Variation in Boll Weevil (Coleoptera: Curculionidae) Captures in Pheromone Traps Arising from Wind Speed Moderation by Brush Lines

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ABSTRACT Paired trap lines of five boll weevil pheromone traps each were placed on opposite sides of a brush line at six different sites on a plantation in the Lower Rio Grande Valley of Texas. Temperature, wind speed, and wind direction were monitored with a nearby weather station. We observed a strong negative relationship between mean daily wind speed and total daily capture of boll weevils. About half of the day-to-day variation in weevil captures was explained by wind speed alone. In addition, our data indicate that much of the variation between traps within days may arise from differences in local wind speed as governed by local vegetation depending on wind direction. Brush lines in this study slowed the wind by 40–70% and mitigated its effects such that traps on the leeward side averaged 2.5–2.9 times higher captures than traps on the windward side. The magnitude of the effect of windward or leeward placement of traps on weevil captures depended on the relative strength of the wind. Under light winds (<10 km/h), there were no increases in leeward trap captures. However, on days of moderate (10–20 km/h) or strong (>20 km/h) winds, leeward trap captures averaged 3.9- or 2.4 times greater than windward captures, respectively. By accounting for the ability of vegetation to dampen the effects of wind on boll weevil trap captures, we should be able to dampen daily and positional variation in trap captures by more careful placement of traps. Furthermore, judicious placement of traps in locations protected from prevailing winds should improve detection efficiency in areas where early warning of weevil presence is critical, such as in eradication and posteradication zones.

KEY WORDS boll weevil, *Anthonomus grandis*, pheromone trap, wind, sampling

TRAPS BAITED WITH the synthetic pheromone of the boll weevil, *Anthonomus grandis grandis* Boheman, are used extensively to detect and monitor populations and potential problem fields, and to guide treatment decisions (Ridgway and Inscoe 1996, Hardee and Mitchell 1997). Trapping is an integral part of the Boll Weevil Eradication Program (Ridgway and Inscoe 1996, Smith 1998), with capture thresholds employed to determine the need for and timing of insecticide applications (Hardee and Mitchell 1997). The ability of pheromone traps to efficiently detect low populations of weevils (Rummel et al. 1980, Walker 1984) is considered a key to eradication program success (Hardee and Mitchell 1997). Despite heavy reliance on pheromone traps to provide information on local boll weevil populations, relationships between trap capture and actual weevil population density have not been clearly established.

Variations in microclimatic conditions around individual traps are undoubtedly accountable for considerable intertrap capture variation (Jones et al. 1992). Quantification of the effects of environmental factors and their interactions on boll weevils captured in traps is important to efforts to optimize trap deployment, and to appropriate interpretation of capture data. Apart from the requirement of temperatures warm enough for flight, we reasoned that wind speed may be the most important meteorological variable affecting trap capture through its influence on the ability of weevils to approach the trap, because they are not strong fliers (McKibben et al. 1988, 1991). Nearby vegetation in turn moderates wind speed on the leeward side (Rosenberg 1974). We report here the results of an experiment designed to determine the effects of a nearby brush line on weevil captures relative to wind speed and direction.

Materials and Methods

Twelve trap lines were deployed in pairs parallel to six brush lines (sites) on a plantation south of San Benito, Cameron County, TX. Each trap line consisted of five Hercon 'Scout' traps (Hercon Environmental, Emigsville, PA) spaced 15 m apart. Each trap was baited with a 10-mg Hercon pheromone lure that was replaced weekly. At each site, paired trap lines were placed on opposite sides of the brush line, but were

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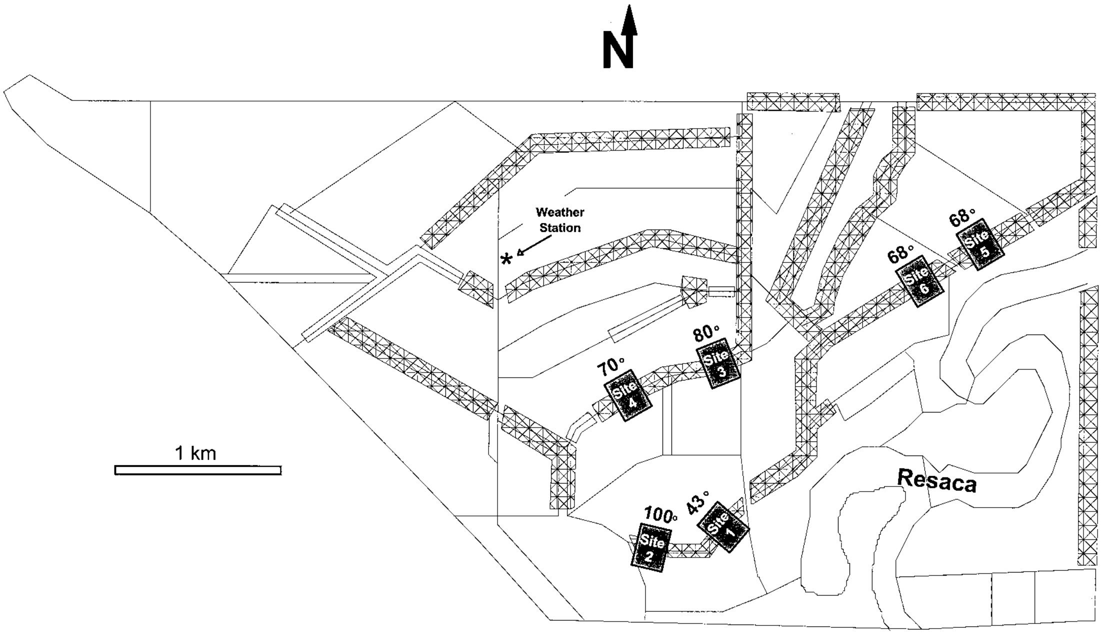

Fig. 1. Plantation locations of six paired trap lines (sites) along brushy drainage ditches. Clockwise compass orientation of brush lines is indicated in degrees from north. Cross-hatches indicate brush lines (width not to scale).

offset by 30 m rather than being directly abreast of each other. The traps were positioned flush with the edge of the brush line, and a space of ≈1-m radius around the trap was maintained clear of vegetation. Traps were checked before 0930 hours (CST) daily from 15 December 1998 through 19 March 1999, except on weekends and holidays or when muddy conditions prevented access. We assumed the majority of captured weevils were caught on the previous day, because peak boll weevil response to traps is at midday with only a small percentage captured before 1000 hours (Guerra 1983). Multiple-day captures were not included in the analyses. Captured weevils were sexed by the tergal notch method (Agee 1964), as described by Sappington and Spurgeon (2000).

Brush lines were oriented predominantly east–west to northeast–southwest and were roughly perpendicular to the prevailing winds (Fig. 1). Brush lines were ≈6–8 m wide, each harboring a drainage ditch, with vegetation consisting primarily of mesquite.

A weather station was placed in an open area within three km of all traps. Wind speed, wind direction, and temperature were measured at 2.5 m above the ground every 5 min, and means of these parameters were logged at 15-min intervals. Mean daily wind speed and mean daily wind direction were calculated from data collected between 0930 hours and sunset when the temperature was above 15°C, the approximate threshold for boll weevil flight (Fenton and Dunnam 1928, Gaines 1932, Jones and Sterling 1979). The effect of the brush lines on wind speed was monitored over several days during a 2-wk period by two small weather stations placed directly facing each other on opposite sides of the brush line at three sites (1, 3, and 5). Measurements were taken at the height of the traps (1 m) and were logged every minute.

Data Analysis. All analyses were performed with Statistix software (Analytical Software 1998). Unless otherwise indicated, all trap capture data were $\log_{10}(x + 1)$ transformed, because changes in animal populations tend to follow a geometric progression rather than arithmetic (Sappington and Showers 1983, Fry 1993). On any given day, each trap line of the pair at each site was designated as leeward or windward, depending on mean daily wind direction. However, if the wind direction was within 22.5° of brush line orientation, the traps were not so designated. The general effect of wind speed on trap capture was assessed with a linear regression of running means (of two consecutive values along the x-axis) (Tukey 1977) of total daily capture on mean daily wind speed. Use of running means facilitates exposure of fundamental underlying relationships, but it results in a loss of the data point at each extreme of the distribution on the x-axis. A differential effect of wind speed on trap captures depending on leeward or windward placement of trap lines was assessed by performing linear regressions of the partitioned data and comparing the slopes and distances between the two regression lines with *t*-tests.

Wind speed was categorized as light (<10 km/h), moderate (10–20 km/h), or strong (>20 km/h). Paired comparison *t*-tests were performed between total captures per day in leeward and windward traplines at each site across wind-speed categories and for the sexes both combined and separate. Fold-differences were calculated by dividing the larger of respective windward or leeward values (nontransformed) by the smaller (1 was added to all values to prevent division by 0). If the larger value was the leeward, the ratio was assigned a positive value, otherwise the ratio was assigned a negative value. Thus, fold-differences were ≥1 or less than -1; a fold difference of 1 signified no difference in capture between windward or leeward traps. Statistical significance of fold-differences (different from 1) were facilitated by subtracting 1 from, or adding 1 to, positive and negative fold-differences, respectively, to scale the values to 0. The scaled values were then examined for difference from 0 using a 1-sample t-test. Multiple comparisons of means were made using a Kruskal–Wallis test (Kruskal and Wallis 1952). Any cases in which the captures for both windward and leeward traps were 0 were omitted from the analyses.

The effects of brush lines on wind speed were assessed by regression analyses, with leeward wind speed designated as the dependent variable and windward wind speed the independent variable, for wind direction categories across the three sites where wind speed was monitored. Cases in which wind direction was within 33.75° of parallel to the brush line were omitted from the analyses.

Results

We observed a strong negative relationship between mean daily wind speed and daily capture of boll weevils in pheromone traps (Fig. 2A). Slopes of the regression lines generated from leeward and windward capture data across all sites (Fig. 2 B and C) were not different (t = 1.13, P < 0.26). However, the average distance between the lines (0.40log10) was significantly different from zero (t = 3.18, P < 0.002), indicating that captures in traps positioned on the leeward side of a brush line were on average 2.5 times greater than captures in windward traps.

Paired comparisons of numbers of weevils captured in traps on windward and leeward sides of brush lines indicated that increases observed on the leeward side were significant (Table 1). Overall, a mean fold difference of 2.8 was observed between leeward and windward captures when the paired trap lines at the six sites were examined separately (Table 2). This difference is consistent with the 2.5-fold difference calculated from the regression analyses. The magnitude of the effect of windward or leeward placement of traps on weevil captures depended on the relative strength of the wind (Tables 1 and 2). There were no increases in weevil captures on the lee sides of brush lines when winds were light. However, the increases in leeward captures on days with moderate or strong winds were significant for each sex and for sexes combined (Table 1). The fold-increases in leeward boll weevil captures on days with strong winds (2.0- to 2.4-fold) were numerically less than those on days with winds of moderate strength (2.9- to 3.9-fold), but these differences were not significant for either sex or for sexes combined (Table 2). Differences between sexes in the fold-increase of captures were not significant for any wind strength category, indicating trap

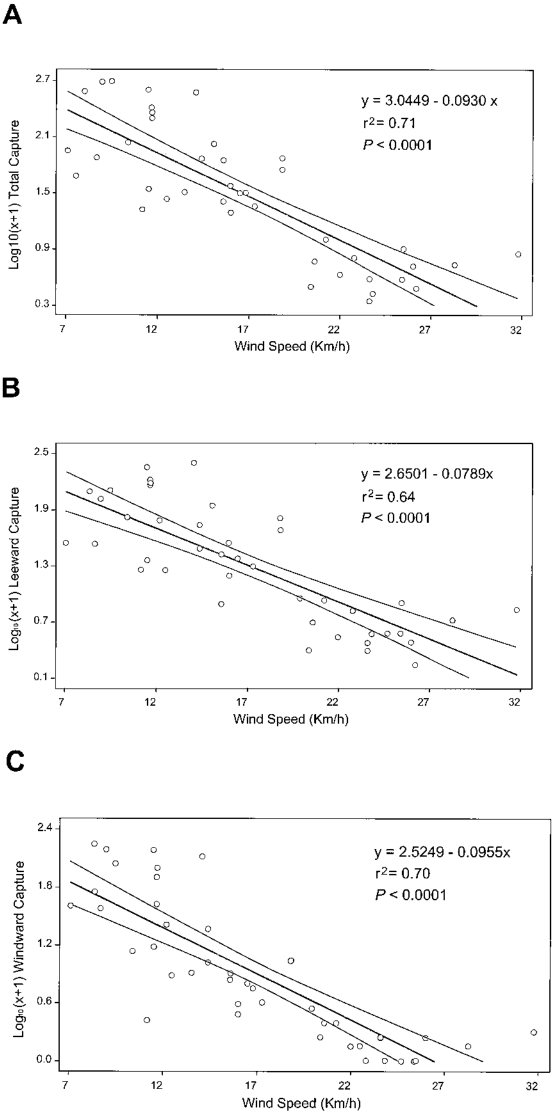

Fig. 2. Linear regressions of running means (of two along the x-axis) of $\log_{10}(x + 1)$ daily captures on mean daily wind speed. (A) Total daily capture from all traps on both sides of the brush lines. MSE = 0.1617. (B) Daily capture from all traps on the leeward side of brush lines. MSE = 0.1530. (C) Daily capture from all traps on the windward side of brush lines. MSE = 0.1372.

responses of the sexes were similarly influenced by wind speed.

Wind speeds on the windward and leeward sides of the brush lines were directly and linearly related, with leeward winds averaging ≈60% of winds on the windward side (Fig. 3A). However, differences between the two sides were significantly less when the density of vegetation in the brush line was relatively light (traps easily visible across the brush line; sites 3 and 4) than when it was moderate (sites 1 and 2) (t = 2.28, df = 36, P = 0.03) or relatively heavy (traps not visible

Table 1. Effect of windward or leeward position of pheromone traps on daily $Log_{10}(x+1)$ captures (±SE) of boll weevils under different categories of wind strength

Winds		Total	Male	Female
All	Windward	0.59 ± 0.040	0.49 ± 0.038	0.53 ± 0.037
	Leeward	0.84 ± 0.037[a]	0.72 ± 0.034[a]	0.73 ± 0.036[a]
	n	247	206	214
Light	Windward	1.04 ± 0.080	0.82 ± 0.071	0.87 ± 0.075
	Leeward	1.04 ± 0.077	0.81 ± 0.067	0.88 ± 0.072
	n	66	62	63
Moderate	Windward	0.54 ± 0.047	0.42 ± 0.045	0.46 ± 0.042
	Leeward	0.88 ± 0.049[a]	0.77 ± 0.043[a]	0.75 ± 0.045[a]
	n	139	115	125
Strong	Windward	0.08 ± 0.023	0.05 ± 0.023	0.08 ± 0.027
	Leeward	0.38 ± 0.033[a]	0.34 ± 0.031[a]	0.32 ± 0.033[a]
	n	42	29	26

Light winds, <10 km/h; moderate winds, 10–20 km/h; strong winds, >20 km/h.
[a] Difference in paired-capture means is significant (paired-comparisons *t*-test, $P < 0.01$).

across the brush line; sites 5 and 6) ($t = 7.41$, df = 42, $P = 0.0001$) (Fig. 3B). The ability of a brush line with moderately dense vegetation to block the wind was significantly less than for densely vegetated sites ($t = 6.43$, df = 42, $P = 0.0001$).

If observed increases in leeward trap captures of boll weevils under moderate and strong winds (Tables 1 and 2) were caused by decreased wind speeds on the leeward sides of the brush lines (Fig. 3A), differences in the ability of brush lines of various densities to block the wind (Fig. 3B) should cause differential captures on their lee sides. This was the case under moderate and strong winds (Table 3), with average captures of weevils on the leeward side of heavy brush lines being significantly greater (critical $Z = 2.39$, $P = 0.02$) than those on the leeward side of light brush lines. The fold-difference in captures between windward and leeward sides was significant for days with moderate wind speeds, regardless of the relative density of the vegetation in the brush lines (Table 4).

Discussion

Difficulty in directly relating pheromone trap data to boll weevil populations in adjacent fields arises from high variability in weevil response and trap efficiency among seasons, days within seasons, and traps within days. Seasonal variation is somewhat predictable. In temperate regions, weevil captures peak in early spring as daily temperatures rise and weevils emerge from overwintering habitat (Ridgway et al. 1971, Rummel et al. 1977, Merkl and McCoy 1978, Lopez 1980,

Table 2. Mean fold-differences (±SE) in pheromone trap captures of boll weevils between paired trap lines on leeward and windward sides of brush lines exposed to different categories of wind strength

Winds	Total	Male	Female
All	2.8 ± 0.34	2.6 ± 0.29	2.3 ± 0.23
n	247	206	214
Light	−1.1 ± 0.23a	−1.3 ± 0.28a	1.1 ± 0.24a
n	66	62	63
Moderate	3.9 ± 0.57b	3.7 ± 0.46b	2.9 ± 0.36b
n	139	115	125
Strong	2.4 ± 0.27b	2.2 ± 0.22b	2.0 ± 0.23ab
n	42	29	26

Light winds, <10 km/h; moderate winds, 10–20 km/h; strong winds, >20 km/h. Absolute values of means within a column (excluding the all winds row) followed by the same letter are not significantly different (Kruskal–Wallis test, $P < 0.05$).

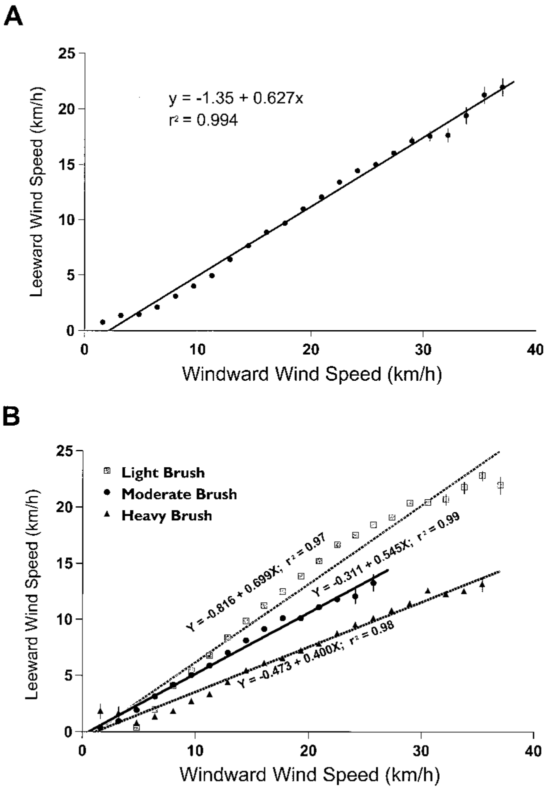

Fig. 3. Linear regressions of wind speed measured on the leeward side of brush lines on windward wind speed. Each point is the mean of 5 to >100 observations. Vertical lines are standard error bars. Points without standard error bars are those standard errors that are less than the height of the symbol. (A) Data from all three brush lines combined. (B) Regressions calculated separately for each of the three sites tested.

Table 3. Effect of windward or leeward position of pheromone traps across brush lines of indicated relative density on daily $Log_{10}(x+1)$ captures (±SE) of boll weevils under different categories of wind strength

Winds		Brush: Light	Moderate	Heavy
All Winds	Windward	0.59 ± 0.070aB	0.57 ± 0.069aB	0.62 ± 0.067aB
	Leeward	0.73 ± 0.066aA	0.88 ± 0.063aA	0.88 ± 0.064aA
	n	74	85	88
Light	Windward	0.95 ± 0.147aA	1.13 ± 0.123aA	1.05 ± 0.148aA
	Leeward	1.01 ± 0.125aA	1.21 ± 0.122aA	0.88 ± 0.152aB
	n	24	23	19
Moderate	Windward	0.51 ± 0.073aB	0.44 ± 0.077aB	0.65 ± 0.086aB
	Leeward	0.70 ± 0.081aA	0.85 ± 0.080abA	1.04 ± 0.084bA
	n	39	50	50
Strong	Windward	0.08 ± 0.042aA	0.03 ± 0.025aB	0.11 ± 0.041aB
	Leeward	0.22 ± 0.042aA	0.38 ± 0.037abA	0.47 ± 0.054bA
	n	11	12	19

Light winds, <10 km/h; moderate winds, 10–20 km/h; strong winds, >20 km/h. Means within a row followed by the same lower-case letter are not significantly different (Kruskal–Wallis test, $\alpha = 0.05$).

Means for windward and leeward captures followed by the same upper-case letter within wind and brush density categories are not significantly different (paired-comparison *t*-test, $P < 0.05$).

Carroll and Rummel 1985). Weevil captures are predictably low during midseason when the cotton is fruiting and weevil populations are increasing (Rummel and Bottrell 1976, Wolfenbarger et al. 1976, Lopez 1980, Segers et al. 1987), probably because trap competitiveness is reduced by increased pheromone production by males when squares are abundant (Hardee et al. 1970, Rummel et al. 1977). There is some evidence that the altitudinal distribution of flying weevils varies with the season (Taft and Jernigan 1964, Rummel et al. 1977). Although the interplay between pheromone plume, height of weevils above the pheromone trap, and variation in responsiveness of weevils to pheromone with physiological state are unknown, seasonal differences in altitudinal distribution may also be a source of seasonal variation in weevil captures.

Daily variation in weevil captures is generated by synoptic weather conditions that affect weevil behavior, such as temperature (Hopkins et al. 1971, Roach et al. 1971b, Guerra et al. 1982, Rummel et al. 1987) and possibly rain, heavy dew, and cloudiness (Hardee et al. 1969, Rummel and Bottrell 1976, Guerra 1983, Rummel et al. 1987). Wind is often postulated as a factor that causes daily fluctuations in trap captures (Rummel and Bottrell 1976, Carroll and Rummel 1985, Jones et al. 1992). Boll weevils are weak fliers, with a maximum flight speed of <4.8 km/h estimated from flight mill studies (McKibben et al. 1991), although their actual speed may be somewhat greater in free flight. Because response to a pheromone trap is necessarily upwind, wind speeds greater than the flight speed of the weevil would inevitably interfere with its ability to approach a trap. Hardee et al. (1969) reported that boll weevil movement to traps appeared to be deterred by winds >7 km/h. Our data indicate that average daily wind speed has a linear negative effect on boll weevil capture on a given day (Fig. 2A), and that about half of the day-to-day variation observed in trap captures can be explained by wind speed alone ($r^2 = 0.50$ without using running means).

Table 4. Mean fold-differences (±SE) in pheromone trap captures of boll weevils between paired trap lines on leeward and windward sides of brush lines of indicated relative density exposed to different categories of wind strength

Winds	Brush: Light	Moderate	Heavy
All	1.8 ± 0.30	3.4 ± 0.71	3.2 ± 0.59
n	74	85	87
Light	1.2 ± 0.44a	1.3 ± 0.23a	−1.9 ± 0.45a
n	24	23	63
Moderate	2.4 ± 0.48b	4.6 ± 1.18b	4.4 ± 0.97b
n	39	50	50
Strong	1.5 ± 0.28ab	2.4 ± 0.27ab	2.9 ± 0.52ab
n	11	12	19

Light winds, <10 km/h; moderate winds, 10–20 km/h; strong winds, >20 km/h.

Absolute values of means −1 within a column followed by the same letter are not significantly different (Kruskal–Wallis test, $P < 0.05$).

However, weevil response to traps on days of moderate and high winds is not nil (Fig. 2A). Part of this response can be attributed to temporary lulls in the wind during the day. We have observed an almost immediate increase in boll weevil response to pheromone-baited sticks during momentary calms on windy days, followed by an abrupt cessation of response as the wind resumed (unpublished data). But our data strongly suggest that decreases in wind speed caused by the microenvironment of the trap can contribute substantially to the response as well. On average, 2.5–2.8 times more weevils were captured per day in traps located on the lee side of brush lines (Fig. 2 B and C; Table 2). Under moderate winds, the increase averaged 3.5- to almost fourfold (Tables 2 and 4). Slosser et al. (1984) measured a decrease in wind speed of ≈75–80% on the lee side of a shelterbelt consisting of one row each of red cedar, red mulberry, and Siberian elm in the northern Rolling Plains of Texas on two days when the winds averaged 16 and 27 km/h, respectively. The brush lines in our experiment decreased wind speed by ≈40–70% depending on the density of the brush (Fig. 3). On days with wind speeds > 10 km/h, the number of weevils captured on the lee side of a brush line was greater along brush lines of greater density (Table 3). Consequently, day-to-day variation in the numbers of weevils captured in a given pheromone trap can arise not only from daily changes in wind speed, but also from changes in wind direction if the trap is positioned near vegetation that can potentially moderate the wind.

Brush lines can influence airflow and the microclimate around traps in other ways that may contribute to differential captures of boll weevils. Aerial density of insects tends to increase in a relatively calm zone located beneath the shear layer of fast moving air on the lee side of a windbreak (Lewis and Dibley 1970). The insects accumulating in this calm zone may include those blown over the vegetation, or in the case of larger insects, may include those blown through a permeable barrier (Lewis 1969). Lewis and Stephenson (1966) observed that aerial density of small insects behind solid barriers range from two to eight times greater than on the windward side, but that this effect is less behind more permeable barriers. This is consistent with the range of increases (2- to 4.5-fold) in boll weevil captures we observed on the lee side of the permeable brush lines used in this study. In addition to the effects on wind, windbreaks tend to increase temperature and humidity, and to decrease rate of evaporation on the lee side (Read 1964), all factors which may affect boll weevil activity and response to pheromone traps. Future studies will attempt to address some of these issues.

It is possible that the observed decreases in boll weevil captures on the windward side of brush lines was caused by a disruption of the pheromone plume by the vegetation; weevils approaching from downwind must cross the brush line to approach the traps. However, this explanation seems unlikely, because on days with light winds, captures on the leeward and windward sides of the brush lines were similar, even though the weevils presumably continued to approach the windward traps across the brush line.

Hardee et al. (1972) found that weevil response to traps placed 1.5–15 m inside the border of a wooded area was similar to response to traps located in an adjacent clearing, suggesting that vegetation may not disrupt the pheromone plume excessively in any event. In addition, the lesser fold-increase in leeward captures under strong winds compared with moderate winds is consistent with the idea that the greater the difference between wind speed and weevil flight speed, the more difficult it is for weevils to approach the trap. It is more difficult to explain how differential effects of wind speed on pheromone plume disruption by the brush line could account for the observed differential captures correlated with wind speed.

In addition to variation among days, variation in captures among traps within days is often considerable, even when the traps are located near one another (Hollingsworth et al. 1978, Taft and Hopkins 1978, Leggett et al. 1988, Jones et al. 1992). The sources of such variation are harder to identify than are factors generating seasonal and day-to-day variation. Consequently, position effects are difficult to predict when placing traps in the field and difficult to account for when interpreting trap data. Position effects are frequently attributed to the proximity of traps to boll weevil overwintering habitat (Roach et al. 1971a, 1972; Mitchell et al. 1977; Guerra and Garcia 1982), and hence to a clumped distribution of the weevils (Boyd et al. 1973). Decisions on initial placement of traps are sometimes guided by the layout of potential overwintering habitat around a field (Rummel et al. 1980, Benedict et al. 1985, Carroll and Rummel 1985). However, our results indicate that such position-related variation can arise from differences in local wind speed as governed by local vegetation, depending on wind direction, independent of any variation caused by a discontinuous distribution of weevils. Thus, caution must be exercised before concluding that large boll weevil captures in traps positioned near woods and brush indicate movement into or out of overwintering habitat, because the increased captures may arise instead from the ability of that habitat to shield the pheromone trap from wind. For example, 70% of >1 million boll weevils captured from 1979 to 1980 near Brownsville, TX, were taken in traps along the wooded south and north sides of a field (Guerra and Garcia 1982). When the woods were removed in 1981, captures became evenly distributed along the different sides of the field. Total captures in the field were similar in all three years (454,000, 622,000, and 563,000, 1979–1981, respectively), suggesting that the primary influence of the woods on captures was likely their effect on the microclimate surrounding nearby traps.

By accounting for the ability of brush lines to dampen the effects of wind on boll weevil trap captures, we should be able to dampen daily and positional variation in trap captures by more careful placement of traps. Consistently placing traps in the open will have this effect, but will result in decreased total captures and more days with zero captures because of their complete exposure to the wind. If the prevailing winds are fairly regular, such as the southeasterly winds of the Lower Rio Grande Valley, the positioning of all traps on the leeward side of brush or tree lines may serve to stabilize trap captures. Another strategy, if traps are serviced daily, is to place traps as pairs on opposite sides of brush lines and use data only from the trap with the highest capture.

Our results also have implications where detection of very low populations of weevils is critical, such as in suppression or eradication programs or in posteradication maintenance. By judiciously placing traps in locations protected from prevailing winds, the probability of catching a lone weevil in the vicinity will be improved by approximately threefold. If such improved detection efficiency resulted in earlier detection, and more accurate delineation of the infested area, economic and environmental costs associated with corrective pesticide treatments could be minimized.

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