; df = 1, 600; $P < 0.01$) and 20 m ($F = 8.72$; df = 1, 600; $P < 0.01$) but not at the 10-m distance ($F = 1.54$; df = 1, 600;

Table 1. Inverse-linked least squares means (± SE) of boll weevil pheromone trap captures (weevil trap^{-1} week^{-1}) relative to trap orientation to and distance from brush lines, October to February, San Benito, TX

Study period	Trap orientation	Trap distance from brush (m)		
		0	10	20
2004–2005[a]	Leeward	10.2 ± 3.05Aa	5.7 ± 1.71Ab	4.3 ± 1.28Ac
	Windward	12.1 ± 3.61Aa	3.7 ± 1.12Bb	4.1 ± 1.23Ab
2005–2006[b]	Leeward	0.8 ± 0.25Ba	0.8 ± 0.22Aa	0.7 ± 0.22Aa
	Windward	1.2 ± 0.36Aa	0.7 ± 0.19Ab	0.5 ± 0.15Bc
2006–2007[bc]	Leeward	0.7 ± 0.31	0.5 ± 0.24	0.6 ± 0.28
	Windward	0.8 ± 0.38	0.6 ± 0.28	0.8 ± 0.35
		0.8 ± 0.33a	0.6 ± 0.26b	0.7 ± 0.31a

Means followed by a different upper case letter within a column within a study period are significantly different; means followed by a different lower case letter within a row are significantly different; ($P < 0.05$; SIMULATE option of the SAS LSMEANS statement).

[a] Means are inverse linked to the data scale from model estimates using the negative binomial distribution.

[b] Means are inverse linked to the data scale from model estimates using the Poisson distribution.

[c] Only the main effect of distance from brush was significant at $\alpha = 0.05$; no comparisons are made among levels of the orientation × trap distance interaction.

$P = 0.22$; Table 1). Captures were significantly higher for windward traps than for leeward traps when traps were set against the brush (0 m), but this trend was reversed for traps set 20 m from the brush. Tests of simple effects within trap orientations indicated a significant trap distance effect for windward traps ($F = 53.30$; df = 2, 600; $P < 0.01$) but not for leeward traps ($F = 1.53$; df = 2, 600; $P = 0.22$; Table 1). For the windward traps, captures were highest against the brush lines (0 m), intermediate at 10 m, and lowest at 20 m.

Analyses of the probability of capturing one or more weevils did not indicate an effect of trap orientation ($F = 0.33$; df = 1, 159), but trap distance ($F = 10.11$; df = 2, 600; $P < 0.01$) and the orientation × distance interaction ($F = 3.12$; df = 2, 600; $P = 0.04$) were significant. Tests of simple effects of trap orientation within trap distances did not indicate differences at 0 ($F = 0.26$; df = 1, 600; $P = 0.61$) or 10 m ($F = 0.64$; df = 1, 600; $P = 0.42$; Table 2). However, at 20 m from the brush the leeward traps had a higher probability of capturing a weevil than did windward traps ($F = 5.40$; df = 2, 600; $P = 0.02$). Slices within trap orientations indicated significant differences among trap distances for both leeward ($F = 3.51$; df = 2, 600; $P = 0.03$) and windward traps ($F = 9.78$; df = 2, 600; $P < 0.01$). For leeward traps, the probability of capture by traps on the brush line (0 m) was higher than for traps set 10 m from brush but not for traps 20 m from brush (Table 2). For windward traps the probability of capture was highest for traps 0 m from brush. Probability of capture by windward traps 10 and 20 m from brush were equivalent (Table 2).

Third Year (2006–2007) Trap Captures

Wind direction was less consistent during the third year of study compared with the previous two years. Winds were from the prevailing direction during only five of the 14 wk for which trapping data were available (Fig. 4a). Trap orientations were functionally reversed (because of northeasterly winds) during six of the 14 wk, and were roughly parallel to the trap lines during 3 wk. Temperatures were suitable for trap response by the weevils during 13 of the 14 wk, although the presumed threshold for response was approached during 5 wk in December and January, each of which was associated with relatively low trap captures (Fig. 4b and d). Wind speeds were lower than the presumed threshold for substantial trap response during 10 of the 14 wk (Fig. 4c). However, captures between 9 and 16 November were among the highest observed during the third year of study despite relatively high wind speeds (Fig. 4c and d).

Analyses of the numbers of weevils captured did not indicate an effect of trap orientation ($F = 3.61$; df = 1, 129; $P = 0.06$) or an orientation × trap distance interaction ($F = 0.16$; df = 2, 481; $P = 0.85$). However, an effect of trap distance from the brush lines was observed ($F = 7.91$; df = 2, 481; $P < 0.01$). Numbers of weevils captured by traps set at 0 and 20 m from brush were higher than for traps 10 m from brush (Table 1).

Differences among the probabilities of weevil capture mimicked patterns in numbers of weevils captured except the effects of trap distance were more distinct. Analyses did not indicate effects of trap orientation ($F = 1.21$; df = 1, 129; $P = 0.27$) or an orientation × distance interaction ($F = 0.22$; df = 2, 481; $P = 0.80$). Tests of trap distance from brush ($F = 7.43$; df = 2, 481; $P < 0.01$) indicated the probability of weevil capture was highest for traps set 0 m from the brush, and lower and equivalent for traps 10 and 20 m from brush (Table 2).

Discussion

In two of the three study years, captures by traps placed on the leeward or windward edges of brush lines were statistically equivalent. During the exceptional year (2005–2006), captures were significantly higher for windward traps compared with leeward traps, although the difference was small (0.4 weevils trap^{-1} week^{-1}). In addition, captures in all three study years were numerically higher for the windward traps at 0 m from brush compared with leeward traps (Table 1). At face value, these results seem inconsistent with the report of Sappington and Spurgeon (2000). However, Sappington and Spurgeon (2000) documented increased capture in leeward traps compared with windward traps only when wind speed was >10 km h^{-1}, and numbers of captured weevils were very low. Assuming the weevils are inhabiting or frequenting the brush lines in preference to fallow fields, which seems likely and is consistent with the findings of Spurgeon and Raulston (2006), traps placed on the windward margin of brush may have some small advantage over leeward traps when wind speeds are low and favorable for weevil response to traps.

During the second two years of study, the probability of weevil capture was also statistically similar between leeward and windward traps established directly on the borders of brush. Although these results do not demonstrate an advantage for windward trap placement, they do show a lack of penalty for windward placement especially when traps will not be relocated in anticipation of short-term changes in wind speed or direction.

The influences on weevil captures of trap distances that were away from brush varied among years and between trap orientations. During the first year of study, when numbers of weevils were relatively high, captures by the leeward traps declined with increased distance from brush whereas captures by windward traps at 10 and 20 m from brush were equivalent to each other (Table 1). Differences in the respective patterns for leeward and windward traps may have been caused by corresponding differences in the

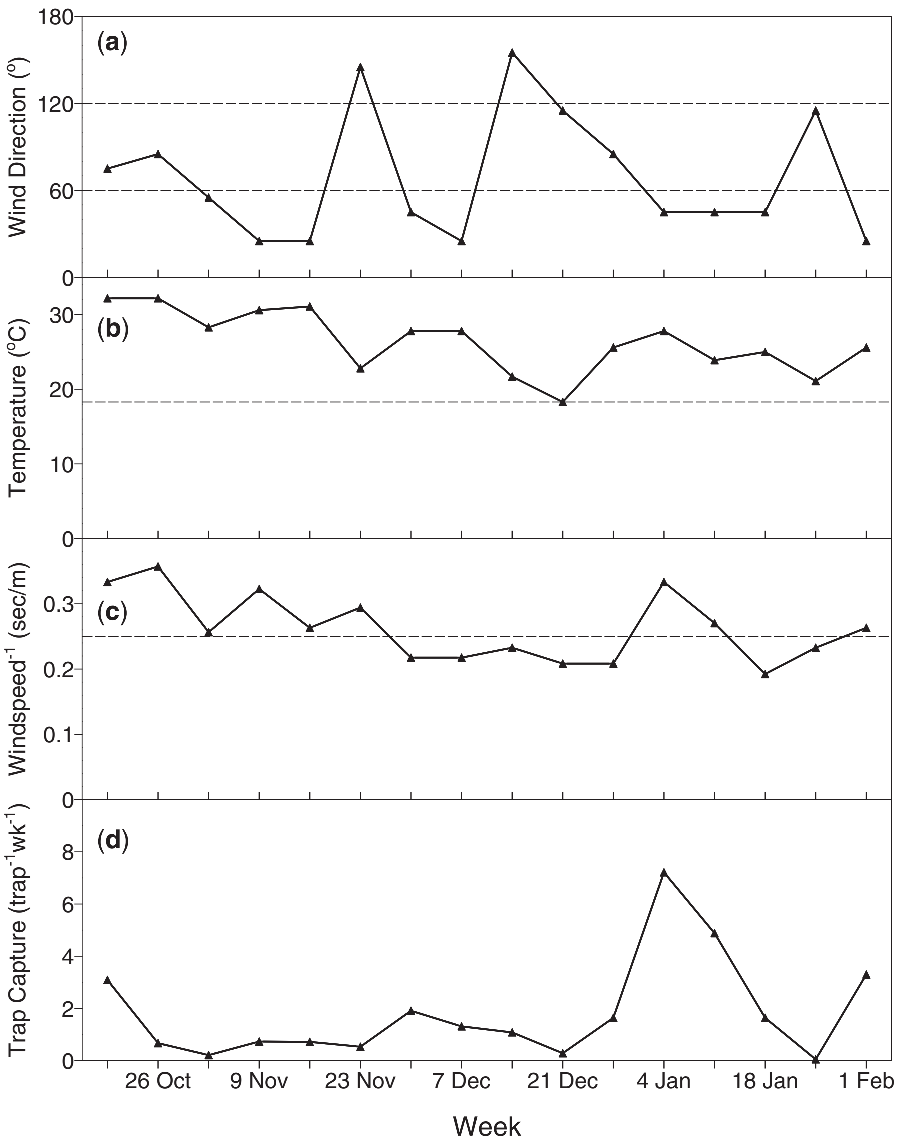

Fig. 3. Weekly medians of daily weather measurements and mean captures of boll weevils in pheromone traps, San Benito, TX, 2005–2006. (**a**) Wind direction is the absolute deviation from 135° magnetic north of the fastest 2-min wind speed; (**b**) temperature is the observed daily maximum; (**c**) windspeed^{-1} is the reciprocal of the average daily wind speed; and (**d**) trap capture is the model-estimated (inverse-linked least-squares mean) number of boll weevils captured per trap. Reference lines (60 and 120° for wind direction, 18.3°C for temperature, 0.25 s m^{-1} for wind speed) are provided as interpretive aids.

extent of wind speed moderation. Windbreaks influence wind speed on both upwind and downwind sides, but the magnitude and extent (distance from the windbreak) of wind speed moderation are greater on the downwind side (Rosenberg 1974). During the second year of study, when weevil captures were lower than the previous year, differences in the numbers of captured weevils between trap distances away from brush were observed only for windward traps (Table 1), but differences in the probability of weevil capture at 10 and 20 m from brush were not significant for either trap orientation (Table 2). During the third year of study no differences in either numbers of weevils captured (Table 1) or the probability of capture (Table 2) were demonstrated between traps at 10 or 20 m from brush, but wind direction was more variable than during the first two years of study. Regardless of the inconsistencies among study years in the patterns of weevil capture by traps away from brush, where differences between distances occurred they were generally too small to be of practical significance.

Table 2. Predicted probabilities (± SE) of boll weevil capture by pheromone traps relative to trap orientation to and distance from brush lines, October to February, San Benito, TX

Study period	Trap orientation	Trap distance from brush (m)		
		0	10	20
2005–2006[a]	Leeward	0.65 ± 0.09Aa	0.46 ± 0.10Ab	0.54 ± 0.10Aab
	Windward	0.68 ± 0.09Aa	0.52 ± 0.10Ab	0.37 ± 0.10Bb
2006–2007[b]	Leeward	0.64 ± 0.14	0.37 ± 0.15	0.43 ± 0.15
	Windward	0.65 ± 0.14	0.47 ± 0.15	0.50 ± 0.16
		0.65 ± 0.14a	0.42 ± 0.14b	0.47 ± 0.15b

[a] Probabilities followed by a different upper case letter within a column are significantly different; probabilities followed by a different lower case letter within a row are significantly different ($P < 0.05$; SIMULATE option of the SAS LSMEANS statement).

[b] Probabilities followed by a different lower case letter within a row are significantly different ($P < 0.05$; SIMULATE option of the SAS LSMEANS statement). Only the main effect of distance from brush was significant at $\alpha = 0.05$; no comparisons are made among levels of the orientation × trap distance interaction.

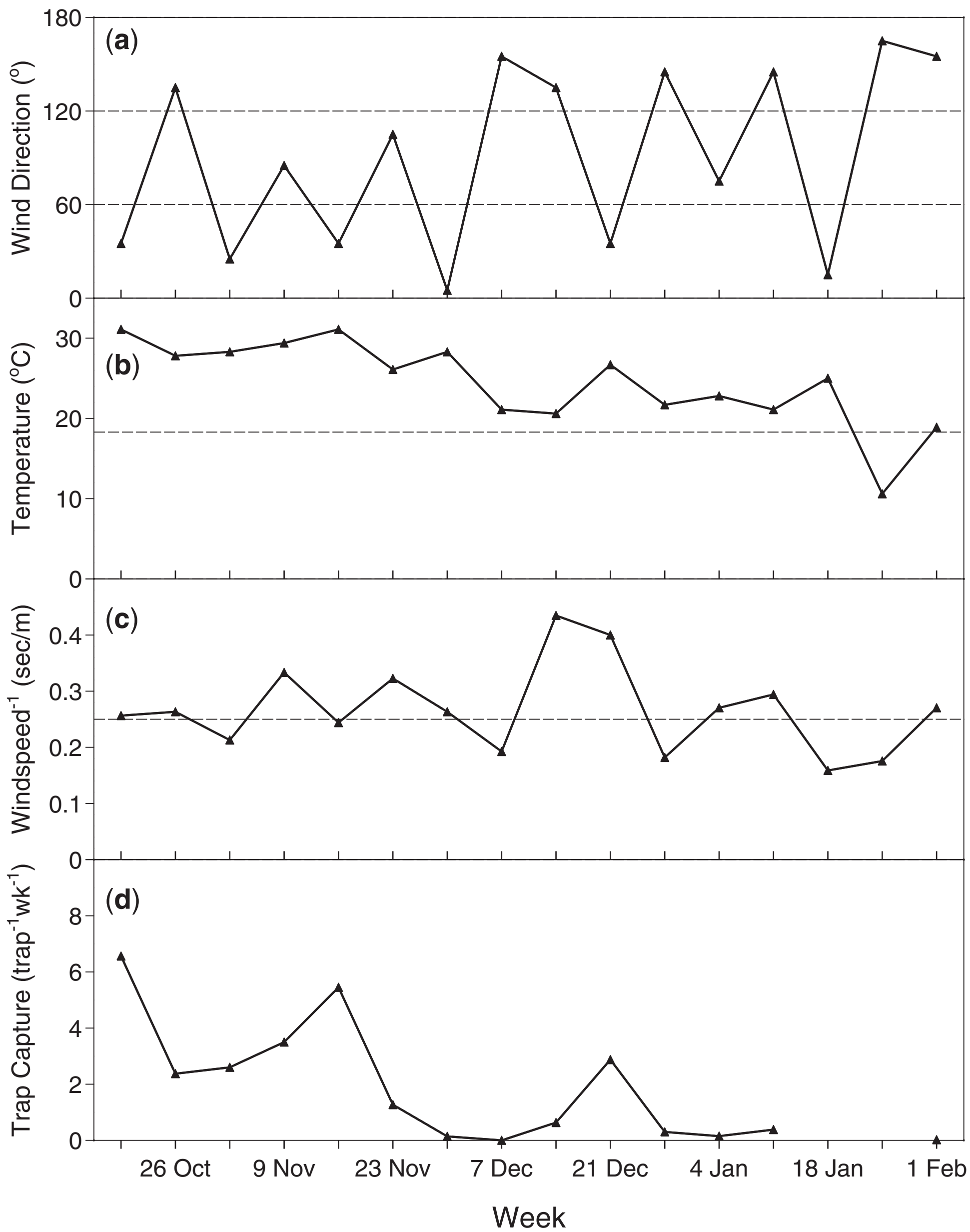

Fig. 4. Weekly medians of daily weather measurements and mean captures of boll weevils in pheromone traps, San Benito, TX, 2006–2007. (**a**) Wind direction is the absolute deviation from 135° magnetic north of the fastest 2-min wind speed; (**b**) temperature is the observed daily maximum; (**c**) windspeed^{-1} is the reciprocal of the average daily wind speed; and (**d**) trap capture is the model-estimated (inverse-linked least-squares mean) number of boll weevils captured per trap. Reference lines (60 and 120° for wind direction, 18.3°C for temperature, 0.25 s m^{-1} for wind speed) are provided as interpretive aids.

In summary, the apparent influence of pheromone trap distance from brush lines varies with boll weevil population level, the index of trap success (numbers of weevils captured or the probability of capture), and with overall weather patterns. Nevertheless, the finding of this study that was most consistent and of the most practical significance was that close association of traps with brush generally increased numbers of captured weevils as well as the probability of capture. When weevil population levels were low and close association of traps with brush provided only modest increases in captures, corresponding increases in the probability of capture were still substantial (≈15–30%). Such increases in the ability of traps to detect low-level populations of the boll weevil would seem important in the latter years of eradication efforts when the costs imposed by untimely detection of weevils are typically high. Therefore, careful trap placement with respect to brush and other prominent vegetation should be an important consideration in maximizing the effectiveness of monitoring efforts in boll weevil eradication programs.

References Cited

Fenton, F. A., and E. W. Dunnam. 1928. Dispersal of the cotton-boll weevil, *Anthonomus grandis* Boh. J. Agric. Res. 36: 135–149.

Gaines, R. C. 1936. Boll weevil activity during normal hibernation period at Tallulah, La. J. Econ. Entomol. 29: 1096–1099.

Hardee, D. D., W. H. Cross, E. B. Mitchell, P. M. Huddleston, H. C. Mitchell, M. E. Merkl and T. B. Davich. 1969. Biological factors influencing responses of the female boll weevil to the male sex pheromone in field and large-cage tests. J. Econ. Entomol. 62: 161–165.

Hardee, D. D., W. H. Cross, E. B. Mitchell, P. M. Huddleston, and H. C. Mitchell. 1972. Capture of boll weevils in traps baited with males: effect of size, color, location, and height above ground level. Environ. Entomol. 1: 162–166.

Jones, D., and W. L. Sterling. 1979. Rate and thresholds of boll weevil locomotory activity in response to temperature. Environ. Entomol. 8: 874–878.

Leggett, J. E. 1984. Detection probability and efficiency of infield and border traps for capturing overwintering boll weevils (Coleoptera: Curculionidae) at low population levels. Environ. Entomol. 13: 324–328.

McKibben, G. H., J. L. Willers, J. W. Smith and T. L. Wagner. 1991. Stochastic model for studying boll weevil dispersal. Environ. Entomol. 20: 1327–1332.

Menne, M. J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R. S. Vose, B. E. Gleason, et al. 2012a. Global historical climatology network - daily (GHCN-Daily), Version 3. NOAA National Climatic Data Center. Asheville, NC. doi:10.7289/V5D21VHZ (accessed 30 June 2015).

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston. 2012b. An overview of the global historical climatology network-daily database. J. Atmos. Oceanic Technol. 29: 897–910.

Ridgway, R. L., J. P. Hollingsworth and D. L. Bull. 1976. Efficiency of boll weevil pheromone traps, pp. 16–19. *In* Detection and management of the boll weevil with pheromone. Texas Agric. Exp. Stn. Res. Monogr. No. 8. Texas A&M University, College Station, TX.

Roach, S. H., H. R. Agee, and L. Ray. 1972. Influence of position and color of male-baited traps on captures of boll weevils. Environ. Entomol. 1: 530–532.

Rosenberg, N. J. 1974. Microclimate: The biological environment. Wiley, New York, NY.

Rummel, D. R., and D. G. Bottrell. 1976. Relationship of overwintered boll weevil to pheromone traps and natural entry into cotton, pp. 26–31. *In* Detection and management of the boll weevil with pheromone. Texas Agric. Exp. Stn. Res. Monogr. No. 8. Texas A&M University, College Station, TX.

Rummel, D. R., J. R. White, S. C. Carroll, and G. R. Pruitt. 1980. Pheromone trap index system for predicting need for overwintered boll weevil control. J. Econ. Entomol. 73: 806–810.

SAS Institute. 2012. SAS release ed. 9.4. SAS Institute, Cary, NC.

Sappington, T. W. 2002. Mutual interference of pheromone traps with trap lines on captures of boll weevils (Coleoptera: Curculionidae). Environ. Entomol. 31: 1128–1134.

Sappington, T. W., and D. W. Spurgeon. 2000. Variation in boll weevil (Coleoptera: Curculionidae) captures in pheromone traps arising from wind speed moderation by brush lines. Environ. Entomol. 29: 807–814.

Spurgeon, D. W., and J. R. Raulston. 2006. Captures of boll weevils (Coleoptera: Curculionidae) in traps associated with different habitats. J. Econ. Entomol. 99: 752–756.

Stroup, W. W. 2013. Generalized linear mixed models: modern concepts, methods and applications. CRC Press, Boca Raton, FL.

Williams, M. R. 1996. 1995 survey of insect losses, pp. 101–103. *In* Proc. Beltwide Cotton Conference, National Cotton Council, Memphis, TN.

Williams, M. R. 2015. Cotton insect loss estimates – 2014, pp. 494–496. *In* Proc. Beltwide Cotton Conference, National Cotton Council, Memphis, TN.