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Proceedings

Reynolds, H. T. 1985. Pesticides: a dependable component of IPM, pp. 21-24. *In* Proceedings, Regional workshop on pesticide management, Nairobi, Kenya, 128 pp.

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Reports

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Colorado Agricultural Experiment Station. 1989. Annual report. Colorado State University, Ft. Collins, 62 pp.

Webster, J. A. & D. H. Smith, Jr. 1983. Developing small grains resistant to the cereal leaf beetle. United States Department of Agriculture Technical Bulletin 1673, Washington, D.C., 12 pp.

Young, D. A. 1986. Taxonomic study of the Cicadellinae (Homoptera: Cicadellidae). Part 3: Old World Cicadellinae. North Carolina Agricultural Experiment Station Technical Bulletin 281, Raleigh, 639 pp.

In Press

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International Rice Research Institute (IRRI). 1977. Title. International Rice Research Institute, Manila. Philippines, 336 pp.

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Abstracts and Translations

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Hooker, M. W. & E. M. Barrows. 1989. Clutch sizes and sex ratios in *Pediobius*. Ann. Entomol. Soc. Am. 82: 460 (abstr.)

Shenderovskaya, L. P. 1979. Introduced insect enemies and microorganisms. Zash. Rast. (Kiev) 3: 52-56 (in Russian).

Shenderovskaya, L. P. 1979. Introduced insect enemies and microorganisms. Zash. Rast. (Kiev) 3: 52-56. (translated in OTS 61: 31267), U. S. Department of Commerce, Washington, D.C.

Magazine Articles

Headley, J. C. 1979. Economics of pest control. Chem. Eng. News, Jan. 15, pp. 55-57.

Other

Code of Federal Regulations. 1986. Title. 7 CFR Chapter III, Section 318.13-46, pp. 128-129.

SAS Institute. 1985. SAS user's guide: statistics, version 5 ed. SAS Institute, Cary, North Carolina, 956 pp.

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Seasonal Occurrence of Alate Hop Aphids (Homoptera: Aphididae) in Washington State[1]

Lawrence C. Wright, Keith S. Pike,
David Allison and Wyatt W. Cone

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J. Agric. Entomol. 12(1): 9-20 (January 1995)

ABSTRACT The hop aphid, *Phorodon humuli* (Schrank), is a serious pest of hop, *Humulus lupulus* L., during the summer and overwinters on plums, *Prunus* spp. To determine the seasonal timing of the spring and fall hop aphid flights, hop aphids were monitored on *Prunus* leaves and by suction trap. The start of spring flight, indicated by the first date that fourth instar hop aphids with wing pads (alatoid IV instars) were found on *Prunus*, ranged from 7 May to 16 May, 1989 to 1991. The last date that alatoid IV instars were found on *Prunus*, marking the end of spring migration, ranged from 16 July to 7 August, 1989 to 1991. Hop aphids were found on *Prunus* throughout the summer in 1989, indicating that the aphids can live on *Prunus* throughout the year. In suction trap catches from 1984 to 1993, the average date when the first hop aphids of the autumn flight were trapped was 3 September for gynoparae (winged females) and 3 October for males. Fall flight started when daylength was about 13.5 h, but accumulated degree-days were also related to the start of flight. In the fall, the suction trap caught more gynoparae than males and more gynoparae than males were collected from hop leaves, indicating that males mate with more than one female. A suction trap in a hop growing area caught more aphids during the fall flight than in the spring flight, but a suction trap in a non-hop growing area caught more hop aphids during the spring flight.

KEY WORDS Insecta, Homoptera, Aphididae, *Phorodon humuli,* hop aphid, *Humulus lupulus*, hops, *Prunus*, life cycle.

The hop aphid, *Phorodon humuli* (Schrank), overwinters in the egg stage on species of ornamental and fruit plums, *Prunus* spp. The eggs hatch in February and March (L. C. W., unpublished data) and aphids feed on buds and leaves of *Prunus* until their flight to hops, *Humulus lupulus* L., which occurs from mid-May through mid-July and sometimes into August (Born 1968, Micinski & Ruszkiewicz 1974, Aveling 1981). Only wingless viviparae are produced on hops during the summer (Campbell 1985), which means that with the possible exception of the spring

[1] Accepted for publication 16 December 1994.

migrants, there is no dispersal by flight from infested hops. Hop is the only important secondary host of the hop aphid (Born 1968, Miciński & Ruszkiewicz 1974, Palmer 1952, Taylor et al. 1979, Knowlton 1983, Eppler 1986). In the fall, gynoparae (winged females) appear and fly back to *Prunus* where they give birth to oviparae (egg-laying females). The oviparae mate with male aphids, which have flown from hops, and lay eggs, thereby completing the life cycle. The main objective of this study was to determine when the seasonal flight of the hop aphid occurred by monitoring when male and female alate (winged) morphs of the hop aphid were present during the spring, summer and fall seasons in the Yakima Valley of Washington State.

Materials and Methods

Spring flight. In early May of 1989, we found seven locations in the lower Yakima Valley of Washington State that each had one or two *Prunus* trees infested with hop aphids. Three residences and one research farm had ornamental varieties and three of the locations were commercial fruit orchards. Up to 10 infested shoots were labeled per tree and the aphids were counted on those shoots as long as the aphids remained. If a shoot had no aphids for one or two weeks, it was replaced with an infested shoot from the same tree, if one could be found. Only infested shoots were observed: the data were not intended to be a measure of the number of aphids in the area. Aphids were counted weekly from 10 May to 11 October except for the weeks of 24 and 31 July, 18 and 25 September and 2 October. From 10 to 25 May, aphid numbers were recorded as the number per shoot. Measurements taken after 25 May were shoot length, number of leaves per shoot, total number of aphids, number of alatoid IV instars (fourth instar nymphs with wing pads) and number of wingless IV instars on each leaf. A 10X hand lens was used to count aphids. Aphid counts from all locations were combined each week to obtain weekly means and standard errors of the means. Alatoid IV instars were counted to indicate the occurrence of flying aphids. Alate adults were not used because they leave *Prunus* trees soon after becoming adults. The species of trees that were sampled in the three years were *P. cistena*, *P. spinosa*, *P. blireiana*, *P. domestica* and *P. cerasifera*.

Weekly observations were continued in 1990 at seven locations but only three of them were the same as in 1989. One commercial fruit orchard, and six locations with ornamental varieties were used. One to six trees were sampled at each location for a total of 14 trees and up to 11 shoots per tree. We sampled each week from 10 May to 2 August 1990 except for the week of 25 June. We counted the total number of aphids and the number of alatoid IV instars per shoot.

Six of the seven locations sampled in 1990 were sampled again in 1991; the commercial orchard was replaced with two ornamental trees at a residence. We counted aphids weekly from 7 May to 26 August except that no sampling was done the week of 19 August. One or two trees were sampled at each location for a total of 11 trees. Up to nine shoots were sampled per tree. Data recorded were the same as in 1990.

To determine if production of alates was related to aphid density, we did a linear regression (Steel & Torrie 1960) of the percent of IV instars that were alatoid (dependent variable) on the log of the total number (all morphs) of IV instars per shoot (independent variable) using the weekly 1989 data for each regression. Similar regressions were done with the 1989, 1990 and 1991 data but we used the percent of the total aphids that were alatoid IV instar (dependent variable) on the log of the total number of aphids per shoot (independent variable). Significant regressions with positive slopes indicated that the production of alates increased with increased aphid density, which was interpreted as evidence of density-dependence.

Celsius degree-days were calculated to determine if some events in the life cycle of the aphid were related to degree-days. The computer program DEGDAY (Higley et al. 1986) was used to calculate degree-days by the sine wave method using temperature data from a weather station located 5 km N. of Prosser, Washington. The 7.5°C developmental minimum of hop aphids on hops (Perju et al. 1979) was used because no minimum is known on *Prunus*. The developmental maximum is not known, so none was used in the degree-day calculations. Degree-days were accumulated each year from 1 February (the approximate date of the start of egg hatch) for spring and summer observations on *Prunus* and from 1 June for the fall flight monitored by the suction trap.

To determine the relationship between degree-days (accumulated from 1 February) and population growth rate of aphids on *Prunus*, linear regressions (Steel & Torrie 1960) were done for each year using degree-days as the independent variable and the log mean number of aphids per shoot per date as the dependent variable. Data from the start of sampling to the peak number of aphids for each season were used in the regressions. The slope, *b*, of each regression was used as a measure of the rate of population increase. A test of the homogeneity of two *b*'s (Steel & Torrie 1960) was used to determine the statistical difference between *b*'s.

Fall flight. Hop aphids were collected in two 8 m tall suction traps (Allison and Pike 1988). One trap was located in a hop growing area 5 km north of Prosser, Washington. Aphids were collected with this trap from 1984 through 1993. The other trap was in a non-hop growing area 2 km north of Vancouver, Washington and was operated from 1987 through 1993. Aphids were removed from the traps weekly starting in April and continuing through the end of October at the earliest and into December in some years. Total numbers for a trapping period were divided by the number of days in the period to get the average number of aphids trapped per day.

As a supplement to the suction trap data, adult alate hop aphids were aspirated off hop leaves in the autumns of 1989 and 1990 to determine aphid sex ratio and to establish when gynoparae and males appear but not to quantify aphid abundance. Aphids were collected from unharvested hop plants at five sites near Prosser, Washington on two or three days per week from 14 September to 17 October 1989. In 1990, aphids were collected on three days per week at each of two locations. Collecting started on 31 August and ended on 29 October 1990 in the Yard I hop yard. At the King-Tull hop yard, collecting started on 19 September and ended on 22 October,

1990. In both years, all of the alate aphids were aspirated off each leaf examined and collections continued until frost killed the leaves causing the end of the aphid populations on hops. We tried to collect at least 100 alate aphids from each site on each sampling day. The numbers of alate female and male aphids were counted on each sampling date.

Results and Discussion

Location of aphids on *Prunus* spp. shoots. Hop aphids were located on the young leaves near the distal ends of *Prunus* shoots until mid-August, 1989 (Fig. 1). Later in the season, the aphids were found on leaves located closer to the bases of the shoots. This change in location coincides with the beginning of the fall flight of gynoparae from hops to *Prunus*. Therefore, it appears that the spring and summer populations on *Prunus* preferred the younger leaves near the shoot tips but the fall populations of gynoparae and oviparae preferred older *Prunus* leaves near the bases of the shoots. This change in location is probably a response to food quality. In general, the young leaves of trees and shrubs in the spring are more nutritious to aphids than mature leaves that predominate in mid-summer. In the fall, food quality increases as leaves get older and senescent (Kennedy & Booth 1951, Dixon 1985).

Occurrence of alatoid IV instars on *Prunus* spp. in spring and summer. The first alatoid IV instars were found on 16 May 1989 (397 degree-days), 10 May 1990 (378 degree-days) and 7 May 1991 (283 degree-days). Alatoid IV instars were found on the first sampling dates in 1990 and 1991, so the first appearance cannot be accurately determined in those years. In Germany, the date that the first alate hop aphids were found on hops ranged from 10 May to 5 June in a four year study (Born 1968). Hop aphids first appeared in suction traps in England between 13 May and 6 June in 15 years of trapping (Thomas et al. 1983). The beginning of migration in England was accurately predicted from maximum temperatures in late March: higher temperatures corresponded to earlier appearance (Thomas et al. 1983). In Poland, aphids were first found on hops on 23 May to 27 May in three years of observations (Miciński & Ruszkiewicz 1974). The dates from Europe generally were later than we found, probably because of temperature differences and because of different monitoring methods. The beginning of aphid flight in the spring is variable and appears to be dependent, at least in part, upon weather.

On *Prunus*, the total number of hop aphids per shoot increased to a maximum in mid-June to mid-July (Fig. 2). The peak in the number of alatoid IV instars was about one week later than the peak in total aphids in 1989 and 1990. In 1991, the number of alatoid IV instars stayed at a relatively high number from early June to late July.

Regressions of the percentage of alatoid IV instars on the total number of IV instars per *Prunus* shoot were statistically significant ($P < 0.05$) with positive slopes in four of the 10 dates in 1989 with R^2 values ranging from 0.250 to 0.579. Regressions on three of the five dates after the middle of June were significant. Regressions of the percentage of alatoid IV instars on

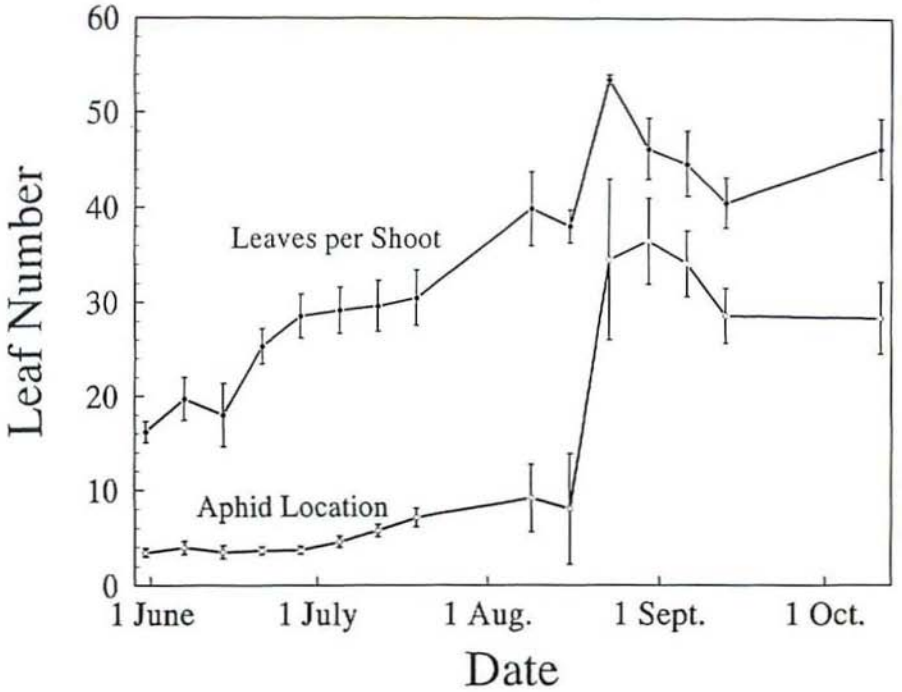


Fig. 1. Mean number of *Prunus* leaves per shoot and mean location of aphids on shoots during the 1989 season. Leaf numbering started at the shoot tip. Vertical bars represent the standard errors of the means.

the total number of aphids per shoot were statistically significant with positive slopes on 10 of 30 dates in the three years combined. The R^2 values of these regressions ranged from 0.038 to 0.643. Two of the 30 regressions were significant with negative slopes. Overall, more regressions were statistically significant late in the season than early. Although some significant relationships were found and most of the slopes were positive, the results were not consistent and are not conclusive in showing that the production of alates on *Prunus* was density-dependent.

The latest date when alatoid IV instars were found on *Prunus* was quite variable from year to year. Alatoid IV instars were last found on: 7 August 1989 (1,381 degree-days), 16 July 1990 (1,111 degree-days) and 31 July 1991 (1,173 degree-days). The mean date was 28 July (mean Julian date = 209.3, SEM = 6.49 days) and the mean number of accumulated degree-days was 1,222 (SEM = 81.65). Variation in the dates (absolute value of the observed date for each year - mean date) was 25 days ($\overline{\chi}$ = 8.33 days). Variation using degree-days (absolute value of the observed date for each year - the date when 1,222 degree-days were accumulated) was 21 days ($\overline{\chi}$ = 7.0 days). Therefore, using degree-days resulted in slightly less variation than the

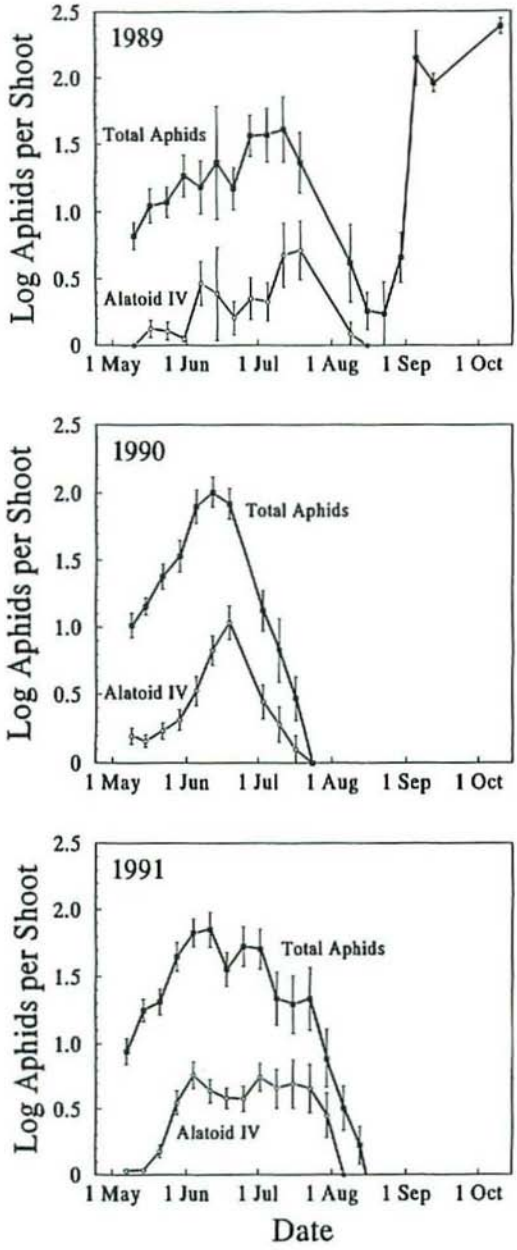


Fig. 2. Log mean number of aphids per shoot and log mean number of alatoid IV instars per shoot on *Prunus* through the 1989, 1990 and 1991 seasons. Vertical bars represent the standard errors of the means.

mean date. Thomas et al. (1983) found that the end of spring migration was related to temperature. Kríz (1966) reported that the production of alates and the end of migration from *Prunus* was related to food quality, which declined as leaves matured. Degree-days may predict the end of the spring aphid flight more accurately than the mean date, but many more years of data are needed to develop and test this method.

In 1989, we found hop aphids on *Prunus* on every sampling date from summer into the autumn (Fig. 2). Hop aphids have been found on *Prunus* or in suction traps all summer and into the autumn in the Rocky Mountain region (Palmer 1952), Germany (Born 1968), Norway (Stenseth 1970) and England (Aveling 1981). Gynoparae, but not males, were produced on *Prunus* in Norway, indicating that aphids can not complete their life cycle on *Prunus* alone. We conclude that the hop aphid can infest *Prunus* the year round but that the aphids disappear from *Prunus* in late summer in most years. The aphids that stay on *Prunus* in late summer probably have little importance in the population dynamics of the hop aphid in hop growing areas because of the small numbers of aphids on *Prunus* compared to the much larger numbers of aphids on hops at that time.

Population growth rate on *Prunus* spp. The regression of log mean number of aphids per *Prunus* shoot per date on accumulated degree-days was highly significant each year (1989: $a = 0.594$, $b = 0.001$, $R^2 = 0.836$, $F = 40.71$, 1,8 df, $P < 0.001$; 1990: $a = -0.534$, $b = 0.0041$, $R^2 = 0.980$, $F = 191.99$, 1,4 df, $P < 0.001$; 1991: $a = 0.024$, $b = 0.0035$, $R^2 = 0.924$, $F = 48.69$, 1,4 df, $P < 0.005$.). The 1989 b was significantly different from that of 1990 ($t = -6.468$, 12 df, $P < 0.001$) and 1991 ($t = -4.977$, 11 df, $P < 0.001$) but the 1990 b was not different from that of 1991 ($t = 0.995$, 8 df, $P > 0.20$). Therefore, the aphid populations in 1989 grew more slowly with respect to degree-days than the 1990 and 1991 populations, but the growth rate in 1990 was not different from the 1991 rate. This indicates that within a year, population growth rate was closely related to accumulated degree-days, but the rate varied among years. Using different species of *Prunus* in different years may have been a factor in the variation in growth rate among years.

Occurrence of alate hop aphids in the autumn. The date when the first gynopara was caught in the Prosser suction trap ranged from 27 August to 12 September in 10 years of trapping (Fig. 3) ($\bar{\chi}$ = 3 September, SEM = 1.58 days, $n = 10$). There was an average of 1,244 accumulated degree-days at that time (range = 1,111 to 1,385, SEM = 28.41, $n = 10$). The average date of capture of the first male was 3 October (range = 28 September to 13 October, SEM = 1.52 days, $n = 9$). The mean accumulated degree-days when the first male was trapped was 1,493 (range = 1,395 to 1,556, SEM = 21.36, $n = 9$). According to Campbell (personal communication cited in Neve 1991), gynoparae are produced when the daylength falls below about 13.5 h, but this daylength threshold is inversely related to temperature: gynoparae appear earlier (at longer daylengths) if cool temperatures prevail. In the Yakima Valley, the daylength first falls below 13.5 h on 29 August (Russelo et al. 1974), five days before the mean first appearance of gynoparae in the suction trap. In Germany and Poland, at 52^{0} latitude, daylength is 13.5 h on 3 September (Russelo et al. 1974) (Julian date = 246), which was the average

date of the first observation of gynoparae in those two countries combined (Born 1968, Miciński & Ruszkiewicz 1974) (mean Julian date = 246.29, SEM = 2.39, n = 7). We found a weak linear relationship between the date when the first gynopara was trapped at Prosser and degree-days (Julian date = 208.53 + 0.031 degree-days, r^2 = 0.310, F = 3.597, P = 0.094, 1,8 df). This suggests that the gynoparae appeared earlier in years with lower accumulated degree-days. We found no significant linear relationship between the first appearance of males in the trap and degree-days. Our data, and that from Europe, support Campbell's (Neve 1991) report that the start of the flight of gynoparae is related to daylength and temperature.

In Washington, there was a weak, inverse correlation between the date when the first gynoparae were caught in the suction traps and the total number of aphids trapped over the whole season (r = -0.623, P < 0.10, 8 df). This is probably connected to the detection limit of the suction trap: in years of high aphid numbers, the detection limit is reached earlier than in years with low numbers.

Gynoparae appeared before males in the collection of alate aphids from hop leaves. The percentage of males increased rapidly at the end of September to early October (Fig. 4). In 1989, over 95% of the alate aphids were males after 6 October. Two males and 165 alate females were collected on 14 September, the first leaf collection date, so the collection started too late to establish the start of female or male flight. However, the first male was caught in the suction trap on 3 October, almost three weeks after males were first found on leaves. The increase in the percent of males was slower in 1990 but followed the same trend (Fig. 4). Collecting started too late to determine the beginning of the female flight. In 1990, the first male was found on 19 September at the Yard I site and on 26 September at King-Tull. No males were captured in the suction trap in 1990 (Fig. 3). Males appeared earlier in the season in Europe than in our suction trap catches, but the results of our leaf collections indicated that males in the Yakima Valley appeared at about the same time as in Europe. The late appearance of males in our suction trap was probably due to the small number of males that were trapped: less than 15 males were trapped per year in six of the 10 years of trapping.

The total number of gynoparae exceeded the number of males each year of the Prosser suction trap catches (Fig. 3) and leaf collections. A total of 4,365 females and 664 males (86.8% females and 13.2% males) were caught during the autumn flight in the Prosser suction trap in the 10 years of trapping. We collected 3,833 gynoparae and 1,552 males (71.2% females and 28.8% males) from hop leaves in two years of collecting. Miciński & Ruszkiewicz (1974) also found more gynoparae than males on hops in Poland but the differences were not as large as we found. Gynoparae produce an average of 13.2 to 15.5 oviparae per female (Miciński & Ruszkiewicz 1974). Therefore, not only are more females than males flying to *Prunus*, but the proportion of females is further increased as oviparae are produced on *Prunus*. The larger number of females in the trap and on the hop leaves suggests that males mate with more than one female. The end of flight occurred when the hop foliage had been killed by frost.

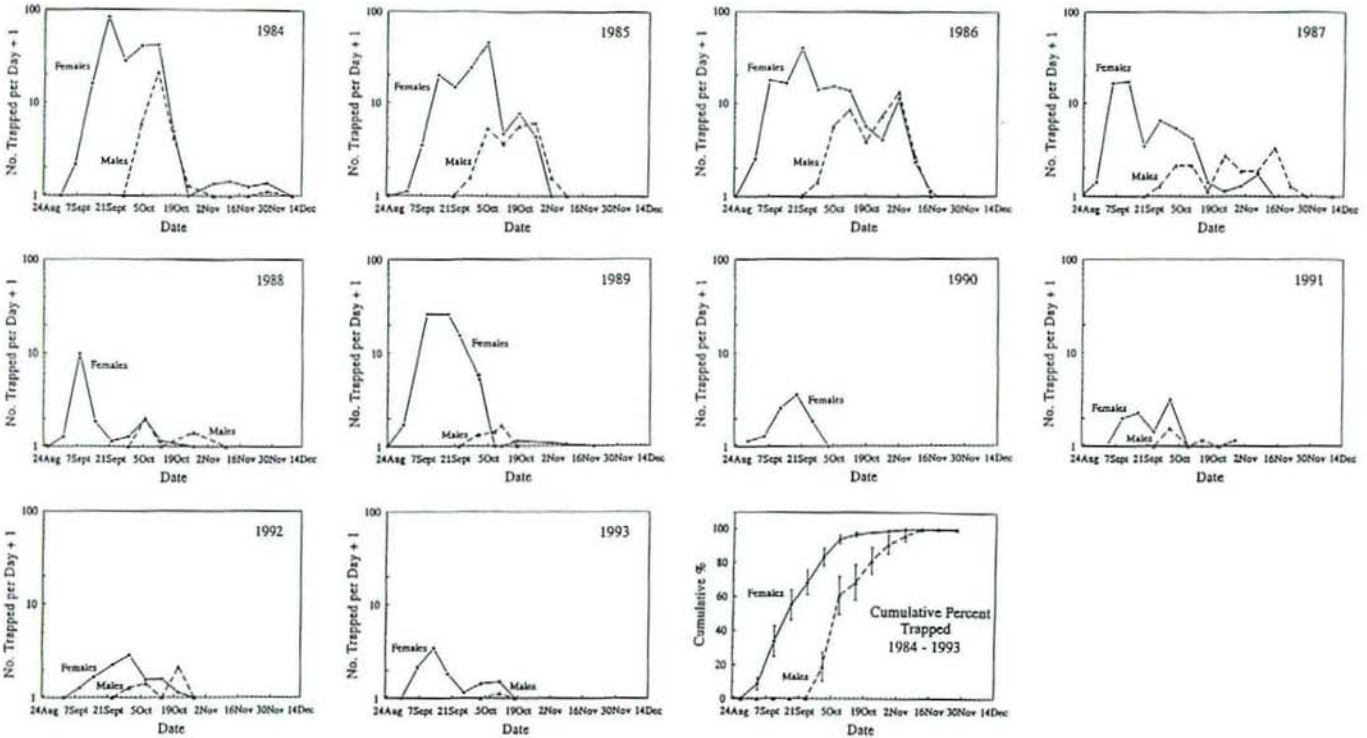
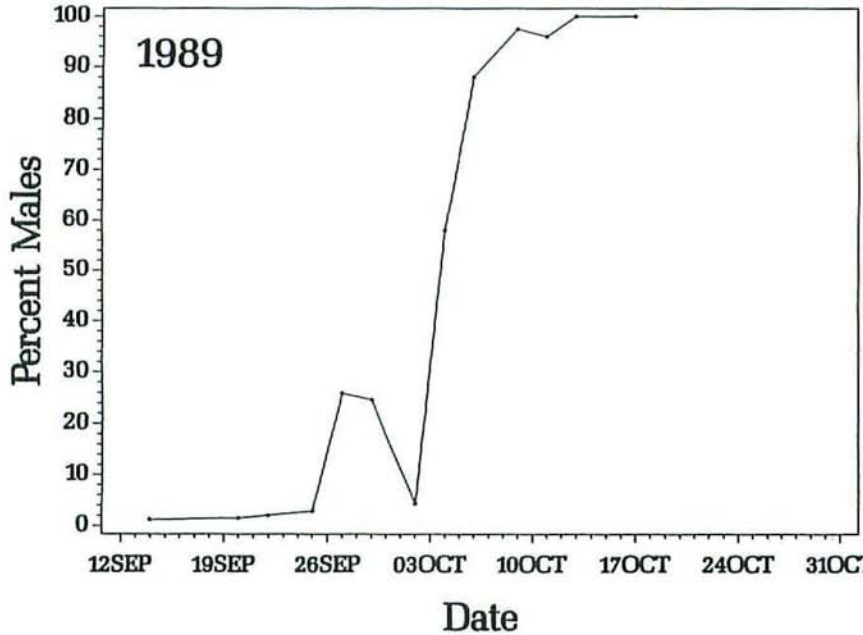


Fig. 3. Numbers of female and male hop aphids caught per week and expessed as number of aphids trapped per day [log (X + 1)] by suction trap, Prosser, Washington, 1984 to 1993. Also included is the mean cumulative percent of female and male hop aphids trapped during the autumn flight from 1984 to 1993; the vertical bars represent the standard errors of the means.



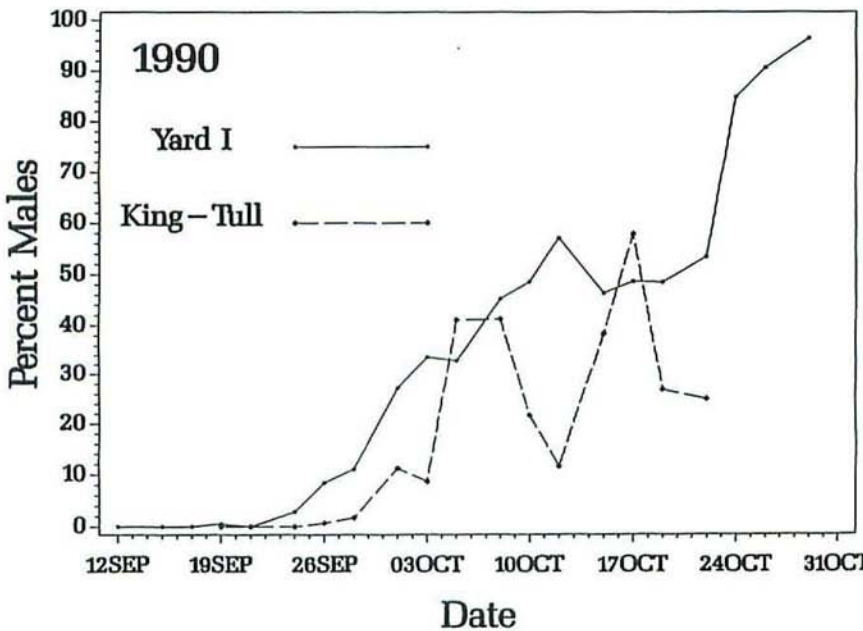


Fig. 4. Percent of adult alate hop aphids that were male. Aphids were collected from hop leaves, Prosser, Washington.

In the 10 years of trapping at Prosser, only eight hop aphids (five of them in 1984) were caught during the time of spring flight from *Prunus*. Seven were trapped in July and one in early August. The situation was reversed in the Vancouver suction trap, which was located in a non-hop growing area. In seven years, the Vancouver trap caught 313 hop aphids during the period of spring flight (before 15 August) and only 8 in the autumn. Taylor et al. (1979) caught about equal numbers of hop aphids in the spring and fall flights in suction traps in hop growing areas of England. In non-hop growing areas, their traps caught more aphids in the spring flight than in the fall flight. The fall flight in the Yakima Valley probably was larger than the spring flight because of the much larger number of hop plants compared to *Prunus* trees. The larger number of aphids in the spring flight in non-hop growing areas of England and in the Vancouver non-hop growing area probably was due to the larger number of *Prunus* plants compared to the number of hops.

Acknowledgment

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NOTE

Spotted Fireworm (Lepidoptera: Tortricidae) in Variegated Leafroller Pheromone Traps, and its Orientation to Traps in Variegated Leafroller Pheromone-Permeated Orchards[1]

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In recent years, moths resembling obliquebanded leafroller, *Choristoneura rosaceana* (Harris), have been collected in pheromone traps for variegated leafroller, *Platynota flavedana* (Clemens), in Virginia. This was considered unusual because there is only a minor degree of overlap in the pheromone blends of the two species. The sex pheromone of variegated leafroller has been reported as *E*11-14:OH/*Z*11-14:OH (90:10) (Hill et al. 1977). That of obliquebanded leafroller is *Z*11-14:Ac/*Z*11-14:OH/*E*11-14:Ac (90.2:5.0:4.8) (Hill & Roelofs 1979). The captures were assumed to represent contamination by obliquebanded leafroller and were recorded as such.

Identification. In 1992, the captures in variegated leafroller traps continued, although traps baited with obliquebanded leafroller lures caught no moths. Furthermore, traps for redbanded leafroller, *Argyrotaenia velutinana* Walker, caught no obliquebanded leafroller moths. Obliquebanded leafroller has been captured in redbanded leafroller traps in the past (Pfeiffer et al. 1993) because of a substantial overlap in pheromone blend. *Z*11-14:Ac is the main component of the sex pheromone of both species (Cardé & Roelofs 1977, Hill & Roelofs 1979). Specimens collected in variegated leafroller pheromone traps were sent to Richard L. Brown (Department of Entomology, Mississippi State University, Mississippi State MS 39762) for identification. The moths were identified as *Choristoneura parallela* (Robinson), commonly known as the spotted fireworm, a pest of blueberry and cranberry. The sex pheromone for that species has been reported as *E*11-14:OH/*E*11-14:Ac/14:OH/*Z*11-14:OH (in the approximate ratio of 84:9:8:0.7) (Neal et al. 1982, Arn et al. 1992); the first (primary) and last components comprise the variegated leafroller sex pheromone.

[1] Accepted for publication 15 November 1994.

Freeman (1958) gave the following criteria separating males of the two species: *C. rosaceana* has a tuft of scales on the upper side of the scape of the antennae, and has a costal fold reaching from the base of the forewing to the inner edge of the median band. The margin of the fold produces a dark scale tuft at midlength (Fig. 1a). These characters are lacking in males of *C. parallela* (Fig. 1b). Males of the two species are similar in size, but females of *C. rosaceana* are distinctly larger than those of *C. parallela* (Freeman 1958, Covell 1984). Females of *C. rosaceana* also differ from those of *C. parallela* by having hind wings that are orange anteriorly and apically.

In the genus *Choristoneura,* the lack of *C. rosaceana* characters does not necessarily indicate *C. parallela*. The latter species is most similar to *C. obsoletana* (Walker), which also occurs in Virginia and feeds of *Fragaria* (strawberry), *Rubus* (brambles), and several other host plant genera (Freeman 1958). While males of both species lack the antennal tuft and costal fold, both sexes of *C. parallela* have a distinct median fascia on the forewing, in contrast to the indistinct fascia in *C. obsoletana* (Freeman 1958). The sex pheromone of *C. obsoletana* is unknown (Arn et al. 1992), and is unlikely to be as close to variegated leafroller as *C. parallela.* The male and female genitalia of both species were illustrated by Freeman (1958).

Behavior in Variegated Leafroller Mating Disruption Blocks. Two apple orchard blocks were treated with dispensers containing a 70:30 blend of the components for variegated leafroller for three years. The Daleville block was 1.9 ha, the Fincastle block 1.8 ha. Each block was associated with a conventionally managed control block (lacking pheromone permeation). Each of the four blocks contained three pheromone traps each for variegated leafroller and obliquebanded leafroller. The blocks were more fully described by Pfeiffer et al. (1993).

Assuming *Choristoneura* moths in the variegated leafroller traps were *C. parallela,* total captures of *C. parallela* in the four orchard blocks are presented in Table 1. Moths were collected in both control blocks in all three years. No *C. parallela* were captured in the Daleville pheromone-permeated block in any of the three years, despite the fact that 18 were caught in that block in 1989, before permeation with variegated leafroller pheromone. No moths were captured in the Fincastle pheromone-permeated block during 1990 or 1991; only a single male was captured during 1992. The difference in male captures between pheromone-permeated and control blocks was significant (ANOVA, P=0.0455). No *Choristoneura* males were collected in obliquebanded leafroller traps in any of the blocks.

This note should aid in interpretation of captures of *Choristoneura* moths in variegated leafroller traps in either pheromone research or IPM implementation, as well as raising the possibility for control of spotted fireworm in areas of importance through the use of mating disruption.

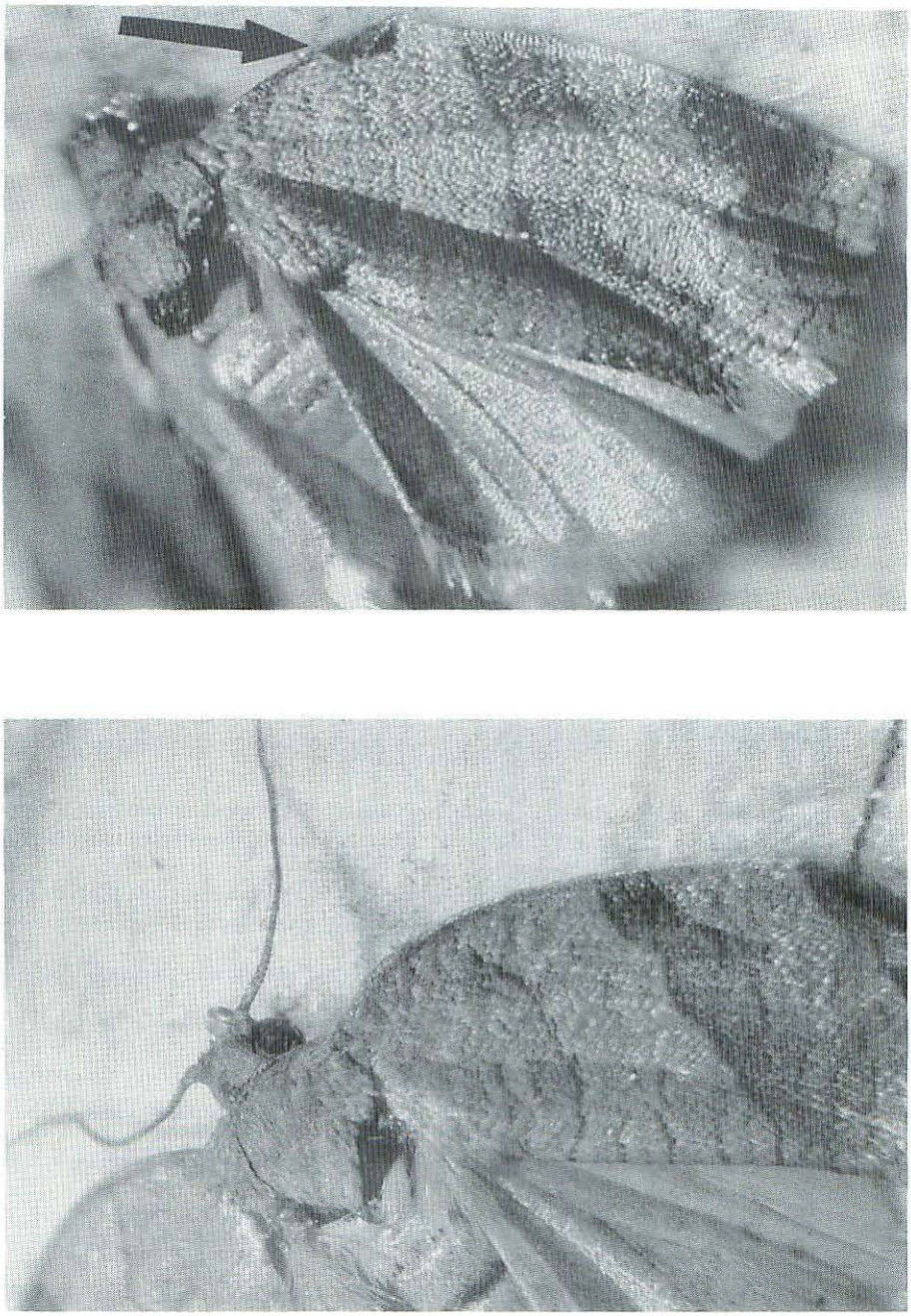

Fig. 1. Forewing of (a) *Choristoneura rosaceana* and (b) *C. parallela*. Arrow in (a) indicates dark tuft on coastal fold of *C. rosaceana*.

Table 1. Annual totals of captures of spotted fireworm males in variegated leafroller traps (three traps per block) in presence vs. absence of variegated leafroller pheromone permeation from 1990-1992[a].

	Daleville		Fincastle	
Year	Pheromone[b]	Control	Pheromone	Control
1990	0	3	0	10
1991	0	24	0	1
1992	0	29	1	35
Total	0	56	1	46

[a] The difference between captures in pheromone versus control blocks is significant, based on ANOVA of transformed means $[(x + 0.5)^{0.5}]$. ($P = 0.0455$).

[b] In 1989, before variegated leafroller pheromone permeation, 18 spotted fireworm males were collected in the Daleville pheromone block.

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The Effects of Drip or Furrow Irrigation of Cotton on *Bemisia argentifolii* (Homoptera: Aleyrodidae)[1, 2]

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ABSTRACT Infestations of immatures of *Bemisia argentifolii* Bellows and Perring (= *Bemisia tabaci* (Gennadius) Strain B), were studied in surface-drip or furrow-irrigated field plots of short staple cotton, *Gossypium hirsutum* L., in central Arizona in 1988, 1991, and 1993. Three levels of irrigation designed to produce low, moderate, or high plant water stress (at the end of irrigation interval) were tested each year. The seasonal average numbers of immatures of *B. argentifolii* on fifth main stem node leaves was greater in biweekly-furrow irrigated than in drip-irrigated plots in 1988 and 1993 but not in 1991. Plants irrigated biweekly with additional supplemental irrigations during mid-season or full season weekly irrigations had intermediate numbers of immatures. Leaf water potentials (-bars) measured in 1993 indicated plant water stress was greatest prior peak blooming and increased whitefly infestations. The 'Deltapine 50' (DPL-50) cultivar had a similar density of leaf trichomes but half as many nymphs per leaf as DPL-77 in the 1991 test. These results indicate that selecting a less susceptible cultivar and avoiding plant water stress may be useful in management of whiteflies.

KEY WORDS Cotton, drip irrigation, *Bemisia argentifolii,* Homoptera, Aleyrodidae

About 12% of the United States cotton, *Gossypium hirsutum* L., is produced in the southwestern U. S. Much of this production is irrigated, primarily by the infurrow method, because of the desert climate. Water is increasingly expensive and has become a limiting factor in some production areas. Drip irrigation (both surface and subsurface) is widely used for the production of high value crops but has found little application in cotton production. Drip irrigation also improves water use efficiency, thus saving water (Bucks et al. 1988). However, the cost of installing and maintaining drip irrigation systems is relatively expensive for cotton production.

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Typically, furrow-irrigated cotton becomes water stressed at the end of the interval between irrigations. Reducing the periods of plant water stress in cotton during the season can significantly increase yield (Radin et al. 1989). Reducing water stress in cotton can be achieved using drip irrigation or by more frequent furrow irrigation (Radin et al. 1992). The effect of reduced water stress on the insects that feed on cotton has received some attention in the past (Leigh et al. 1974, Zwick 1985, Leggett 1993) but little information is available on the effects of various irrigation methods on *Bemisia argentifolii* Bellows & Perring (= *Bemisia tabaci* (Gennadius) Strain B).

Flint et al. (1992) noted that up to four times as many whitefly nymphs were found on cotton in furrow-irrigated plots compared with drip-irrigated plots. The increased numbers of immature whiteflies on water-stressed cotton was previously observed in Israel by Mor (1987) who suggested that water stress increased nymphal survival. With these observations in mind, studies of the effects of various irrigation methods on *B. argentifolii* were undertaken.

Materials and Methods

Experiments with replicated field plots of short staple cotton irrigated by various methods were conducted on the University of Arizona Maricopa Agricultural Center (MAC) farm in 1988, 1991, and 1993. Soil at the test site is a Molrall sandy loam (fine-loamy, mixed, hyperthermic typic Haplargid) and the growing season is approximately 245 d. Three irrigation methods were studied each year with the objective of attaining low, intermediate, or high plant water stress during the irrigation cycle. All plantings were on 1.01-m row centers.

In 1988 comparisons were made between daily surface drip irrigation (low water stress), biweekly furrow irrigation (furrow irrigations every 14 d, high stress) and biweekly furrow with two supplemental irrigations timed to reduce plant water stress during peak fruiting (irrigation interval was 7 days during supplemental irrigations, otherwise every 14 d, intermediate stress). Four replicate plots per treatment (12 total plots, randomized block design) of 'Deltapine 90' (DPL-90) 10 m long by 16 rows wide were planted 26 April. All plots received a total of 127 cm of water during the season. Final furrow irrigations were made on 31 August and final drip irrigations were made on 15 September. The supplemental furrow irrigations were made on 12 and 26 July by dividing the biweekly irrigation allotments in half. Insecticide was applied by air to all plots on 21 and 30 July, 6 and 13 August, and 3 September (lambda-cyhalothrin, Karate, Zeneca Agricultural Products, Wilmington, DE, 0.35 kg [A.I.]/ha) to control leaf-feeding Lepidoptera *Helicoverpa* spp., the saltmarsh caterpillar, *Estigmene acrea* (Drury), and/or the pink bollworm, *Pectinophora gossypiella* (Saunders).

The irrigation treatments in 1991 were similar to those in the 1988 test except that total amounts of irrigation water varied and two cultivars, 'Deltapine 77' (DPL-77) and 'Deltapine 50' (DPL-50) were planted. Total water applied was: 82 cm for biweekly furrow irrigation, 117 cm for biweekly furrow plus three additional supplemental irrigations on 19 July, 2 and 23

August, and 82 cm for daily drip irrigation. Four replicate plots per treatment (24 total plots, 2 × 3 factorial design), each 11 m long by 8 rows wide, were planted 3 April. Final furrow irrigations were made on 21 September and final drip irrigations on 29 September. The numbers of stellate leaf trichomes ("leaf hairs") per cm^2 were determined from two 0.57-cm diam leaf disks from each of 20 leaves per cultivar collected 5 October. Insecticides were applied by air on 30 May for boll weevil, *Anthonomus grandis* Boheman (chloropyrifos, Lorsban 50W, DowElanco, Indianapolis, IN, 2.13 kg [A.I.]/ha), 26 and 31 July, and 2 and 9 Aug. (acephate, Orthene 75S, Valent Corporation, Walnut Creek, CA, 0.56 kg [A.I.]/ha and profenofos, Curacron 8E, Ciba, Greensboro, NC, 0.84 kg [A.I.]/ha) for lygus bugs, *Lygus herespus* Knight, and pink bollworm.

In 1993, the three irrigation treatments were compared in a way similar to the previous years' tests, except weekly furrow irrigations were maintained during the entire season by applying one-half the total water each week that was applied to the biweekly irrigated plots. 'Deltapine 50' was planted because of its lower susceptibility to whitefly in the 1991 test. All plots including the drip-irrigated plots received a total of 107 cm of water. Six replicate plots of DPL-50 per treatment (18 total plots, randomized block design) each 10 m by 12 rows were planted 14 April. Counts of blooms in 10 m per plot were made on 19 dates between 17 June and 12 July. Final furrow irrigations were 13 August and final drip irrigation was applied on 20 August. This test was terminated earlier than planned due to severe whitefly infestations even though insecticide applications were applied by ground rig on 6, 19 and 26 July and 11 August (acephate, 0.56 kg [A.I.]/ha and endosulfan, Thiodan 50WP, FMC Corporation, Philadelphia, PA, 0.55 kg [A.I./ha) for control of lygus bugs and whiteflies.

A pressure chamber was used to measure leaf water potential of cotton leaves during the 1993 season according to the methods of Meron et al. (1987) for leaf collection and Turner (1987) for operation of the chamber. Leaf water potential is an index of plant water stress and is obtained from the pressure (-bars) required to cause the exudation of interstitial leaf sap. Leaves for testing were taken from the fifth mainstem node from the top of the plant. Pressure chamber readings were taken from samples of three leaves per plot each week 10 June to 23 August just prior to furrow irrigation of the appropriate test plots. Thus plots were 7 d post-irrigation (weekly irrigation) or 7 and 14 d post-irrigation (biweekly irrigation) or being irrigated (drip irrigation).

Populations of immature whiteflies were determined from cotton plant leaves collected from the fifth mainstem node from the top of the plant (Ohnesorge & Rapp 1986). Plants for sampling were randomly selected from the central area of each plot. In 1988, nymphs were counted on whole leaves because infestations were very low. In 1991, the numbers of nymphs per gram of wet leaf tissue were determined from whole leaf counts or various size leaf disks as the numbers of nymphs increased during the season (the weight of various size samples was more easily obtained than area). In 1993, eggs and nymphs were counted separately and standardized on one 3.88-cm^2 disk per leaf taken from leaf sector two (Naranjo & Flint, 1994). Fifteen

leaves per plot were sampled in 1988 (9 sample dates, 27 June to 16 September) and 1991 (7 samples, 11 July to 16 September) and 10 leaves per plot were sampled in 1993 (12 samples, 17 June to 1 Sept.). Specimens of whiteflies from field plots at MAC in 1993 were submitted to Dr. A. C. Bartlett (USDA-ARS; Phoenix) and identified as "B" strain by RAPD-PCR analysis (Gawel & Bartlett 1993). Subsequently the "B" strain became *B. argentifolii* (Bellows et al. 1994).

The 1988 and 1993 data were subjected to analysis of variance using a split-plot design with irrigation treatments as whole plots and dates as split plots and an LSD test conducted where significant "F" values were obtained (Gomez & Gomez 1984). The 1991 data were analyzed by factorial analysis of variance using the MSTAT-C statistics software program (Michigan State University 1990), with irrigations and cultivars as whole plots and dates as split plots. Non-significant means are presented with their standard errors.

Results

The 1988 seasonal average number of nymphs per whole leaf was greater in the biweekly (every 14 d) furrow-irrigated plots than in the daily drip-irrigated plots; however, the number in the biweekly plus supplemental (every 7 days during supplemental irrigation period) irrigation plots were not different from those in either drip or biweekly irrigations (drip = 0.83 nymphs per leaf; biweekly plus supplemental = 1.24; biweekly = 1.60; F = 8.27; df = 2, 6; $P < 0.025$). There were significant differences in the numbers of nymphs per leaf between sample dates because the numbers of nymphs on leaves were greater in samples collected later in the season (overall average of 1.0 ± 0.1 nymphs 27 June, compared to 2.9 ± 0.7 nymphs per leaf on 12 Sept., for example). The interaction between treatments and dates was not significant. No further samples were collected because the leaves in the furrow-irrigated plots had deteriorated. The numbers of whitefly nymphs found on cotton leaves in 1988 were relatively low and were never targeted for control.

In 1991, the seasonal average number of nymphs per gram of leaf tissue (± SE) was not affected by the irrigation treatments (drip = 211 ± 23 nymphs per gram, biweekly plus supplemental = 318 ± 19 biweekly = 297 ± 16; F = 0.08; df = 2, 15; $P > 0.10$). However, the number of nymphs per gram of leaf was greater in plots of 'DPL-77' than in plots of 'DPL-50' ('DPL-77' = 388 nymphs per gram; 'DPL-50' = 161; F = 9.66; df = 1, 15; $P < 0.001$). The interaction between sampling dates and cultivars were significant due to inconsistencies in the numbers of nymphs found in the two cultivars during the season. There were no other significant interactions. The numbers of stellate trichomes per cm^2 were not different for the two cultivars ('DPL-77' = 9.5 ± 2.3 'DPL-50' = 5.6 ± 1.6 t = 1.75; df = 78; $P > 0.05$). These results indicate that 'DPL-50' is less susceptible to whitefly infestation than is 'DPL-77'.

The 1993 seasonal average counts of eggs on 3.88 cm^2 leaf disks indicated that drip and weekly irrigation had reduced oviposition compared to biweekly irrigation (drip = 2.23 eggs per cm^2; weekly = 3.52; biweekly = 8.33; F = 10.27; df - 2, 10: $P < 0.005$). Similarly, the seasonal average numbers of

nymphs on leaf disks in drip and weekly irrigated plots were reduced compared to biweekly irrigation (drip = 0.71 nymphs per cm^2; weekly = 1.37; biweekly = 2.71; $F = 6.91$; df = 2, 10; $P < 0.025$). The numbers of eggs and nymphs began to increase in early July but were brought under control by insecticide applications that began 6 July and ended 11 August, allowing the numbers to increase again in late August (Fig. 1). The seasonal total numbers of eggs and nymphs counted in each treatment were, respectively (% nymphs of eggs): drip = 7211, 2538 (35%) weekly = 11940, 4714 (39%), and biweekly = 26164, 8925 (34%). These percentages are not different (n = 72, arc sin transformation, $P = 0.05$) and indicate that nymphal survival was comparable in the three treatments. These results show that infestations of the sweetpotato whitefly were lower in drip and weekly irrigated plots than in biweekly irrigated plots and that these reductions were due to fewer eggs (antixenosis) and not reduced survival of nymphs (antibiosis).

Leaf water potentials were lowest at the beginning and end of the season (Fig. 2). The seasonal average leaf water potentials in -bars (n) for drip, weekly, biweekly and 7 d and biweekly at 14 d were 17.5 (216), 18.3 (216), 18.4 (108) and 19.3 (108). There was no difference between the seasonal average leaf water potentials for the weekly and biweekly treatments at 7 d. However, the leaf water potentials for drip irrigation were lower than for either weekly (t = 2.68; df = 142; $P < 0.01$) or biweekly at 7 d (t = 2.17; df = 105; $P < 0.01$). Similarly, the leaf water potentials for biweekly irrigations at 14 d were greater than for either the weekly (t = 2.92; df = 106; $P < 0.01$) or biweekly irrigations at 7 d (t = 2.41; df = 69; $P < 0.05$). These results indicate that drip irrigation produced the least water stress while biweekly irrigations produced the greatest water stress, and that weekly irrigations were intermediate in effect. The greatest levels of water stress during the season were (date): drip = 19.7 ± 0.03 -bars (30 June), weekly = 20.3 ± 0.3 (8 July), and biweekly = 21.3 ± 0.4 (30 June). The greatest daily numbers of blooms per 10 m of row were (date): drip = 67 ± 7 (13 July), weekly = 75 ± 6 (12 July), and biweekly = 72 ± 9 (12 July). Thus, maximum water stress occurred prior to maximum blooming and prior to increases in the numbers of immature whiteflies.

Discussion

Whiteflies prefer pubescent cotton leaves for oviposition (Butler et al. 1986). The 'DPL-90' cultivar used in our 1988 tests has approximately 10 leaf trichomes per cm^2 and had relatively low infestations of whiteflies in previous tests (Flint & Parks 1990). In 1991 tests, 'DPL-77' and 'DPL-50' had similar numbers of leaf trichomes (about the same as 'DPL-90'), but 'DPL-50' averaged about one-half as many nymphs per gram of leaf. 'Deltapine 77' had greater infestations of whitefly nymphs than three other short staple cultivars in previous tests (Flint et al. 1992). Our results indicate considerable natural resistance in 'DPL-50' compared to 'DPL-77' and are encouraging because lower susceptibility based on other than pubescence is uncommon. Screening available commercial cultivars for resistance to the sweetpotato whitefly would be worthwhile in view of the large differences in infestations we have observed.

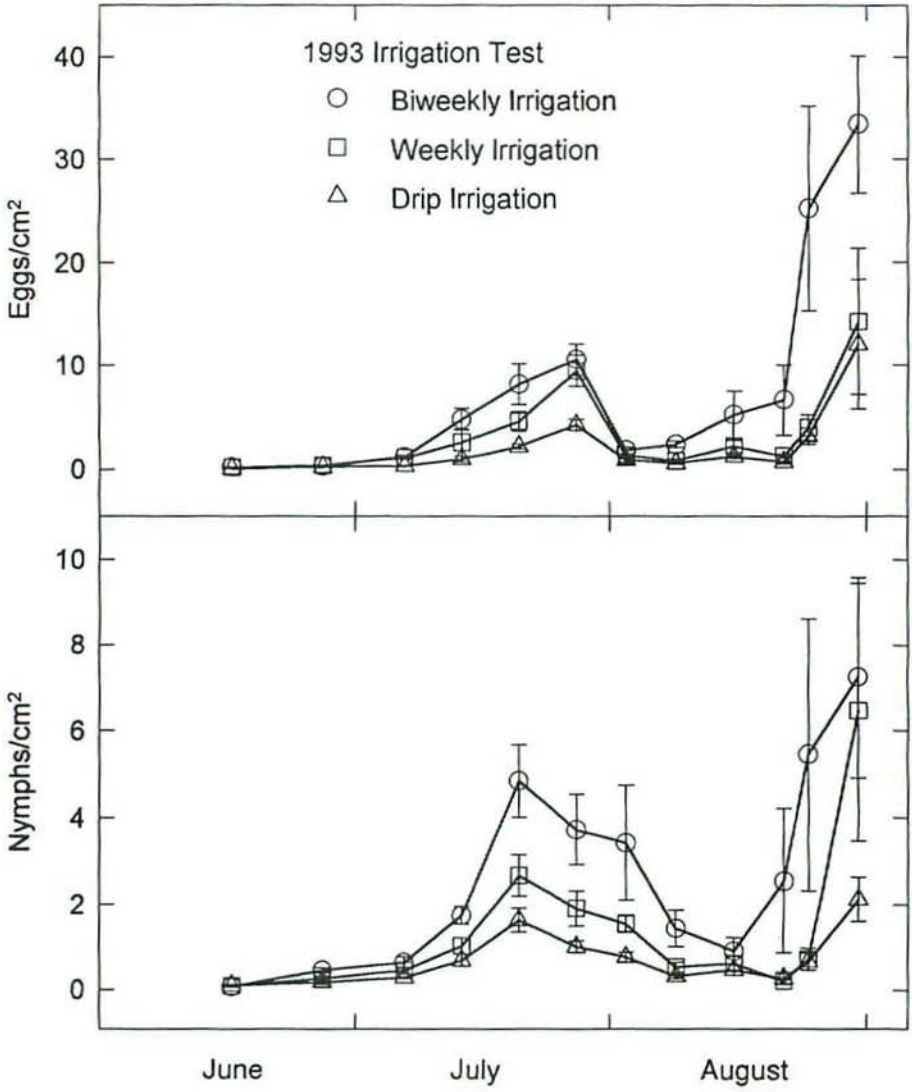

Fig. 1. Numbers of eggs and nymphs per cm^2 ± SEM of the sweetpotato whitefly on cotton plants under drip or furrow irrigation, Maricopa, AZ, 1993.

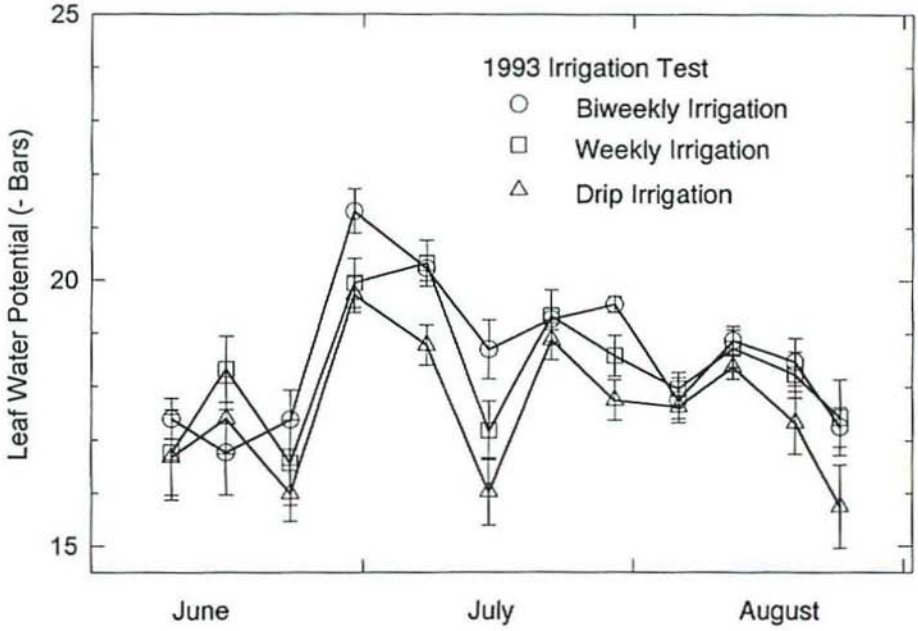

Fig. 2. Leaf water potentials (-bars) ± SEM for cotton plants under drip or furrow irrigation, Maricopa, AZ, 1993.

Mor (1983) wrote that water deficiency resulted in increased numbers of whitefly larvae on cotton but provided no data. In the present tests, drip irrigation resulted in fewer whitefly nymphs on cotton leaves than did biweekly irrigation in 1988 and 1993 (in 1991 the trend was apparent). Intermediate numbers of nymphs were generally observed on cotton that received more frequent furrow irrigation. Increasing the frequency of furrow irrigations seems to be the most practical way to achieve the lower populations of whiteflies associated with less water stress. Increased irrigation frequency is also compatible with short season production methods that require optimum conditions to produce maximum fruiting early in the season. Selecting a short-season cultivar with natural resistance to the whitefly and avoiding plant water-stress should be major components of an integrated management program for whiteflies.

The reasons for the greater numbers of eggs and nymphs found on water-stressed cotton are unknown. Many physical and physiological changes occur in water stressed cotton plants that may affect whitefly biology. Understanding the reasons for increased oviposition on these plants may suggest ways to make cotton plants less suitable for whitefly infestation.

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Evaluation of Starch-Encapsulated Diflubenzuron for Use in Management of Fall Armyworm (Lepidoptera: Noctuidae) Larvae[1, 2]

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ABSTRACT Diflubenzuron, a chitin synthesis-inhibiting insect growth regulator, was encapsulated with Mira-gel, a pregelatinized starch material, and tested under laboratory and field conditions. Results demonstrated that encapsulated diflubenzuron can be used for managing larval populations of *Spodoptera frugiperda* (J. E. Smith), the fall armyworm, in whorl stage corn (*Zea mays* L.). Granules containing the feeding stimulant Coax resulted in higher fall armyworm larval mortality in the laboratory than did granules without Coax, but did not improve management in the field. The use of starch for encapsulating diflubenzuron may increase the probability of establishing areawide management programs for this important insect pest.

KEY WORDS *Spodoptera frugiperda*, diflubenzuron, corn, Mira-gel, Lepidoptera, Noctuidae

Fall armyworm, *Spodoptera frugiperda* (J. E. Smith), remains a significant pest of corn, *Zea mays*, L., as well as other agronomic crops, in the southern United States. Laboratory studies have recently been conducted to evaluate the effectiveness of various insect growth regulators (IGRs) for use in management of fall armyworm larvae (Chandler et al. 1992a, b). These studies show that benzoylphenyl urea molting inhibitors and insect molting hormone agonists provide high levels of mortality against 1- and 7-d-old fall armyworm larvae. Additionally, Chandler (1993) found that the mortality of fall armyworm larvae exposed to leaves treated with a water-based suspension of the chitin synthesis inhibitor diflubenzuron, a first generation benzoylphenyl urea IGR, could be increased with the addition to the mix of Coax®, a cottonseed flour-based insect feeding stimulant.

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The addition of Coax provided an effective tool to reduce the time needed for the usually slow-acting diflubenzuron to cause death, because the larvae were presumed to ingest more material, resulting in faster kill (Chandler 1993). Results suggested that the use of diflubenzuron against fall armyworm larvae could provide a safe, environmentally sound method to suppress its population effectively over a large area (Chandler et al. 1992b).

In general, chitin synthesis-inhibiting IGRs have been regarded as excellent integrated insect control tools because of their specificity to the target pest, their relative nontoxicity to beneficial organisms, and their general safety to vertebrates, mollusks, and plants (Wilkinson et al. 1978, Deakle & Bradley 1982, Horn 1988). However, field application of diflubenzuron must be strictly monitored. It is commonly known that diflubenzuron is highly persistent in field situations (Horn 1988). This persistence can result in restrictions on use patterns and the quantity of material that can be applied to any one crop during a year. Diflubenzuron is toxic to some aquatic invertebrates, and therefore, care must be taken to avoid drift and runoff from treated areas into environmentally sensitive locations (Uniroyal Chemical Co. 1992). An application of diflubenzuron flowable or wettable powder formulations as foliar sprays increases the probability of off-target insecticide deposition onto ecologically sensitive areas. New diflubenzuron formulations which deliver the amount of active ingredient needed to render effective control are needed to reduce the likelihood of off-target deposition and to provide an incentive for use of diflubenzuron in areawide management programs.

Starch macroencapsulation technology has recently been developed to protect entomopathogens from rapid environmental degradation (Dunkle & Shasha 1988). This technology essentially provides a method of insecticide formulation which results in a granular material of a desired size, density, and porosity. Studies using pregelatinized starch encapsulation of *Bacillus thuringiensis* Berliner for control of European corn borer, *Ostrinia nubilalis* (Hübner), have proven successful (Dunkle & Shasha 1988, 1989, Bartelt et al. 1990, McGuire & Shasha 1990, McGuire et al. 1990). When alcohol is used to replace part of the water in the formulation, granules will adhere to wet surfaces (McGuire & Shasha 1992). After drying, the granules remain firmly attached to the surface and resist removal by rain or wind. This type of formulation can be used with most insecticides to provide increased pesticide residual activity and improved effectiveness with decreased amounts of pesticides. Precision application of encapsulated diflubenzuron (mixed with a feeding stimulant) to the whorl of corn plants may provide an acceptable method of developing areawide management programs that emphasize reduced drift, plant washoff and off-target deposition. The amount of diflubenzuron needed to affect control of fall armyworm in the whorl-stage plant could also be decreased. This study reports the results of laboratory and field trials using diflubenzuron mixed with a phagostimulant and encapsulated in pregelatinized starch to manage fall armyworm populations.

Materials and Methods

Formulation preparation. Starch granules were prepared to test the effects of a phagostimulant and two levels of diflubenzuron on *S. frugiperda* survival (measured as percent mortality in the laboratory) and on whorl damage on field-grown corn. Six starch formulation mixes were prepared. One formulation contained only pregelatinized cornstarch (Mira-gel, A. E. Staley, Inc., Decatur, Illinois) with no additives. Additional formulations contained a phagostimulant alone, a phagostimulant + either of two levels of diflubenzuron, and two levels of diflubenzuron alone. The phagostimulant added to the starch was a wettable powder formulation of Coax (CCT Corporation, Litchfield Park, Arizona), a cottonseed oil-based product previously used in starch encapsulation with *B. thuringiensis* (Bartelt et al. 1990). Coax was added to the preparation at 10% of the starch dry weight. Technical grade diflubenzuron (Uniroyal Chemical Co., Middleburry, Connecticut) was incorporated into the starch granules at rates of either 1 or 5% active ingredient per starch dry weight.

Granules were prepared using procedures modified from McGuire & Shasha (1992). Mira-gel (200 g) was mixed at room temperature with 50 ml of 2-propanol containing 2.2 g of technical diflubenzuron. For those formulations with feeding stimulant, Coax (20 g) was mixed with 180 g of starch before being mixed with the 2-propanol. Water, cooled to 4°C (100 ml), was then added to the starch, and the crumbly mixture that formed was dried at room temperature. Granules that passed through 20 but not 35 mesh/cm screening were used in all tests.

Laboratory bioassays. Neonate fall armyworms were obtained from laboratory culture (Perkins 1979) at the Insect Biology and Population Management Research Laboratory in Tifton, Georgia. The larvae were held on bean diet at 25°C for 1 d before being exposed to treated leaves, to allow all insects to reach a uniform age and size. Two-wk-old (post emergence) greenhouse-grown southern pea, *Vigna unguiculata* (L.), plants were moved into the laboratory, and mature leaves were excised from the plants. A 3-cm diam. disk was then cut from each leaf. To prevent desiccation, a single leaf disk was then placed on absorbent paper in a plastic petri dish (10 cm diam.) to which 15 ml of distilled water had been added. The previously prepared starch granule formulations were then weighed into 0.015- and 0.03-g batches. Dry granules were applied directly to the leaf surface, and 0.10 ml of distilled water was applied to the granules. Each starch formulation was added to each of 10 leaf disks. The granules were allowed to dry, and five 1-d-old fall armyworm larvae were then placed on the leaf surface. The petri dishes, sealed with parafilm to prevent larval escape, were placed completely at random in environmental cabinets and held at 24 ± 1°C, a photoperiod of 12:12 L:D, and 50 ± 5% RH. The number of live, dead, and missing larvae were recorded in each dish 72 and 120 h after test initiation. Reasons for missing larvae included cannibalism and loss during evaluation of mortality. Larvae were considered dead if they did not respond to touch by a dissecting needle within two probes. The entire procedure was repeated three times. Leaves without Mira-gel on the leaf surface were not included in the tests

because preliminary data indicated that percent mortality of 1-d-old fall armyworm larvae after exposure to leaves with 0.015 g of Mira-gel only formulations per leaf surface did not differ from mortality on leaves with no Mira-gel ($\bar{X}$ = 6.9 ± 10.6 SD% vs. $\bar{X}$ = 1.3 ± 5.0%, respectively; t = 1.92, df = 30, $P > 0.05$).

Field trials. Field evaluation of the six previously mentioned starch-diflubenzuron-Coax formulations were conducted on whorl-stage field corn on the USDA-ARS Belflower Farm in Tift County, Georgia, during 1991 and 1992. 'Sunbelt 1803' variety corn was planted on 20 July 1991 and 5 September 1992 on 91-cm wide rows. At approximately the 3rd to 4th leaf stage, one-row plots 10 m in length were established. Two-row buffers were maintained between plots and a 3-m alley was maintained between plots within rows. The six starch formulations were hand-applied to each of 15 corn plants per plot at the rate of 0.0175 g/whorl in 1991, and 0.0175 and 0.035 g/whorl in 1992. Both tests were replicated four times in a randomized complete block design. Immediately before granule application and approximately twice a week for the next 2 wk, each treated plant was examined for the presence of fall armyworm larvae on leaves or within the whorl, fresh feeding damage, or fresh frass. Plants were considered damaged on a particular date if any of the criteria listed above were observed.

Statistical analysis. Means and standard deviations were calculated for all data. Laboratory data were analyzed by analysis of variance using a completely randomized design in a 3 × 2 × 2 factorial. Diflubenzuron rate, amount of Mira-gel per leaf, and presence or absence of Coax were the main effects. Field data were analyzed in a randomized complete block and a similar factorial design. Factor means were compared using the least squares means procedure (SAS Institute 1985).

Results and Discussion

Laboratory bioassays. Fall armyworm larval mortality following exposure to diflubenzuron formulated in Mira-gel ranged from 17.4 to 82.4% and 69.5 to 99.3% at 72 and 120 h after treatment, respectively (Table 1). At both sampling times, granules with diflubenzuron killed significantly more fall armyworm larvae than granules without diflubenzuron (Table 2). However, the two rates of diflubenzuron did not differ in effectiveness. Also granules with Coax killed significantly ($P < 0.05$) more larvae than did granules without Coax (Table 2). Within 120 h, granules with Coax alone killed a higher percentage of insects. This unexpected mortality also probably led to the significant Coax X diflubenzuron interaction(Table 2). Previous studies with Coax formulated in water and applied to southern pea leaves did not result in high levels of fall armyworm larval mortality (Chandler 1993). Bartelt et al. (1990) indicated that European corn borer larvae fed on starch granules containing Coax in preference to corn leaf tissue. Although we did not measure feeding preference in our study, fall armyworm larvae were observed readily feeding on Coax-impregnated granules. If fall armyworm larvae prefer Coax granules over corn in a confined area, one then could question whether the nutritional requirements

Table 1. Mortality of 1-d-old *S. frugiperda* larvae after exposure to formulations of starch-encapsulated diflubenzuron in the laboratory.

Treatment[a]	Starch per leaf surface (g)	Mean ± S. D. percent mortality	
		72-h observation	120-h observation
M	0.015	8.1 ± 8.8	14.7 ± 13.6
	0.030	0.8 ± 1.4	10.7 ± 7.5
M + 1% D	0.015	30.1 ± 29.7	69.5 ± 24.7
	0.030	17.4 ± 10.1	87.7 ± 5.9
M + 5% D	0.015	39.5 ± 25.6	75.6 ± 24.8
	0.030	35.3 ± 12.7	94.2 ± 3.2
M + 10% C	0.015	23.5 ± 23.0	67.5 ± 30.3
	0.030	22.7 ± 29.3	70.3 ± 10.7
M + 1% D + 10% C	0.015	61.8 ± 20.5	78.9 ± 20.5
	0.030	80.7 ± 7.1	99.3 ± 1.3
M + 5% D + 10% C	0.015	59.0 ± 24.5	77.8 ± 24.0
	0.030	82.4 ± 7.5	97.1 ± 3.2

[a] M, Miragel; D, diflubenzuron; and C, Coax.

of maturing larvae could be met by Coax mixed with Mira-gel. It appears likely that larvae that fed on Coax may have died prematurely due to nutritional deficiencies. Larvae fed Coax mixed in Mira-gel appeared smaller in size than larvae feeding on Mira-gel only treatments. A significantly ($P < 0.05$) effect was also observed with the amount of granules per leaf at the 120-h sample period. This difference is probably due to the higher number of granules on the leaf surface, thus increasing chances of discovery by the insect. These results suggest that the addition of relatively small amounts of diflubenzuron, especially with the addition of Coax, to starch-based granule may be an effective insect control tactic.

Field trials. A non-uniform distribution of fall armyworm infestation patterns within the field in 1991 resulted in pre-treatment damage counts that were not similar ($F = 4.49$, df = 8, 23, $P = 0.006$) among treatments. All plant damage in this test was attributed to fall armyworm. Application of starch-encapsulated diflubenzuron to plots did, however, result in a reduction in the number of infested (according to Table 3) plants starting at 7 d after application. These differences persisted throughout the next 12 d of the study (Tables 3, 4). Coax had a significant ($P < 0.05$) effect only on the 3 October sampling date, as those plots receiving granules containing Coax had fewer damaged plants than did plots receiving granules without Coax (Table 4). This difference was lost by the next sampling period, however, as Coax apparently lost its effectiveness under the field conditions that existed

Table 2. Analysis of variance of mortality data collected during exposure of *S. frugiperda* to starch-encapsulated diflubenzuron in laboratory.

Source	df	72-h observation F[a]	120-h observation F[a]
Diflubenzuron rate	2	15.32*	26.46*
Amt. granules/leaf	1	0.21	4.76*
Coax presence	1	27.05*	16.15*
Diflubenzuron X Amt.	2	0.38	1.32
Diflubenzuron X Coax	2	1.70	8.50*
Amount X Coax	1	2.96	0.08
Diflubenzuron X Amt. X Coax	2	0.37	0.03
Error MS	24	0.0366	0.0296
		Avg. % mortality[b]	
Diflubenzuron Amount		72-h	120-h
0		13.8 a	40.8 a
1%		47.5 b	83.9 b
5%		54.0 b	86.2 b
Coax Presence			
Absent		21.9 a	58.7 a
Present		55.0 b	81.8 b
Granule Amount			
150 mg		37.0	64.0 a
300 mg		39.9	76.5 b
		N.S.	

a * indicates significant F-test ($P < 0.05$).

b Factor means/observation period followed by the same letter are not significantly different ($P > 0.05$, Least Squares Means). N. S. indicates not significantly different.

at the time of the study. The two rates of diflubenzuron did not result in differences in the number of damaged plants on 3 and 10 October, but differences were observed on 7 October (Table 4). By the last sampling date (15 October), unacceptably high damage occurred in all treatments. Apparently as the corn plant increased in height and leaf number, the Mira-gel remaining on older plant tissue did not come in contact with new leaf growth where primary larval feeding occurred. Fall armyworm egg masses can be distributed over most parts of the plant including leaves emerging from the whorl, and therefore they may have escaped contact with diflubenzuron residues. Thus, after about 2 wk, rapid plant growth resulted in leaf surface area without any toxicant. Additional applications of Mira-gel would then be required at this time.

In 1992, fall armyworm infestations were low at the beginning of the study (Table 5) and no significant ($P > 0.05$) differences existed in the number of damaged plants among plots before treatment. All damage to plants during this test was attributed to fall armyworm. Within 5 d after treatment application, plots receiving granules of either rate of diflubenzuron had significantly fewer damaged plants than did plots receiving granules without diflubenzuron (Table 6). Again, these differences existed until the 31 August sample date, about 19 d after treatment. The percentage of diflubenzuron in the granules did not seem to influence the resulting number of damaged plants per plot and, apparently the low rate of diflubenzuron was sufficient to achieve effective control. The presence of Coax had no effect on the number of fall armyworm larvae-damaged plants across the sampling dates (Table 6). Additionally, plant damage in plots receiving 175 mg of granules/plant was not different from damage in plots receiving 350 mg/plant across all sampling periods. The low rate of 175 mg represents a field application rate of abut 11 kg/ha. When using 1% diflubenzuron formulations, only 100 g AI/ha would need to be applied to control fall armyworm larvae over a 2-wk period. As in the 1991 field trial, reductions in the number of fall armyworm damaged plants were achieved with diflubenzuron during the first 2 wk following application. Additional applications would be needed to maintain season-long whorl stage fall armyworm control. The use of starch-encapsulated Coax alone resulted in similar levels of fall armyworm plant damage as that observed in the Mira-gel only treatments throughout the 1992 test period (Tables 5, 6). Thus, as previously noted in 1991, use of Coax alone did not adversely affect fall armyworm larval populations.

These data demonstrate that encapsulating diflubenzuron within a Mira-gel starch matrix provides a viable way for applying the toxicant for management of *S. frugiperda*. Feeding stimulants, other than Coax, should also be evaluated to determine their potential for enhancing the effectiveness of diflubenzuron. Chandler (1993) found that the cotton flour product Konsume (Fermone Inc., Phoenix, Arizona) mixed with an insect molting hormone agonist provided significantly higher levels of fall armyworm larval mortality than did other tested phagostimulants. Further refinement of application methodologies could aid in the development of granular starch encapsulation techniques for use in areawide management programs.

Table 3. Number of corn plants damaged by *S. frugiperda* larvae after treatment with formulations of starch-encapsulated diflubenzuron - field test, 1991.

Treatment[a]	Mean ± S.D. no. of infested plants per plot					
	26 Sept. (Pre)	30 Sept. (4 d post.)	3 Oct. (7 d post.)	7 Oct. (10 d post.)	10 Oct. (13 d post.)	15 Oct. (18 d post.)
M	8.0 ± 2.8	8.5 ± 4.4	8.8 ± 4.5	12.3 ± 4.2	9.5 ± 3.8	15.0 ± 0.0
M + 1% D	3.3 ± 1.0	3.3 ± 1.5	2.0 ± 0.8	8.3 ± 1.0	5.8 ± 1.7	11.0 ± 1.9
M + 5% D	4.8 ± 2.5	6.0 ± 2.6	3.0 ± 0.8	5.5 ± 1.1	4.0 ± 3.7	9.3 ± 3.7
M + 10% C	6.5 ± 1.0	6.3 ± 2.6	5.0 ± 0.0	11.0 ± 1.6	8.0 ± 0.8	12.8 ± 1.5
M + 1% D + 10% C	6.5 ± 0.6	5.5 ± 4.7	1.5 ± 1.3	9.3 ± 1.3	5.3 ± 4.3	12.8 ± 2.1
M + 5% D + 10% C	3.3 ± 1.5	2.5 ± 2.4	2.0 ± 0.8	5.8 ± 1.7	2.5 ± 1.0	11.3 ± 1.0

[a] M, Miragel; D, Diflubenzuron; and C, Coax. All treatments applied at 0.0175 g/whorl.

Table 4. Analysis of variance of 1991 field damage data collected during exposure of *S. frugiperda* to starch-encapsulated diflubenzuron.

		F-values[a]				
Source	df	30 Sept.	3 Oct.	7 Oct.	10 Oct.	15 Oct.
Block	3	4.05*	1.23	0.42	0.52	5.33*
Diflubenzuron Rate	2	3.61	15.95*	13.62*	6.69*	11.01*
Coax Presence	1	1.18	4.78*	0.00	0.89	0.28
Diflubenzuron X Coax	2	2.63	1.59	0.50	0.07	4.31*
Error MS	15	6.94	3.84	5.29	9.14	2.39
		Mean no. damaged plants/15 plants[b]				
Diflubenzuron Amt.						
0		7.4	6.9 a	11.6 a	8.8 a	13.8
1%		4.4	1.8 b	8.8 b	5.5 b	12.1
5%		4.3	2.5 b	5.6 c	3.3 b	10.3
		N. S.				N. S.
Coax Presence						
Absent		5.9	4.6 a	8.7	6.4	12.3
Present		4.8	2.8 b	8.7	5.3	11.9
		N. S.		N. S.	N. S.	N. S.

[a] * indicates significant *F*-test ($P < 0.05$).
[b] Factor means/date followed by the same letter are not significantly different ($P > 0.05$, Least Squares Means). N. S. indicates not significantly different.

Table 5. Number of corn plants damaged by *S. frugiperda* larvae after treatment with formulations of starch-encapsulated diflubenzuron - field test, 1992.

Treatment[a]	Starch per corn whorl (g)	Mean ± S.D. no. of infested plants per plot					
		12 Aug. (Pre)	17 Aug. (5 d post.)	20 Aug. (8 d post.)	24 Aug. (12 d post.)	27 Aug. (15 d post.)	31 Aug. (19 d post.)
M	0.0175	3.3 ± 2.1	2.0 ± 1.8	4.0 ± 1.4	7.0 ± 3.5	7.5 ± 2.4	9.8 ± 2.9
	0.0350	2.3 ± 2.6	3.0 ± 2.2	5.8 ± 0.5	5.8 ± 1.3	5.0 ± 0.8	7.3 ± 2.8
M + 1% D	0.0175	2.3 ± 2.9	0.8 ± 1.0	2.8 ± 2.1	2.5 ± 1.7	3.8 ± 2.4	7.0 ± 1.2
	0.0350	4.5 ± 4.7	0.8 ± 0.5	5.0 ± 2.8	3.3 ± 2.2	3.8 ± 1.7	8.5 ± 1.9
M + 5% D	0.0175	1.8 ± 1.5	0.0 ± 0.0	1.5 ± 1.3	2.0 ± 1.4	4.5 ± 2.9	9.0 ± 2.6
	0.0350	3.0 ± 1.8	1.5 ± 1.7	2.8 ± 2.1	1.8 ± 1.7	3.0 ± 2.2	6.3 ± 4.2
M + 10% C	0.0175	0.5 ± 1.0	4.8 ± 3.3	5.0 ± 2.9	5.5 ± 2.1	4.8 ± 1.5	6.3 ± 1.0
	0.0350	3.0 ± 1.4	4.3 ± 3.5	5.5 ± 4.1	7.5 ± 3.1	6.3 ± 2.6	7.8 ± 2.2
M + 1% D + 10% C	0.0175	1.8 ± 1.7	1.3 ± 1.9	2.8 ± 2.5	2.3 ± 2.1	4.5 ± 2.9	7.8 ± 2.6
	0.0350	3.8 ± 3.5	1.3 ± 1.3	1.0 ± 0.8	1.8 ± 2.2	2.8 ± 2.2	8.3 ± 0.5
M + 5% D + 10% C	0.0175	3.3 ± 4.7	2.5 ± 2.6	1.5 ± 1.9	1.3 ± 1.0	1.8 ± 1.0	6.0 ± 4.1
	0.0350	4.0 ± 3.2	0.5 ± 1.0	1.3 ± 1.0	1.5 ± 1.7	1.3 ± 0.5	4.0 ± 2.9

[a] M, Mira-gel; D, Diflubenzuron; and C, Coax.

Table 6. Analysis of variance of 1992 field damage data collected during exposure of *S. frugiperda* to starch-encapsulated diflubenzuron.

		F-values[a]				
Source	df	17 Aug.	20 Aug.	24 Aug.	27 Aug.	31 Aug.
Block	3	11.20*	1.04	1.61	2.44	0.98
Diflubenzuron Rate	2	9.87*	9.49*	25.03*	12.11*	1.73
Coax Presence	1	4.04	1.57	0.49	3.59	2.88
Diflubenzuron X Coax	2	0.50	1.18	0.24	1.32	1.21
	1	0.00	0.98	0.08	2.07	0.67
Diflubenzuron X Amt.	2	0.36	0.17	0.03	0.07	1.64
Amount X Coax	1	4.04	3.18	0.49	0.97	0.67
Diflubenzuron X Amt.	2	1.62	0.48	1.21	2.28	0.92
Error MS	33	8.6673	4.78	4.24	3.63	6.96
		Mean no. damaged plants/15 plants[b]				
Diflubenzuron Rate						
0		5.9 a	5.1 a	6.4 a	5.9 a	7.8
1%		1.8 b	2.9 b	2.4 b	3.7 b	7.9
5%		2.1 b	1.8 b	1.6 b	2.6 b	6.3
						N. S.
Coax Presence						
Absent		2.4	3.6	3.7	4.6	8.0
Present		4.1	2.8	3.3	3.5	6.7
		N. S.	N. S.	N. S.	N. S.	N. S.
Granule Rate						
175 mg		3.3	2.9	3.4	4.5	7.6
350 mg		3.3	3.5	3.6	3.7	7.0
		N. S.	N. S.	N. S.	N. S.	N. S.

[a] * indicates significant *F*-test ($P < 0.05$).

[b] Factor means/date followed by the same letter are not significantly different ($P > 0.05$, Least Squares Means). N. S. indicates not significantly different.

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Efficacy of Three Insecticides to Control Insect Pests of Stored Seed Corn[1, 2]

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ABSTRACT Bagged seed corn treated on 1 November at the rate of 8 ppm AI pirimiphos-methyl formulated from pirimiphos-methyl ULV, pirimiphos-methyl (Actellic 5E), chlorpyrifos (Lorsban 3E), or distilled water was stored in an unheated shed for 10 months. Every 2 mo, the shed was artificially infested with the red flour beetle, *Tribolium castaneum* (Herbst), the maize weevil, *Sitophilus zeamais* (Motschulsky), and the Indianmeal moth, *Plodia interpunctella* (Hübner). Measured residue deposition at moth 0 for pirimiphos-methyl ULV, Actellic 5E, and Lorsban 3E was 1.74 ± 0.16, 6.86 ± 1.06, and 7.08 ± 1.58 ppm. respectively. After 10 mo, residues had declined to 0.61 ± 0.07, 2.03 ± 0.08, and 3.78 ± 0.51 ppm, respectively. Insect populations in untreated corn remained low throughout the cooler months and began increasing in May (6 mo). At month 10, red flour beetle populations trapped in untreated corn averaged 83.0 ± 18.2 adults per 17.25 kg corn, while the maximum in the three chemical treatments was 11.5 ± 4.2 adults per 17.25 kg. At month 10, maize weevil populations in untreated corn averaged 643.5 ± 381.3 adults per 17.25 kg, with a maximum of only 11.5 ± 4.2 per 17.25 kg in the chemical treatments. Few live Indianmeal moths were detected in untreated controls or the chemical treatments at month 10. Both Actellic 5E and Lorsban 3E are suitable protectants for seed corn.

KEY WORDS pirimiphos-methyl, chlorpyrifos, corn, *Tribolium castaneum,* Coleoptera, Tenebrionidae, *Sitophilus zeamais,* Curculionidae, *Plodia interpunctella,* Lepidoptera, Pyralidae

The organophosphate insecticide malathion is being removed from the post-harvest market and may not be labeled in the United States as a protectant for seed corn (Abramson 1991). Pirimiphos-methyl, another organophosphate insecticide, is the only alternative to malathion for use on seed corn. Because harvested corn stored as bagged seed in warehouses is extremely vulnerable to insect infestations, additional protectants would greatly benefit pest management programs.

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[2] This article reports the results of research only. Mention of a proprietary product does not constitute a recommendation or endorsement by the USDA.

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Lahue (1976, 1977) established the efficacy of pirmiphos-methyl as a seed treatment, but in these tests, 1-kg lots of treated corn were stored inside bags and the stored bags were not subject to constant infestation pressure from insects. The objectives of this study were to: 1) evaluate residual protection of pirimiphos-methyl ULV and chlorpyrifos on bagged seed corn, and 2) determine residue degradation of these insecticides during storage.

Materials and Methods

Three insecticide formulations were obtained from Wilbur-Ellis Company (Burlington, IA): 1) WECO 111015, 227 g [AI]/3.784 liters Ready-to-use (RTU) pirimiphos-methyl ULV; 2) pirimiphos-methyl (Actellic 5E) 2.27 kg[AI]/3.784 liters EC; and 3) chlorpyrifos (Lorsban 3E, Dow Elanco, Indianapolis, IN) 1.36 kg [AI]/3.784 liters EC. Wilbur-Ellis also provided the seed corn, which had been treated with captan fungicide as a standard procedure for storing seed corn prior to bagging. Each bag contained approximately 17.25 kg of corn.

Each insecticide treatment was applied at a calculated dosage of 8 ppm per 17.25 kg of corn. A Microgen ULV fogger (Microgen Equipment Corporation, San Antonio, TX) was used to apply the RTU formulation, and remaining treatments were applied using a delivery system equipped with a Teejet 650033 nozzle (Spraying Systems, Wheaton, IL). Each treatment was replicated 4 times and an equal number of untreated controls treated with distilled water were included. Treatments were applied by removing the corn from the bag and spraying the corn as it fell from a conveying chute into the bag. Immediately after treatment, a 300 g corn sample was taken from each bag for residue analysis and the bags were re-sewn.

After the treatment process was completed (1 November), the bags were transported to an insulated metal shed (12.2 m by 3.7 m by 2.8 m) and the treatments and replicates were randomly arranged along the side walls. One thousand unsexed 1 to 2-wk-old adult maize weevils, *Sitophilus zeamais* (Motschulsky), 1,000 unsexed adult red flour beetles, *Tribolium castaneum* (Herbst), and 1,000 unsexed 1 to 2-day-old adult Indianmeal moths, *Plodia interpunctella* (Hübner), were released into the shed. All insects were obtained from pesticide-susceptible colonies maintained at the USDA-ARS Savannah Laboratory and were reared under controlled conditions (28 ± 1°C, 60 ± 2% RH, 12:12[L:D]).

After 3 weeks, the seams in a small area in the top center of the bag were cut to make a hole, and beetle populations inside the bag were assessed using a plastic pitfall trap (Grain Guard, Verona, WI) that was pushed through the hole into the bag. Each trap was tied with a cord so it could be easily removed. Indianmeal moth populations were assessed by placing a rolled cardboard pupation trap just below the surface of the corn. These traps were left for one week before they were removed. When traps were removed, a grain trier was used to take two 300 g samples, one for residue analysis and one to determine the percentage of insect-damaged kernels by examining 100 randomly-selected whole kernels. Kernels were classified as insect-damaged if they contained emergence holes or visible feeding damage

(tunnels, chewed ends, etc.). After sampling was completed, a clamp was placed over the area cut near the top of each bag, and the shed was reinfested with the numbers and species listed above. The corn was stored in the shed for 10 mo and sampled after 1, 2, 4, 6, 8, and 10 mo (10 December, 14 January, 3 March, 15 May, 9 July, and 11 September, respectively) in the manner described above. Temperature and relative humidity in the shed were monitored using a recording hygrothermograph.

Corn samples were held at -17.8°C until analyzed for pirimiphos-methyl and chlorpyrifos residues using the following generalized procedure for organophosphates, described by Arthur et al. (1987, 1988). The corn was ground in a Waring blender, 40 g were extracted in 120 ml pesticide-grade acetone by shaking 3 h on a wrist-action shaker, and the extract filtered. Analysis was performed on a Varian model 3700 gas chromatograph (Varian Corporation, Walnut Creek, CA), equipped with a flame photometric detector (FPD). Two subsamples were taken from each replicate sample. For each subsample, one microliter of the filtrate was injected into a 2m × 2mm Inside Diameter glass column packed with 5% OV-101 on 60/80 mesh Gas-Chrome Q (Applied Science Laboratories, State College, PA). The temperature of the injection port was 290°C, detector and column oven temperatures were 300 and 210°C, respectively. Flow rates were: helium, 30 ml/min; hydrogen, 140 ml/min; air #1, 80 ml/min, air #2, 170 ml/min. Residues were quantified using a Varian CDS 111 recording integrator.

Trap catches for each insect species were combined on each sample date and analyzed using the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute 1987) to determine significant differences between treatments at each sampling interval. Orthogonal contrasts were used to compare differences among treatments.

Results and Discussion

Average daily temperatures in the storage shed were below 20°C for the first 120 d of storage (Fig. 1A), which is near the minimum developmental temperture range of 18 to 22°C for most stored-product insects (Howe 1965). After 180 d of storage, average temperatures generally exceeded 20°C, and ranged between 20 and 30°C until the conclusion of the test. Average relative humidity fluctuated from day to day, and there was no general pattern of increase as temperatures warmed in the spring (Fig. 1B).

Measured residue deposition of the ULV pirimiphos-methyl formulation was 21.7% of the calculated dosage of 8 ppm (Fig. 2). The specified application rate was 3690 ml per 27,272 kg, or 2.34 ml per 17.27 kg of corn, and the Microgen misting unit evenly distributed this 2.34 ml onto the corn. Residue deposition from the more conventional Lorsban 3E and Actellic 5E formulations was 88.5 and 85.7% of the calculated dosage of 8 ppm, respectively.

Red flour beetle populations in untreated seed corn did not exceed 1.0 adults until month 6 (15 May); when the test was concluded at month 10 (11 September) populations averaged 83.0 ± 18.2 per trap (Table 1). At month 8 (9 July), 1.2 ± 0.2 adults were trapped in seed corn treated with the

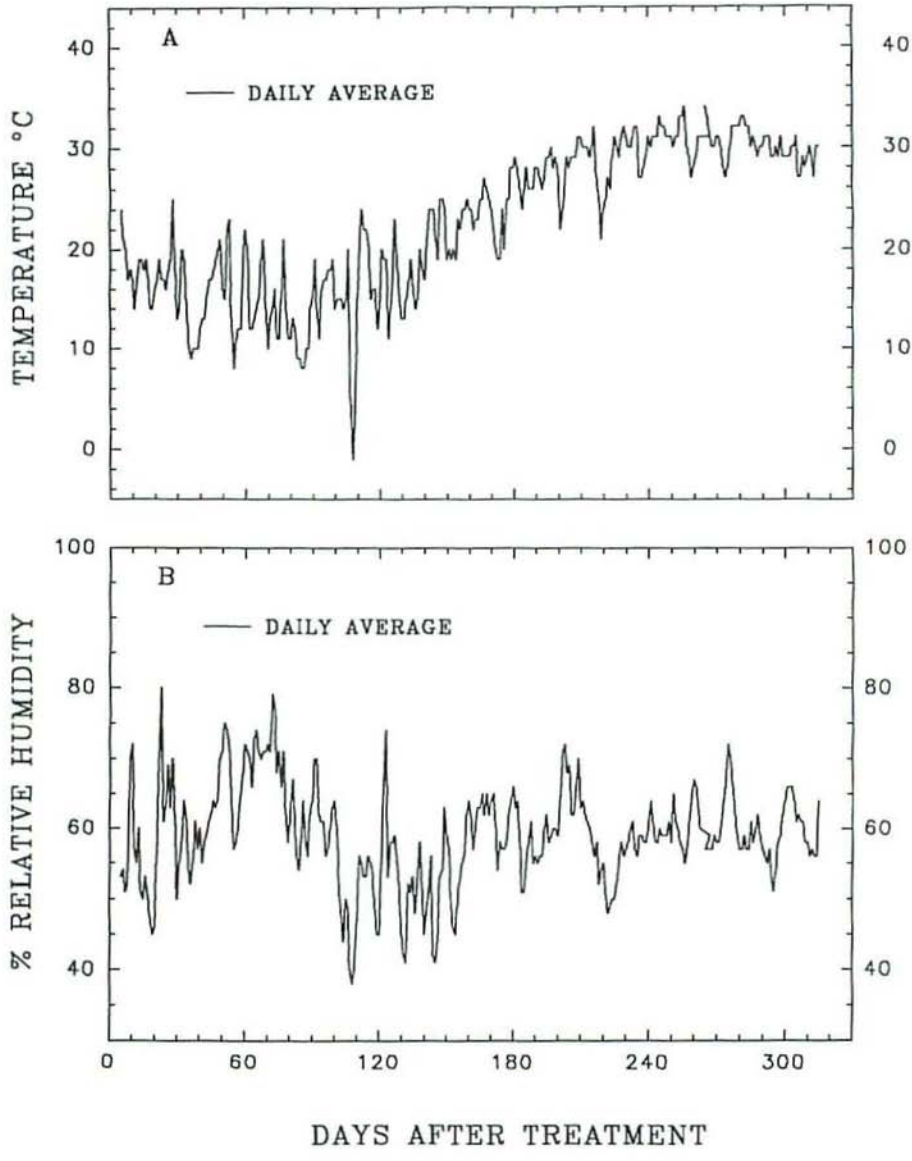

Fig. 1. Average daily maximum and average daily minimum temperatures (A) and relative humidity (B) in the corn storage shed from 1 November (day 0) to 11 September (day 311).

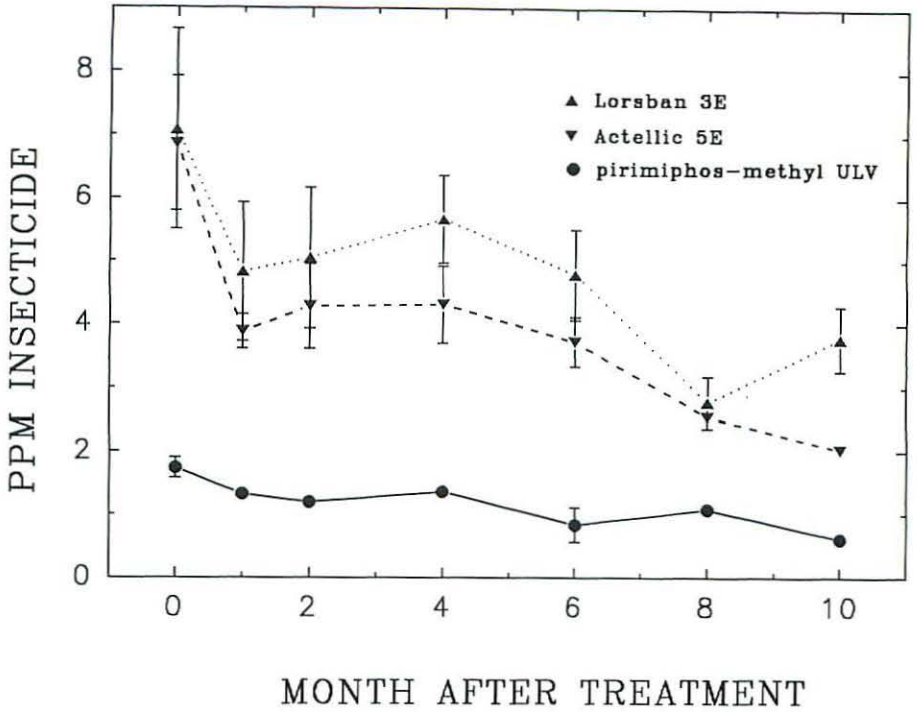

Fig. 2. Insecticide residue (means ± SEM) on seed corn immediately after treatment and at 1, 2, 4, 6, 8, and 10 months of storage in an insulated metal shed (dots = pirimiphos-methyl ULV, upright triangles = Lorsban 3E, inverted triangles = Actellic 5E). Each value is an average of 4 replications and 2 subsamples for each replication.

pirimiphos-methyl ULV formulation, but no adults were found in corn treated with either the Actellic 5E or Lorsban 3E until month 10. At the conclusion of the test, red flour beetle populations in the controls were significantly greater than those in the three treatments (F = 46.61; d f= 1,12, P = 0.0001). There were no significant differences in red flour beetle populations from corn treated with Actellic 5E vs ULV pirimiphos-methyl and Lorsban 3E (F = 0.02; df=1,12; P = 0.8987) or ULV pirimiphos-methyl vs Lorsban 3E (F = 0.17; df=1,12; P = 0.6869).

Substantial maize weevil populations in untreated seed corn apparently did not develop until month 6 (15 May), but by the conclusion of the test at month 10 (11 September) an average of 643.5 ± 381 adults per trap were collected from the bags containing the untreated seed corn (Table 1). Populations in corn treated with ULV pirimiphos-methyl, Actellic 5E, or Lorsban 3E did not exceed 1.0 until month 10. Maize weevil populations in untreated controls were significantly greater than those in the three

Table 1. Mean number (± SEM) of adult red flour beetles, adult maize weevils, and Indianmeal moths (larvae, pupae, and adults) trapped from untreated corn (UTC) and in corn treated with 0.5 ULV pirimiphos-methyl (PM), Actellic 5E (A), or Lorsban 3E (L) and stored for 10 months. Corn was sampled after 1, 2, 4, 6, 8, and 10 months of storage.

	Months After Treatment					
Treatment	1	2	4	6	8	10
Red Flour Beetle						
UTC	0.2 ± 0.2	0.2 ± 0.2	0.5 ± 0.3	4.2 ± 1.5	9.0 ± 3.6	83.0 ± 18.2
0.5 PM	0.0 ± 0.0	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.0	1.2 ± 0.2	12.0 ± 2.2
5.0 A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	7.7 ± 4.2
3.0 L	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	6.5 ± 1.4
Maize Weevil						
UTC	0.0 ± 0.0	1.2 ± 0.2	2.0 ± 1.7	10.7 ± 10.1	137.0 ± 101.2	643.5 ± 381.8
0.5 PM	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	11.5 ± 4.2
5.0 A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	5.2 ± 2.8
3.0 L	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.7 ± 0.5	2.7 ± 1.1
Indianmeal Moth						
UTC	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.2 ± 1.3	4.5 ± 2.2	0.2 ± 0.2
0.5 PM	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
5.0 A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
3.0 L	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.0

treatments (F = 8.25; df=1,12; P = 0.0136). There were no differences between Actellic 5E vs ULV pirimiphos-methyl and Lorsban 3E (F = 0.00; df=1,12; P = 0.9937), or ULV pirimiphos-methyl vs 3E chlorpyrifos (F = 0.00; df=1,12; P = 0.9747).

Few Indianmeal moths were detected in seed corn treated with the three insecticide formulations. Indianmeal moth populations were trapped in untreated controls only at months 6 and 8, and the average of all life stages (larvae, pupae, and adults) was 2.2 ± 1.3 and 4.5 ± 2.2 per trap, respectively. This low number could have been related to the beetle infestations; the red flour beetle can prey on moth eggs (Lecato & Flaherty, 1973). Similar results have been reported in other studies with corn (Arthur et al., 1990) and peanuts (Arthur et al. 1988, Arthur 1989).

Although there were no insect-damaged kernels in the untreated controls until 6 months, the percentage of insect-damaged kernels had increased to an average of 18.5 ± 7.8% at month 10 (Table 2). This extensive damage was primarily caused by the heavy maize weevil infestation that had developed in the untreated controls. Previous tests have established a consistent positive correlation between insect infestations and commodity damage (Arthur et al. 1991, Arthur 1992). The percentage of insect-damaged kernels in the seed corn treated with the three chemical formulations did not exceed 1% at month 10. After 10 mo the damage percentage in the untreated controls was significantly greater than damage in the three treatments (F = 23.13; df = 1,12; P = 0.0004), but there was no significant difference in percentage of damaged kernels between Actellic 5E vs ULV pirimiphos-methyl and Lorsban 3E (F = 0.09; df = 1,12; P = 0.7725), or ULV pirimiphos-methyl vs Lorsban 3E (F = 0.07; df = 1,12; P = 0.8022).

The ULV pirimiphos-methyl formulation was effective even with the low deposition of active ingredient, and the protection given by Actellic 5E and Lorsban 3E appeared to be equal. Both Actellic 5E and Lorsban 3E appear to be suitable as protectants of seed corn, however, additional developmental work may be necessary for the ULV formulation. Although insects were introduced into the storage environment during the entire test, significant populations did not develop in untreated seed corn until late spring. Low winter temperatures in the storage shed probably limited insect populations because they were below optimum levels for the 3 species used in the test (Howe 1965).

Table 2. Mean percentage (± SEM) of insect-damaged kernels from untreated corn (UTC) and corn treated with 0.5 ULV pirimiphos-methyl (PM), Actellic 5E (A), or Lorsban 3E (L). Corn was sampled after 1, 2, 4, 6, 8, and 10 months of storage.

	Month After Treatment					
Treatment	1	2	4	6	8	10
UTC	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.3	4.7 ± 1.9	18.5 ± 7.8
0.5 PM	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.0	0.0 ± 0.0	0.7 ± 0.5
5.0 A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
3.0 L	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2

Acknowledgment

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Anatomical Characteristics of Maize Resistant to Leaf Feeding by Southwestern Corn Borer (Lepidoptera: Pyralidae) and Fall Armyworm (Lepidoptera: Noctuidae)[1]

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ABSTRACT Maize, *Zea mays* L., inbred lines with resistance to leaf feeding by the larvae of the southwestern corn borer. *Diatraea grandiosella* Dyar, and the fall armyworm, *Spodoptera frugiperda* (J. E. Smith) have been released. The mechanisms of resistance are larval antibiosis and nonpreference; however, the factor or factors causing the resistance are not fully understood. In this study, selected anatomical characters of inner whorl tissue of several leaf feeding susceptible and resistant maize inbreds were compared. For both insect species, correlations were calculated between the anatomical characters and leaf feeding damage scores and between the anatomical characters and weights of larvae. Significant differences were detected between several anatomical characters of the resistant and susceptible inbreds. The most striking and consistent difference between the resistant and susceptible inbreds was the thickness of the cuticle and the epidermal cell wall (cell wall complex). The cell wall complex of the resistant inbreds was 1.7x thicker than that of the susceptible inbreds. Significant correlations existed between anatomical characters of the inner whorl and both leaf feeding damage scores and larval weights. The characters most closely associated with leaf feeding damage and larval weights were the upper and lower cell wall complexes. The inner whorl tissue from the resistant inbreds tended to be tougher than comparable tissue of the susceptible inbreds.

KEY WORDS Maize, Plant resistance, *Diatraea grandiosella, Spodoptera frugiperda*

Nine maize, *Zea mays* L., inbred lines with leaf feeding resistance to the southwestern corn borer, *Diatraea grandiosella* Dyar, and the fall armyworm, *Spodoptera frugiperda* (J. E. Smith), have been released by researchers at the Crop Science Research Laboratory (ARS-USDA) located at Mississippi State, MS.

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[5] This article reports the results of research only. Mention of a proprietary product for reader information does not constitute an endorsement or recommendation for its use by the USDA.

The resistant inbreds were derived from exotic germplasm originating in the Caribbean Islands, primarily Antigua (Williams & Davis, 1989; Williams et al. 1990a). In over 20 years of screening a large amount of germplasm, we have not found any other source of resistance to leaf feeding (FMD, unpublished data). The mechanisms of resistance are larval nonpreference and antibiosis (Wiseman et al. 1981, 1983; Davis et al. 1989a). Additionally, this germplasm has been found to be resistant to other lepidopterans such as the sugarcane borer, *Diatraea saccharlis* (Fab.) and the European corn borer, *Ostrinia nubilalis* (Hübner) (Davis et al. 1988).

The factor(s) responsible for this resistance may be biochemical and/or anatomical. Research continues to be conducted to determine if the basis of the resistance is biochemical. Results so far have shown that the leaf feeding resistant Mississippi ('Mp') maize genotypes differ from susceptible genotypes in amounts of crude fiber and residue, hemicellulose, crude protein, and certain nonessential amino acids (Hedin et al. 1984, 1990). Additionally, Callahan et al. (1992) found differences in polypeptides between whorl tissue of resistant and susceptible maize inbred lines. The importance of the polypeptide differences to resistance has not been determined. The compound DIMBOA associated with leaf feeding resistance to the European corn borer was found to be in very low concentrations in the 'Mp' lines and relatively nontoxic to the southwestern corn borer (Hedin et al. 1984).

Ng (1988) compared several anatomical characters of the leaf feeding resistant maize inbred line 'Mp704' to those of a highly susceptible inbred line `Ab24E' using light and scanning electron microscopy. He found that the whorl leaf tissue of 'Mp704' differed from like tissue of 'Ab24E' in the number of vascular bundles per unit distance and thickness of the cuticle and outer cell wall of the epidermis on both upper and lower leaf surfaces. The objectives of our current study were to broaden the scope of his study to compare anatomical characters and toughness of whorl leaf tissue from several additional resistant and susceptible maize inbred lines and to correlate the anatomical characters with southwestern corn borer and fall armyworm leaf feeding ratings and larval growth.

Materials and Methods

Anatomical Study. In 1990, four leaf feeding resistant and six leaf feeding susceptible maize inbred lines (Table 1) were grown in the field to obtain inner whorl tissue for anatomical observations and measurements. The lines were planted in single-row plots (5.08 m long and 0.97 m apart) arranged in a randomized complete block design with three replications. Each row was planted with 35 seeds and thinned to 20 plants at the early whorl stage. Agronomic practices common to our area of Mississippi were followed.

When the plants reached the V7-8 stage according to the description of Ritchie & Hanway (1982), six plants per row were cut and tissue was excised from the whorl portion. This stage was selected because it corresponds to the stage we infest plants for resistance screening.

Table 1. Anatomical characters of inner whorl tissue taken from maize inbred lines with varying levels of leaf feeding susceptibility to the southwestern corn borer and the fall armyworm.

Inbred line	Classification of susceptibility[a]	Thickness (± SD μm) of			No. vascular bundles per 1.5 mm[b] ± SD
		Overall leaf[b]	Upper cell wall complex[b]	Lower cell wall complex[b]	
Mp708	R	235.17 ± 3.07	5.69 ± 0.13	5.54 ± 0.18	11.18 ± 0.29
Mp704	R	218.17 ± 3.73	4.87 ± 0.10	4.78 ± 0.09	13.00 ± 0.50
Mp496	R	216.04 ± 5.02	4.25 ± 0.10	4.13 ± 0.09	12.67 ± 0.29
Mp706	R	203.65 ± 1.62	4.73 ± 0.09	4.67 ± 0.20	12.67 ± 0.29
SC229	S	201.03 ± 2.58	2.79 ± 0.09	2.75 ± 0.05	10.00 ± 0.00
Tx601	S	189.48 ± 2.21	3.38 ± 0.08	3.21 ± 0.09	10.50 ± 0.50
Va35	S	188.78 ± 3.73	3.26 ± 0.13	3.24 ± 0.30	11.33 ± 0.76
L678	S	177.09 ± 3.25	2.14 ± 0.13	2.11 ± 0.08	9.67 ± 0.29
GT106	S	164.49 ± 2.03	3.31 ± 0.17	3.26 ± 0.13	9.33 ± 0.29
Mp313E	S	155.13 ± 1.84	2.90 ± 0.13	2.87 ± 0.15	10.33 ± 0.29
	LSD (0.05)	4.36	0.19	0.26	0.68

[a] R = leaf feeding resistant; S = leaf feeding susceptible.

[b] Results of analysis of variance:
[overall leaf thickness - $F = 289.85$; df = 9,18; $P < 0.01$]
[upper cell wall complex thickness - $F = 288.21$; df = 9,18; $P < 0.01$]
[lower cell wall complex thickness - $F = 155.43$; df = 9,18; $P < 0.01$]
[number of vascular bundles - $F = 33.47$; df = 9,18; $P < 0.01$]

The whorl leaf adjacent to the furl leaves, which sustains substantial feeding by the southwestern corn borer and fall armyworm larvae, was removed from each plant. Tissue sampling was restricted to the larval feeding area (yellow-green) which begins approximately 7.6 cm below the point where the margins of the whorl leaf fold and touch each other. Two pieces (about 1 cm^2) were taken from each leaf. One was examined by scanning electron microscopy (SEM) and the other by light microscopy (LM).

The leaf sections were freeze-dried, mounted on aluminum stubs, and coated with gold-palladium for SEM. They were examined for differences in trichome type and density using JEOL35CX and Cambridge 360S SEMs at 10 kv. Material for LM was fixed in 3% glutaraldehyde in phosphate buffer, pH 7.0. After dehydration in a graded series of ethanol, the specimens were embedded in Spurr's low viscosity medium. The 1-μm sections were stained with toluidine blue. Six sections, each 1 μm thick and 5 μm apart, were taken from each plant for evaluation. Measurements were taken with a light microscope that had a calibrated ocular micrometer. The overall leaf thickness and the thickness of the upper and lower cell wall complex (cuticle plus outer cell wall of epidermis) were measured. Additionally, the number of vascular bundles were counted. Counts were always started with the first vascular bundle on the left hand side of the tissue section, and the number of bundles in a 1.5 mm distance was recorded.

Leaf Toughness Study. In 1990 and 1991, the same leaf feeding susceptible and resistant maize inbreds used in the anatomical study were tested for differences in whorl leaf toughness, except 'L678' was replaced by 'Ab24E' in 1991. The statistical design and procedures to grow the field plants were the same as described for the anatomical study.

When the plants reached the V7-V8 stage of growth, eight plants per row were removed and taken to the laboratory. The plants from each row were held in a plastic bag placed in a chest containing ice to preserve their turgidity. The first whorl leaf adjacent to the furl leaves was excised from each plant just prior to testing for toughness. A section of tissue (minus mid-rib) about 5.0 cm by 7.5 cm was cut from the yellow-green area of each leaf. The section was then placed into a Mullen Tester (Fig. 1) to determine the pressure required to split the leaf tissue (TAPPI Test Methods, 1991). The Mullen Tester was designed to determine tensile strength of paper and utilizes hydraulic fluid to provide pressure for splitting the test material.

Leaf Feeding Damage and Larval Growth. Leaf feeding damage and larval growth data for both species were obtained from two other experiments conducted during 1990 for the purpose of determining correlations with anatomical characters of whorl leaf tissue. In each experiment, the inbreds were planted in a randomized complete block design with three replications. Each inbred was represented within a replication by a single row of 20 plants. When the plants of each experiment reached the V6-V8 leaf stage, they were infested with southwestern corn borer or fall armyworm neonate larvae at a rate of 30 larvae per plant (Davis et al. 1989b). The larvae were obtained from our laboratory culture using the rearing procedures described by Davis (1989). Voucher specimens of both species have been deposited in the Mississippi Entomological Museum located at Mississippi State University.

Fourteen days after infestation, leaf feeding damage caused by the southwestern corn borer was scored using a visual rating scale of 1 to 9, where 1 = slight damage and 9 = heavy damage (Davis et al. 1989b). On the same day, 10 plants were dissected from each row and the surviving larvae were counted and weighed. For the fall armyworm, plants were scored for leaf feeding damage 7 days after infestation using a visual rating scale described by Davis et al. (1992). On the 10th day after infestation, 10 plants per row were dissected and the surviving fall armyworm larvae were counted and weighed.

Statistical Analyses. Plot means for all traits were calculated and used in the analysis of variance (SAS Institute 1987). Data on toughness of the whorl tissue were analyzed by year and by combining data over years. Means were separated using the Least Significant Difference Test at $P = 0.05$.

Coefficients of determination were calculated for each insect species between anatomical characteristics of the inner whorl tissue and 1) leaf feeding damage and 2) weights of larvae reared on the inbred lines.

Results

The selected whorl leaves from resistant lines were significantly thicker than those from susceptible lines with one exception. Leaf thickness of the

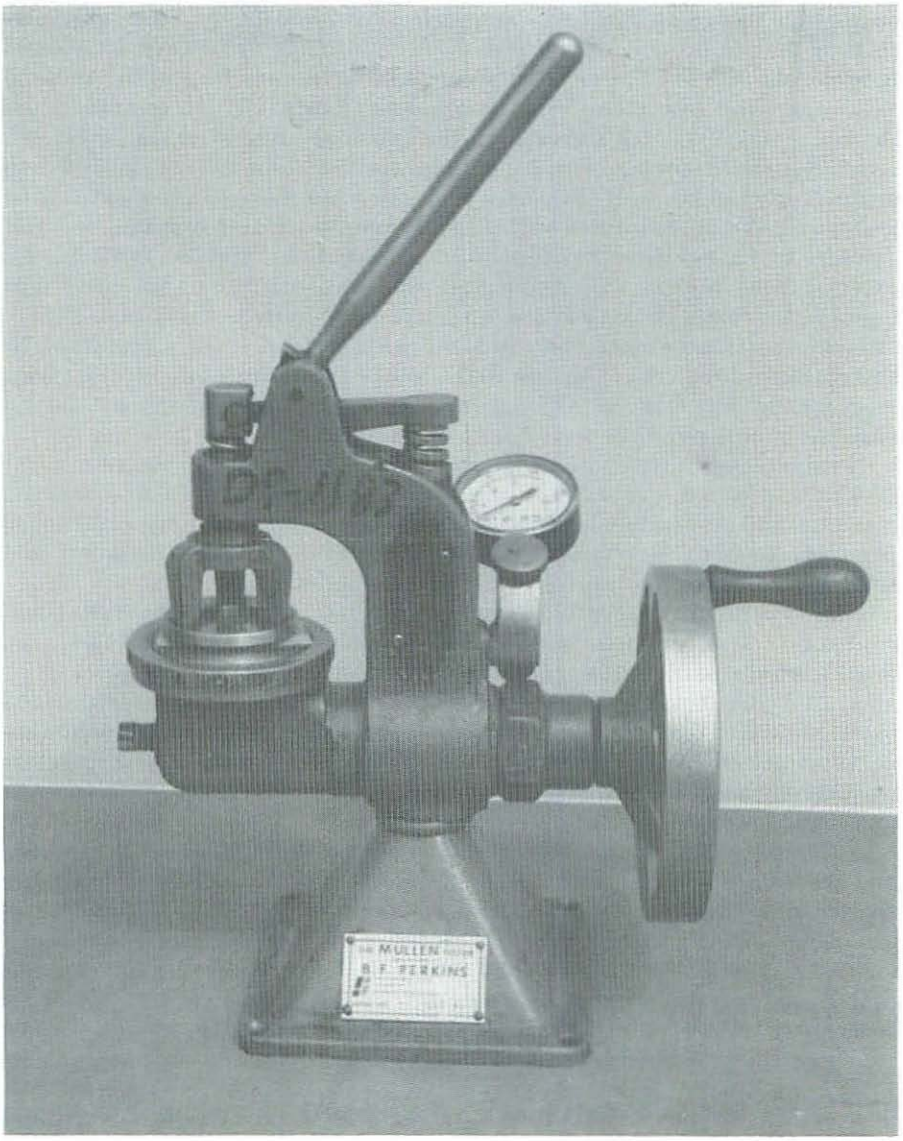

Fig. 1. Mullen Tester used to determine toughness of inner whorl tissue of maize.

resistant inbred 'Mp706' did not differ significantly ($P > 0.05$) from the susceptible inbred 'SC229'. The resistant inbred 'Mp708' had a significantly thicker leaf than any other inbred. A significant difference was found between the leaves of resistant and susceptible inbreds for the thickness of the upper and lower cell wall complexes (Table 1). On average, leaf thickness was about 1.7 X greater in the resistant inbreds for the upper and lower cell wall complex (Fig. 2). Again, the resistant inbred 'Mp708' had significantly thicker wall complexes than the other inbreds. The leaves from resistant inbreds contained significantly more vascular bundles per unit distance of 1.5 mm than did those of the susceptible inbreds (Table 1). An exception was 'Mp708' where no significant difference in number of vascular bundles was found between it and the susceptible inbreds 'Va35' and 'Tx601'. It is interesting to note that 'Mp708' was derived from a resistant by susceptible inbred cross ('Mp704' and 'Tx601') (Williams et al. 1990b). This may explain why 'Mp708' differed from the other resistant inbred lines in vascular bundle numbers per 1.5 mm of distance.

No significant differences in numbers of nonglandular trichomes per cm^2 ($F = 0.99$; df = 9,8; $P > 0.05$) on the upper leaf surface were found between resistant and susceptible inbreds. The number of trichomes per cm^2 ranged from 241 to 271. Trichome types were the same for both resistant and susceptible inbreds and were only of the nonglandular type.

Highly significant correlations existed between the anatomical leaf characters and leaf feeding damage scores of both species (Table 2). Significant correlations also existed between the anatomical characters measured and larval weights of the southwestern corn borer. Upper and lower cell wall thicknesses and number of vascular bundles per 1.5 mm were significantly correlated to fall armyworm larval weights. The characters most closely associated with leaf feeding damage and larval weights were the upper and lower cell wall complexes.

A significant interaction was found between leaf toughness of the inbreds and the environment ($F = 3.11$; df = 8,8; $P > 0.05$). Analyses within years showed significantly greater pressure was required to split or tear the whorl leaf tissue of the resistant inbreds 'Mp496' and 'Mp706' than was required for the susceptible inbreds in 1990 (Table 3). Leaf toughness of the other resistant inbreds 'Mp704' and 'Mp708' differed significantly from all susceptible inbreds except 'L678' and 'Tx601'. In 1991, 'Mp704' and 'Mp708' exhibited the greatest toughness. When data over years were combined, no significant differences among inbreds were detected (Table 3). Even with the lack of consistency in toughness among the resistant and susceptible inbreds, the tendency was for the tissue from the resistant inbreds to require more pressure to split than like tissue of the susceptible inbreds.

Discussion

Our results show significant anatomical differences between the resistant and susceptible maize inbreds, thus confirming the differences observed by Ng (1988) for the inbreds 'Mp704' and 'Ab24E'. The most prominent and consistent difference is the thickness of the upper and lower cell wall

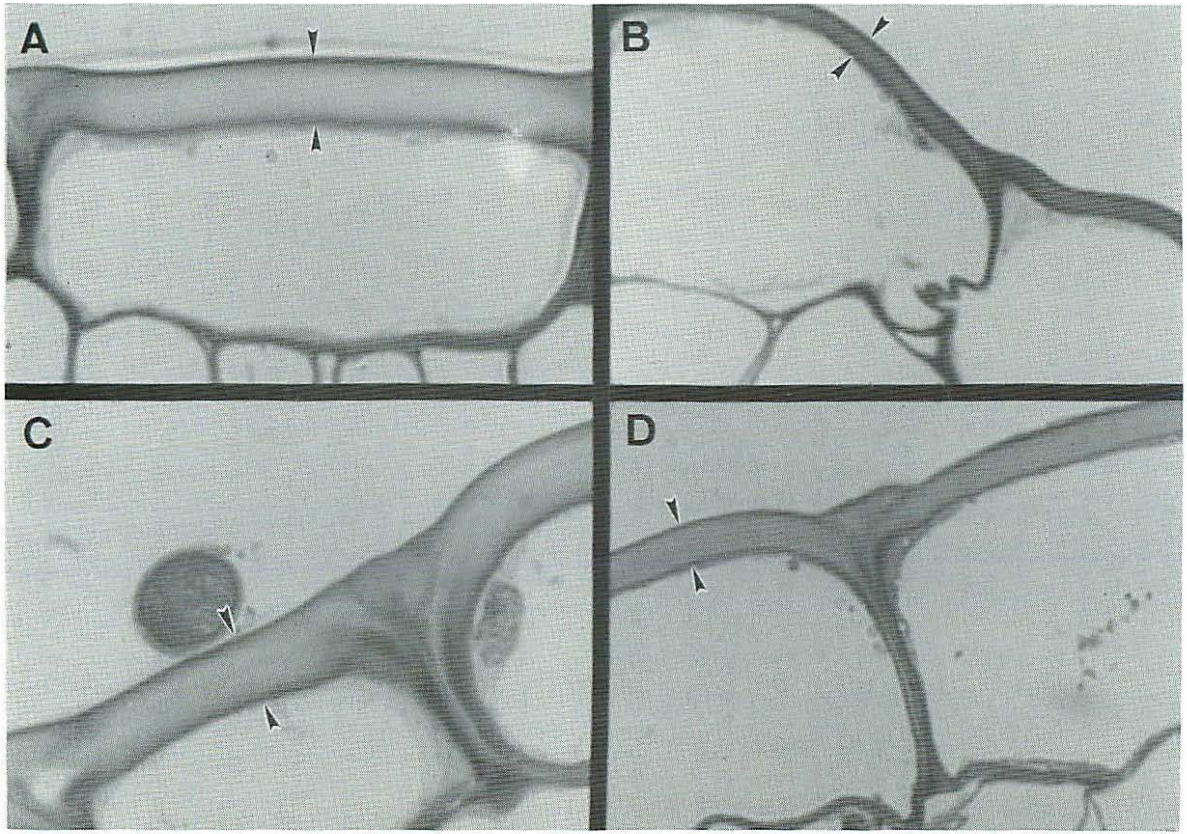

Fig. 2. Upper cell wall complex thickness (arrows) of four maize inbreds: (a) 'Mp708' and (c) 'Mp706' resistant inbreds; (b) 'Mp313E' and (d) 'L678' susceptible inbreds. Magnification is 400X for all photomicrographs.

Table 2. Correlations (r^2 values) of leaf damage scores and larval weights of southwestern corn borers and fall armyworms reared on leaf feeding susceptible and resistant maize inbred lines to anatomical characters of the inner whorl tissues.

Insect	Anatomical leaf characters			
	Overall leaf thickness	Upper cell wall complex thickness	Lower cell wall complex thickness	No. vascular bundles per 1.5 mm
Southwestern corn borer				
Damage score	0.73**	0.85**	0.85**	0.46*
Larval weight	0.64**	0.73**	0.72**	0.56**
Fall armyworm				
Damage score	0.64**	0.82**	0.83**	0.60**
Larval weight	ns	0.50*	0.50*	0.49*

* Significant at ($P < 0.05$); ** Significant at ($P < 0.01$).

complexes. Anatomical characteristics, such as thickened cell walls, have been associated with resistance of plants to insect attack (Norris & Kogan 1980; Southwood 1986; Smith 1989). These characters can result in the insects' food being tough to tear apart, ingest, and digest. However, the lack of consistency in leaf toughness among the resistant and susceptible lines appears to indicate that this character as measured in this investigation may not be as closely associated with resistance as expected.

Thicker cell walls and more vascular bundles per unit distance may result in food of lower nutritional quality, causing reduced growth of larvae feeding on it. Since we previously demonstrated that both southwestern corn borer and fall armyworm fed on diets containing finely ground lypholized leaf tissue grow more slowly on tissue of resistant genotypes (Williams et al. 1990b), thicker cell walls and more vascular bundles may be more closely associated with resistance by nutrition rather than by toughness.

Researchers at the International Center for Improvement of Maize and Wheat (CIMMYT) in Mexico have produced a multiple borer resistant (MBR) maize population. In developing the MBR population, our 'Mp' inbred lines and our 'MpSWCB-4' population were used substantially as donors of resistant genes (Benson 1986). Bergvinson (1993) investigated the possible factors in the MBR population that confer resistance to the European corn borer. He found significant correlations between field resistance based on leaf feeding damage scores and fiber, cell wall dehydrodiferulic acid, and protein contents. Also, leaf toughness as recorded by an instron technique was found to be inversely related to leaf feeding damage ratings. Fiber and dehydrodiferulic acid content were observed to give the best regression variables to account for leaf toughness and leaf feeding damage ratings in both field and laboratory experiments. His results with CIMMYT's MBR germplasm parallel, generally, the findings on 'Mp' resistant germplasm by Hedin et al. (1984) and by our present study.

Table 3. Pressure (Pascals ± SD) required to split whorl tissue of resistant and susceptible maize inbred lines (toughness test).

Line	Classification of susceptibility[a]	Pascals ± SD - Year - 1990[bc]	1991[bc]	Combined years
Mp496	R	57,960 ± 6,900	44,160 ± 6,210	51,060 ± 9,660
Mp706	R	57,960 ± 2,070	37,950 ± 2,760	47,610 ± 11,040
Mp704	R	51,060 ± 1,380	51,750 ± 4,830	51,750 ± 2,760
Mp708	R	51,060 ± 4,140	55,890 ± 7,590	53,820 ± 6,210
L678	S	46,920 ± 6,210	—	–
Tx601	S	44,850 ± 1,380	33,120 ± 1,380	38,640 ± 6,210
GT106	S	43,470 ± 2,760	28,290 ± 2,070	35,880 ± 8,970
Mp313E	S	37,260 ± 2,760	29,670 ± 2,070	33,120 ± 4,830
Va35	S	33,120 ± 3,450	33,120 ± 1,380	33,120 ± 2,070
SC229	S	31,050 ± 5,520	37,950 ± 1,380	34,500 ± 4,830
Ab24E		—	28,980 ± 6,900	–
LSD (0.05)		6,900.0	6,900.0	ns

[a] R = leaf feeding resistant; S = leaf feeding susceptible.
[b] Pressure in pounds per squre inch was converted to pascals (6900 × PSI).
[c] Results of analysis of variance: [1990 - $F = 15.45$; df = 9,18; $P < 0.01$]; [1991 - $F = 17.87$; df = 9,18; $P < 0.01$]; [1991-1992 - $F = 3.11$; df = 8.8; $P > 0.05$].

These studies suggest that the leaf feeding resistance in both the 'Mp' inbreds and the CIMMYT/MBR population is caused by a combination of factors involving fiber content, cell wall anatomy and biochemistry, and protein content. These resistant factors manifest themselves as being a tougher tissue for the neonates to tear apart and consume. Once consumed, the larvae have to digest and assimilate food of a lower nutritional value.

Even though differences in biophysical and biochemical properties of the whorl leaves appear to be factors responsible for resistance, we must be cautious since conclusions have been and are presently based on correlations. For example, the resistant inbreds used in the present study were derived from a common background (Antigua), whereas none of the susceptible inbreds were derived from this background. It is possible that the anatomical characters common to the resistant inbreds are not really related to resistance. On the other hand, these characters, which are significantly different from those of the susceptible inbreds, could be responsible for at least part of this resistance. Additional experiments using susceptible and resistant genotypes derived primarily from Antigua germplasm will be necessary to determine the true relationship of these characters to resistance.

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Efficacy of Topically Applied Pyrethroids Against Eggs of *Boophilus microplus* (Canestrini) (Acari: Ixodidae)[1]

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ABSTRACT Efficacy of three pyrethroid acaricides (permethrin, cypermethrin, and cyfluthrin) at concentrations of 0.1, 0.05, 0.01 and 0.005% active ingredient (AI) applied topically to *Boophilus microplus* (Canestrini) eggs of three different age classes was determined. At the rate of 0.1% AI, permethrin provided ≥ 94% reduction of hatch in all age classes of eggs. However, at the two lower concentrations (0.01 and 0.005% AI) reduction of hatch was ≤ 35% except against 1-d-old eggs at the 0.01% AI concentration; thus permethrin was less effective at the lower concentrations than the other materials tested. Cypermethrin provided ≥ 93% reduction of hatch at concentrations of ≥ 0.01% AI, but was not effective against 10- and 21-d-old eggs at 0.005% AI (71.1 and 75.9% reduction, respectively). Based on the effect of concentration and age class, cyfluthrin provided ≥ 96% reduction of hatch against all ages at all concentrations. It was concluded that all three compounds applied at manufacturers' recommended concentration (0.1% AI for permethrin and 0.05% AI for cypermethrin and cyfluthrin) would be excellent candidates in the cleaning and disinfesting of premises to eliminate *B. microplus* eggs.

KEY WORDS Acari, Ixodidae, ovicides, *Boophilus microplus*, pyrethroids

Although *Boophilus* ticks have been eradicated from all but eight South Texas counties along the Texas-Mexico border, occasional outbreaks still occur in livestock originating from Mexico where these ticks are endemic. Among the regulation procedures required are those to be followed when infested animals are detected at livestock sale barns and feedlot facilities. Aside from acaricidal treatment of the infested animals, regulations also require treatment of facility grounds with an approved acaricide. Treatment of facility grounds is known as cleaning and disinfesting (C & D) the premises. Replete females have been reported to begin oviposition in as few as two d after detachment (Davey et al. 1980 a,b); thus if there is a time lapse of this magnitude between the discovery of the infestation and the initiation of C & D procedures, it is possible that treatment may be aimed at eggs, as well as engorged females.

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At the present time, when C & D operations are warranted, the eradication program specifies the use of either of two organophosphorus (OP) acaricides that are registered for premise application against ticks (chlorpyrifos and diazinon). While chlorpyrifos and diazinon are highly effective against engorged females and larvae of *Boophilus microplus* (Canestrini) (Rawlins & Mansingh 1977, 1978, 1981; Drummond & Davey 1981), neither has been shown to be particularly effective as an ovicidal agent (Davey et al. 1989). In addition, numerous studies have documented the existence of OP-resistant *B. microplus* strains (Shaw 1966; Baker et al. 1978; Roulston et al. 1981; Stone & Youlton 1982; Harris et al. 1988). Another critical concern to the continued use of OP compounds relates to environmental safety. In recent years in the United States, concerns over environmental safety have resulted in a number of OP compounds being removed from the public marketplace with many more having a precarious future.

During the past 15 yrs, a number of non-OP classes of pesticides have been developed that are effective against target arthropod pests, environmentally safe, and relatively less toxic to mammals and other nontarget organisms than OP compounds. Among the most prominent of these pesticides is a wide array of pyrethroids. Some of these pyrethroids have good to excellent activity against several tick species, including *Boophilus* spp. (Rupes et al. 1980; Stubbs et al. 1983; Visvanathan et al. 1983; Davey & Ahrens 1984; de Leon et al. 1987; Solberg et al. 1992). Although some pyrethroid-resistant tick strains have been reported in Africa and Australia (Coetzee et al. 1987; Nolan et al.1989), none have been reported from the Americas.

The purpose of the present study was to determine the ovicidal activity of several pyrethroids applied topically to *B. microplus* eggs of different age classes. Information from the study could be of great value to the U.S. Eradication Program because, if effective, these materials would provide viable alternatives to the use of OP acaricides, thus ensuring continued success of C & D operations in the elimination of *Boophilus* ticks within the U.S. borders.

Materials and Methods

The study was conducted at the USDA, ARS, Cattle Fever Tick Research Laboratory, Mission, TX. Commercial formulations of permethrin (Atroban® 11% Emulsifiable Concentrate, Coopers Animal Health, Kansas City, KS), cypermethrin (5% Emulsifiable Concentrate, Y-Tex Corp., Cody, WY), and cyfluthrin (Tempo® 20% Wettable Powder, Miles Laboratories, Kansas City, MO) were evaluated in the study. Concentrations of 0.1, 0.05, 0.01, and 0.005% active ingredient (AI) of each compound were selected for evaluation because 0.1% AI (permethrin) and 0.05% AI (cypermethrin and cyfluthrin) are the manufacturers' recommended dosage for premise application, while 0.01 and 0.005% AI represented a 10-fold decrease in the recommended dosage of each compound, respectively. Appropriate concentrations of each compound were diluted in water immediately prior to each evaluation to ensure the use of fresh material in all treatments.

A single Hereford heifer was infested with ca. 10,000 larval *B. microplus* 2-3 wk of age. As engorged females began detaching from the host, 400 females were collected on the day of maximum detachment (24 d after infestation) and placed in an incubator at 25 ± 2°C, 92.5% RH using a saturated solution of KNO_3 (Winston & Bates 1960), and a 12:12 photoperiod (L:D). After 5 d, females were separated from the eggs they had deposited and the eggs were discarded. The females were returned to the incubator and allowed to oviposit for 24 h, after which all eggs were collected for use in the study. This procedure provided eggs that were a known age (≤ 24-h-old) at the time of treatment. A portion of 1-d-old eggs was tested to determine the ovicidal activity of the three pyrethroids. The remainder of the eggs was returned to the incubator until they were 10- and 21-d-old, at which time a portion of the eggs of each age group was subjected to the three pyrethroids at the four concentrations.

Eggs from each age class (1-, 10-, and 21-d-old eggs) were weighed into 20 mg lots (ca. 400 eggs) and placed on 9 cm diameter filter paper. Four replicates were prepared for each of the three pyrethroid formulations at the four concentrations (0.1, 0.05, 0.01, and 0.005% AI), as well as four replicates which were treated with water only to serve as untreated controls. A microsyringe applicator containing sufficient volume to ensure complete coverage of all eggs (2 ml) was used to topically apply the water and each of the four appropriate pyrethroid concentrations. After treatment each egg sample was allowed to air-dry and was placed in a clean, coded 15 × 45 mm shell vial (1-dram) stoppered with a cotton plug and then was placed in an incubator until hatching was complete (ca. 4 wks). The percentage larval hatch of all treatment and control groups was determined by counting the number of larvae in proportion to the number of unhatched eggs in the sample.

To determine the percentage reduction of larval hatch afforded by each treatment, the larval hatch within each replicate for each treatment (pesticide, concentration, and age class of eggs) was subjected to the following formula (Abbott 1925):

$$\textit{Percent Reduction} = 100\ x\ \frac{\textit{Hatch in Control Group} - \textit{Hatch in Treated Group}}{\textit{Hatch in Control Group}}$$

Once the percentage reduction of larval hatch was established, the data were subjected to a two-way analysis of variance (ANOVA) using a general linear model (GLM) to determine differences between concentrations and age class of eggs (SAS Institute Inc. 1987). A Fisher's Least Significant Difference (LSD) was calculated to determine differences among means. Arcsine transformation was applied to the data prior to analysis.

Results

The mean larval hatch (± SE) of 1-, 10-, and 21-d-old eggs treated with water only (untreated control group) was 80.3 ± 3.2, 83.7 ± 1.7, and 82.0 ± 2.3%, respectively. Results of the studies of the efficacy of the pyrethroids against *B. microplus* eggs are presented in Table 1. For eggs treated with permethrin, there was a significant interaction between the concentrations and age classes of eggs (F = 7.7; df = 6,36; $P < 0.01$; LSD = 15.1) indicating that reduction of larval hatch in the three age classes of treated eggs was not constant across the four concentrations. At the 0.1% AI concentration, there was no difference in reduction of larval hatch across the three age classes of treated eggs. At the 0.05% AI concentration, 21-d-old treated eggs were significantly less sensitive to the material than 1- or 10-d-old treated eggs. At the two lowest concentrations (0.01 and 0.005% AI), there were no differences across age classes within either concentration, except in 1-d-old eggs treated at 0.01% AI, there was significantly higher reduction of larval hatch than eggs in the older age classes (10- and 21-d-old eggs). Reduction of larval hatch at the two lower concentrations (0.005 and 0.01% AI) was significantly lower than at the two high concentrations (0.1 and 0.05% AI). Based on the effects of all concentrations upon all age classes of treated eggs, permethrin was less effective than the other materials tested.

Cypermethrin was highly effective in controlling larval hatchability at the 0.1, 0.05, and 0.01% AI concentrations (Table 1). ANOVA for cypermethrin showed a significant interaction between age classes and concentrations (F = 7.1; df = 6,36; $P < 0.01$; LSD = 6.8) indicating that reduction in larval hatch in the age classes was not constant across the four concentrations. At concentrations of 0.1, 0.05, and 0.01% AI, there were no differences in reduction of larval hatch across the age classes. However, at the lowest concentration (0.005% AI) larval hatch reduction was high in 1-d-old treated eggs (97.1%) and then diminished significantly in 10- and 21-d-old treated eggs (<76%).

Cyfluthrin was more effective than the other pyrethroids tested when all concentrations and age classes of treated eggs were considered (Table 1). The larval hatch reduction was ≥96% in all age classes at all four concentrations. Unlike the results obtained for permethrin and cypermethrin, ANOVA of the cyfluthrin data showed no significant interaction between concentration and age class of treated eggs (F = 1.3; df = 6,36; P = 0.3). This indicated that reduction of larval hatch in the three age classes of treated eggs was consistently high across all four concentrations tested. Although ANOVA showed that there were statistical differences within both concentration (F = 11; df = 3,36; $P < 0.04$) and age class of treated eggs (F = 3.7; df = 2,36; $P < 0.01$) (LSD = 1.4), it should be noted that the difference between the lowest reduction of hatch (96.4%) and the highest level of reduction (99.9%) was equivalent to the hatch of only 12 larvae.

Table 1. Percent reduction of hatch of *Boophilus microplus* larvae after treatment of eggs of various age classes with three pyrethroids at four concentrations.

Acaricide	Concentration (%) AI)	Percent reduction at indicated age of eggs (± SE)		
		1-d-old	10-d-old	21-d-old
Permethrin	0.005	30.8 (7.6)	22.5 (5.4)	16.4 (5.8)
(LSD[a] = 15.1)	0.01	89.7 (3.6)	27.0 (9.3)	34.8 (10.3)
	0.05	98.8 (0.4)	93.4 (1.1)	76.8 (5.4)
	0.1	99.9 (0.1)	94.1 (1.8)	95.9 (0.5)
Cypermethrin	0.005	97.1 (0.7)	71.1 (6.9)	75.9 (4.3)
(LSD - 6.8)	0.01	98.6 (0.3)	93.4 (1.5)	94.4 (1.4)
	0.05	99.7 (0.1)	99.7 (0.2)	98.3 (0.6)
	0.1	99.9 (0.1)	100 (0)	99.5 (0.3)
Cyfluthrin	0.005	97.6 (0.7)	98.0 (0.6)	98.7 (0.5)
(LSD = 1.4)	0.01	97.7 (0.6)	96.4 (0.7)	98.4 (0.7)
	0.05	99.1 (0.1)	98.4 (0.6)	99.8 (0.1)
	0.1	99.5 (0.1)	99.9 (0.2)	99.6 (0.1)

[a] LSD = Fisher's Least Significant Difference; $P < 0.05$ for all concentrations with the same acaricide.

Discussion

Because egg laying is a dynamic process, C & D treatments applied under natural field conditions might be applied to eggs of any age. Thus, to be effective, an acaricide must prevent hatch regardless of the age of eggs to which it is applied. Therefore, the lowest acceptable concentration for C & D treatments would be dictated by the age of eggs which still result in a high level of hatch reduction (i.e. ≥90%).

While the OP acaricides traditionally used in C & D operations have excellent activity against engorged females and larvae of *B. microplus* (Rawlins & Mansingh 1977, 1978, 1981; Drummond & Davey 1981), they do not possess the ovicidal activity needed to prevent hatching of eggs that may be present when treatments are applied (Davey et al. 1989). In contrast, the pyrethroids evaluated in this study have not only been shown to be highly

effective against the parasitic stages (adults, nymphs, and larvae) of a number of ixodid species, including *B. microplus* (Rupes et al. 1980; Roberts et al. 1980; Heller-Haupt & Varma 1982; Khan & Srivastava 1988; Deblinger & Rimmer 1991; Stafford 1991; Solberg et al. 1992), but were shown to have excellent ovicidal properties as well.

Permethrin provided excellent ovicidal activity against *B. microplus* eggs of all age classes at the manufacturer's recommended concentration for premises application (0.1% AI), but efficacy diminished sharply as the concentration was reduced, particularly when older eggs were treated. Cypermethrin and cyfluthrin were also highly effective against all treated eggs at manufacturers' recommended concentration for premises treatment (0.05% AI); however, in contrast to permethrin, cypermethrin remained highly effective at a dosage that was 5-fold below the recommended level (0.01% AI), while cyfluthrin was highly effective at a dosage that was 10-fold below the recommended level (0.005% AI).

Results of the study indicated that each of the pyrethroids would be an excellent candidate for use in C & D treatment applications against *B. microplus*. The three pyrethroids evaluated in this study certainly appear to have much higher ovicidal activity than any of the OP compounds that are presently used (Davey et al. 1989). Even under practical application situations in the field, where conditions are often less than ideal, as was the case in this laboratory study, it is likely that if manufacturers' recommended concentrations for premises application are maintained, the hatch reduction of treated *B. microplus* eggs could be expected to be high.

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Inorganic Colloid Gel with Oxamyl for Control of *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae) in Fluid-drilled Tomatoes

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ABSTRACT Field trials were conducted in 1981 and 1982 with oxamyl (Vydate L) added to a 1.5% Laponite® organic colloid gel and pregerminated tomato seed for protection from Colorado potato beetles, *Leptinotarsa decemlineata* (Say). Rates of 1.12 or 2.24 kg (AI)/ha of oxamyl in the gel mixture with the seed resulted in significnatly fewer Colorado potato beetle larvae, significantly less percentage plant defoliation caused by Colorado potato beetles, and significantly higher yields each year. No significant differences between the oxamyl rates were observed for any parameter each year, and no phytotoxicity as a result of the insecticide was observed. The benefits of a fluid-gel-oxamyl mixture in an intergrated pest management program for Colorado potato beetle on tomatoes are discussed.

KEY WORDS Tomatoes, *Leptinotarsa decemilineata*, fluid-drill, oxyamyl

Fluid drilling of vegetable seed, also referred to as gel seeding, is the technique of direct sowing of seeds into the soil using a gel carrier (Anon. 1979). One of the advantages of this system is that fluid drilling is less expensive than producing and transplanting transplants. Another advantage of gel seeding is that pregerminated seeds can be mixed in the gel and seeded when the soil temperatures do not allow dry seeds to germinate. Thus, vegetable crops such as tomatoes can be established in the field sooner using pregerminated seed rather than ungerminated seed. The gel seeding method has other advantages over conventional dry-seed sowing (Gray 1981, 1984), including rapid and even seedling emergence and establishment, available moisture at seeding, and other benefits (Gray 1981, 1984; Salter 1978). Also, Gray (1984) reported yield increases for fluid-drilled crops compared with dry-seeded crops as 22% for carrots, 107% for parsley, and 12% for tomato.

Ghidiu (1980a) reported that fluid-drilled, pregerminated tomato seed resulted in accelerated emergence and growth and a significantly greater number of plants per meter compared with dry-seeded tomatoes. Further, tomato plant stems generally were larger in diameter (mm) in the fluid-drilled, pregerminated seed plots than in dry-seeded plots.

[1] Accepted for publication 7 December 1994.

One approach to modification of the fluid-drilling method is that of a "gel-mix", which was successfully used in planting bell peppers in Florida (Schulthesis et al. 1988). The pepper seed were pregerminated, mixed in a media containing a hydrophilic polymer, and planted at 60 ml/hill. Various gels including natural-based gels are available (Orzolek 1987; Pill & Rojas 1987). Salter (1978) reported that a gel carrier, in addition to holding the seeds, would be ideal for carrying additives such as fertilizer salts, plant growth regulators and pesticides, thus creating a complete seeding package for the seedling. Ohep et. al (1984) reported that fungicides controlled damping-off in tomatoes when the fungicide was added to the direct-seeding gel.

In New Jersey, the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), is the most serious pest of young tomato plants, either direct-seeded or transplants. Beetles overwinter as adults, emerge in mid- to late May, and feed on the stems, leaves and flowers of tomato plants. Direct-seeded plants are very susceptible to Colorado potato beetle damage, and emerging seedlings can be totally destroyed by the feeding of one or two adult beetles. Contact insecticides applied as sprays are ineffective because there is little foliage or plant surface for the pesticide to adhere.

Oxamyl (Vydate L [liquid], E.I. du Pont de Nemours Inc., Wilmington, DE) is a carbamate insecticide with systemic activity registered in NJ for control of potato beetles. It is toxic to potato beetles when applied as a soil drench (Ghidiu & Linduska 1989), as a slow release soil tablet (Ghidiu & Oetting 1987) or as a foliar spray (Ghidiu 1980b). Vydate L is also miscible with water and thus is suitable for mixture in the gel.

Our objectives were to: 1) examine the potential of Vydate L as an additive to pre-germinated seed suspended in gel, and 2) determine the effectiveness of Vydate L in protecting fluid-drilled, pregerminated tomatoes from Colorado potato beetle damage.

Materials and Methods

1981. Three sets of 1595 tomato seeds, 'US 28', were each wrapped in a 14.3 x 14.3 cm^2 sterile cheesecloth square and suspended in a 22.2^o C water bath on 20 April. On 4 May, when radicles were about 1.5 mm in length, three separate gel mixtures (treatments) were prepared. The first mixture was 1 liter of tap water added to 15 g of Laponite® 508 inorganic colloid gel (making a 1.5% colloid gel) (Laporte Industries Ltd., Bedfordshire, England) with no insecticide. The second mixture was 3753.5 ml of water with 31.5 ml of Vydate L and 15 g of Laponite® gel, and the third mixture was 3722.9 ml of water with 63.0 ml of Vydate L and 15 g of gel. Each set of germinated seed was carefully removed from the cheesecloth to prevent damage to the radicles and slowly mixed into one of the prepared Vydate-gel mixtures. A single row, fluid-drill seeder equipped with a roller pump on the drive wheel was made from the combination of Stanhay and Planet Jr. seeders. The seeder was calibrated to deliver 1 liter of gel per 44.2 m (145 ft). With 1595 seeds per liter, a field seeding rate of 11 seeds per 30.5 cm (one foot) of row resulted with Vydate L at a rate of either 0, 1.12 or 2.24 kg (AI)/ha (1.0 and 2.0 lb/acre, respectively). The pregerminated seed-gel mixtures were

immediately fluid-drilled into a Sassafras sandy loam field on 4 May. All four untreated control plots were seeded first, followed by the low rate or Vydate-gel mixture, and then the high rate. To ensure an infestation of Colorado potato beetles, a field which had been planted to tomato in previous years was selected for this experiment. Plots were 7.6-m long and 1.5-m wide replicated four times in a complete block design. An untreated buffer row was seeded on each side of each treated row. Plant stands (plants per meter of row) were recorded on 8 June, and plant heights were recorded on 8 June and 1 July. The numbers of Colorado potato beetle larvae/10 plants in each plot were recorded on 1 and 15 July, and percentage plant defoliation caused by Colorado potato beetle was visually rated and recorded on 8 June and 1 July. Total marketable yields were harvested, weighed and recorded on 29 August. Tomato plants were closely monitored for phytotoxicity due to oxamyl, but none was observed (data not reported).

1982. Tomato seed, cultivar 'U.S. 28' were pregerminated in a warm water bath on 21 May and mixed into a 1.5% Laponite® 508 inorganic colloid gel on 27 May (radicles = about 1.5 mm in length) as described above. The two rates of Vydate L and the untreated control were mixed into the seed-gel mixture on 27 May as previously described and immediately fluid-drilled into a Sassafras sandy loam field (again calibrated to deliver 11 seeds per 31 cm of row). Plot size, seeding, arrangement and replication were the same as in 1981.

Plant stand was recorded on 25 June, plant height on 25 June and 9 July, Colorado potato beetle larvae were counted on 7 and 13 July, and percentage plant defoliation caused by Colorado potato beetle was recorded on 25 June and 7 July. Total marketable yields were harvested, weighed and recorded on 23 August. Plants were closely monitored for phytotoxicity, but none was observed (data not reported).

Statistical Analyses. Field data for all parameters in both years were subjected to analysis of variance (ANOVA) (SAS Institute 1985). Separation of the means was determined by Tukey's HSD studentized range tests (SAS Institute, 1985).

Results

1981. The number of plants per row was significantly lower (F=11.3, n=12, P=0.001) in the plots receiving the Vydate L-gel mixture compared with the untreated gel plots. The flexible seed tube on the planter developed a small kink after the untreated plots were seeded but during the Vydate L-treated seeding, resulting in reduced and uneven seed distribution in the Vydate L-treated plots (Table 1). The gel continued to flow from the tube but the seed occasionally clumped. In 1982, a new seed delivery tube was installed on the seeder and the uneven seeding did not recur. Although fewer seeds per row were deposited in the oxamyl-treated plots, the mean plant heights were not significantly different among treatments on either 8 June or 1 July, indicating that Vydate L had no effect on plant growth at the rates used (Table 1). Greenhouse tests showed that high concentrations of Vydate L, drenched at the base of tomato transplants, can cause phytotoxicity

Table 1. Effect of oxamyl with a 1.5% inorganic colloid gel-pregerminated tomato seed mixture on plant growth, Bridgeton, NJ, 1981.[a]

	Plants/m	Plant height (cm)	
Treatment & rate (kg [AI/ha)	8 June	1 July	8 June
Vydate 2L 1.12	17.0 b	21.6 a	8.9 a
Vydate 2L 2.24	21.0 b	29.2 a	9.9 a
Untreated	33.0 a	31.2 a	11.6 a
(SEM)	0.224	0.919	4.554

[a] Numbers in a column with a letter in common are not significantly different (Turkey's HSD 5% level).

and stunted plant growth (Ghidiu 1980b), although greenhouse plants are probably more tender and thus more susceptible to phytotoxicity damage than field plants.

Tomato plants seeded with the Vydate L-gel mixture had significantly less damage caused by Colorado potato beetle on 8 June and 1 July as compared with the untreated gel (F=42.0, n=12, P=0.001 and F=4.2, n=12, P=0.001, respectively), although there were no significant differences between the Vydate L treatments (Table 2). These results agree with those of Forgash (1981) who reported that the Colorado potato beetle was not resistant to oxamyl in laboratory trials. Both rates of Vydate L-gel treatments had less defolation on 8 June and 1 July than did the untreated (Table 2) on those dates. Tomato seedlings and transplants can be severely defoliated by early season Colorado potato beetle because plants have few leaves at this time. However, even after almost total defoliation, tomato plants will re-grow and new leaves will emerge if the beetles leave the plant.

No significant differences were observed among treatments for the early Colorado potato beetle infestation (1 July), with only about 2 beetles/plant. However, within 2 wk (15 July), significantly fewer beetles were recorded on the Vydate L treatments as compared with the untreated (F=32.6, n=12, P=0.001) (Table 2).

Significantly higher yields (F=56.2, n=12, P=0.001) were harvested in the Vydate L-gel plots compared with the untreated gel (Table 2). These differences were likely a result of the severe defoliation (88%) caused by Colorado potato beetle to the untreated tomatoes recorded on 15 July. Although the plant stands were significantly higher in the untreated gel plots, the beetle-damaged plants were unable to compensate for the defoliation and thus, significantly lower yields were obtained in untreated plots compared with Vydate L-gel plots.

Table 2. Effect of oxamyl with a 1.5% colloid gel-pregerminated tomato seed mixture on *Leptinotarsa decemlineata* infestation, plant damage and yield, Bridgeton, NJ, 1981.[a]

Treatment & rate (kg[AI]/ha)	% Defoliation		No. larvae/5 plants		Yield
	8 June	1 July	1 July	15 July	T/ha
Vydate 2L 1.12	17.3 a	19.5 a	5.5 a	6.4 a	27.5 a
Vydate 2L 2.24	17.8 a	25.5 a	9.0 a	8.6 a	30.8 a
Untreated	84.5 b	88.0 b	11.0 a	19.3 b	8.5 b
(SEM)	5.777	5.909	5.937	1.993	3.072

[a] Numbers in a column with a letter in common are not significantly different (Tukey's HSD 5% level).

1982. No significant differences in the number of plants per meter of row were recorded among treatments on 25 June (Table 3). The fluid-gel seeder distributed the pregerminated seed evenly into the row as previously discussed.

Plant heights were not significantly different (F=0.4, n=12) among treatments on 25 June, but there was a significant difference (F=23.6, n=12, P=0.001) on 9 July (Table 3). This difference was due to Colorado potato beetle damage, with 98% defoliation of plants in the untreated plots. Potato beetles fed on the upper leaves of the small seedlings, and then fed on the upper portions of the stems after the leaves were gone, resulting in stunted and shortened plants.

Both rates of Vydate L protected the plants from Colorado potato beetles, and plants in both Vydate L treatments had significantly less defoliation caused by potato beetles than did the untreated on 25 June and 7 July (F=13.1, n=12, P=0.001 and F=32.4, n=12, P=0.001, respectively) (Table 4). There were no significant differences between the Vydate L treatments for defoliation caused by potato beetles.

The number of Colorado potato beetle larvae/5 plants was not significantly different between the Vydate L treatments on 7 July or 13 July. Although the analyses showed no significant differences among any of the treatments, the untreated plants were completely defoliated, and thus supported no potato beetle larvae (Table 4).

Significantly higher yields were harvested from plots that were treated with either rate of Vydate L compared with the untreated control (F=20.7, n=12, P=0.001), but there were no significant differences between the Vydate L-gel treatments (Table 4). The low yields obtained in the untreated plots were due to the severe plant damage caused by Colorado potato beetles in late June until early July, when defoliation increased from 68 to 98%. Plants in the untreated plots were "topped" (defoliation and stem cutting at the top of the plants), resulting in lower plant heights, removal of the new growth, and significant reduction of yield potential.

Table 3. Effect of oxamyl with a 1.5% inorganic colloid gel-pregerminated tomato seed mixture on plant growth, Bridgeton, NJ, 1982.[a]

	Plants/m	Plant height (cm)	
Treatment & rate (kg [AI/ha)	25 June	25 June	9 June
Vydate 2L 1.12	26.4 a	4.6 a	23.6 a
Vydate 2L 2.24	22.1 a	5.3a	20.3 a
Untreated	26.8 a	4.6a	9.1 b
(SEM)	1.099	0.460	0.183

[a] Numbers in a column with a letter in common are not significantly different (Tukey's HSD 5% level).

Table 4. Effect of oxamyl with a 1.5% inorganic colloid gel-pregerminated tomato seed mixture on *Leptinotarsa decemlineata* infestation, plant damage and yield, Bridgeton, NJ, 1982.[a]

Treatment & rate	% Defoliation		No. larvae/5 plants		Yield
(kg[AI]/ha)	5 June	7 July	7 July	13 July	T/ha
Vydate 2L	3 a	18 a	2.3 a	2.8 a	25.8 a
Vydate 2L	5 a	20 a	1.3 a	1.3 a	21.3 a
Untreated	68 b	98 b	defol.	defol.	2.7 b
(SEM)	1.021	0.803			

[a] Numbers in a column with a letter in common are not significantly different (Tukey's HSD 5% level).

Discussion

Emerging direct-seeded tomatoes and newly-set tomato transplants are highly susceptible to Colorado potato beetle damage. Current recommendations for growers are to apply foliar sprays of esfenvalerate, endosulfan or oxamyl. Because the small plants have little leaf surface area for the spray to adhere, new unprotected leaves continue to emerge after an insecticide spray is applied. Growers thus may need to apply multiple applications of pesticides on a 4 to 6 d schedule, depending upon beetle density. Pre-germinated fluid-drilled tomato seedlings can be protected from Colorado potato beetle damage with the addition of Vydate L to the gel mixture. The seedlings absorb and translocate the Vydate L to the leaves, resulting in significantly less Colorado potato beetle defoliation through July, significantly fewer beetles and significantly higher yields compared with fluid-drilled tomatoes without Vydate. A single application of a systemic insecticide such as oxamyl, added to the seed-gel mixture, is less costly (because fewer applications are used) and an effective alternative to the use of post-transplanting multiple pesticide spray applications.

Results of this study can easily be incorporated into a commercial seeding system because farmers currently using fluid-drill seeders will not require additional equipment to apply pregerminated seed suspended in gel. Although oxamyl is has a federal registration for use on tomato, EPA approval would still be required to use this material in the seeding gel.

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Mating Disruption of Codling Moth (Lepidoptera: Tortricidae) with Polyethylene Tube Dispensers: Determining Emission Rates and the Distribution of Fruit Injuries[1]

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ABSTRACT Emission characteristics of three sex pheromone components of codling moth, *Cydia pomonella* (L.), from a polyethylene tube dispenser used for mating disruption were determined and regression models predicting the emission rate of each component as a function of temperature and accumulated degree hours above 0°C were developed. Field experiments were conducted in small plots of apple during 1989-90 to measure intraseasonal changes in the distribution of fruit injury within pheromone-treated blocks. Fruit injury was < 0.5% in 0.4 ha plots treated with 1,000-4,000 dispensers per ha in 1989 except in plots situated along the border of the orchard adjacent to a non-pheromone-treated orchard with high levels of fruit injury. In a separate orchard in 1990, the differential application of pheromone dispensers (2,000 per ha) and insecticides was used to create four 1-ha plots with moderate to high population densities of codling moth larvae during the first generation (50-fold range in densities of injured fruits per tree). Subsequently, all plots were treated with pheromone prior to the second generation. Fruit injury at harvest was < 1.0% for 'Delicious' in all plots except the highest density (HD) plot (4.0%), but was ca. 1.0% or higher for 'Golden Delicious' in all plots (14% in the HD plot). The mean number of injured fruits per tree for 'Delicious' and 'Golden Delicious' increased 10 and 25 fold between generations in the plot adjacent to and within 100 m of the HD plot, respectively. Results from both years demonstrated the effectiveness of mating disruption in suppressing the population buildup of codling moth in plots of apple not exposed to immigration of moths.

KEY WORDS Insecta, codling moth, mating disruption, sex pheromone, E8, E10-12:OH

Codling moth, *Cydia pomonella* (L.) is a major pest of pome fruits and walnuts in most temperate regions of the world (Shel'deshova 1967). Codling moth resistance to organophosphate insecticides in the United States has been reported in populations in pear (Varela et al. 1993) and apple (Bush et al. 1993, Knight et al. 1994).

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Combined with increasingly stringent regulations for pesticide use and soaring costs for registration of new compounds, the development of alternative management tactics for codling moth is urgently needed (Beers 1990).

Following the identification of codlemone, (E,E)-8,10-dodecadien-1-ol, as the major sex pheromone component of codling moth (Roelofs et al. 1971), mating disruption of codling moth using codlemone has been explored for nearly 20 years (see Vickers & Rothschild 1991 for a review). Studies by Arn et al. (1985), Einhorn et al. (1986), and Bartell et al. (1988) found that secondary compounds improved the attractiveness and a commercial patent of a three component blend for mating disruption was obtained (Rothschild et al. 1988). Several authors (Howell et al. 1992, Barnes et al. 1992, Pfeiffer et al. 1993) have recently reported on the use of this multicomponent blend in two different types of polyethylene dispensers for control of codling moth (Brown et al. 1992, McDonough et al. 1992).

Studies with the multicomponent dispenser system have shown that mating disruption of codling moth can be effective when the moth population density is low and orchards are isolated either physically (Barnes et al. 1992) or by use of sprayed-buffer zones (Howell et al. 1992). Yet control failures of codling moth with pheromones have been reported (Pfeiffer et al. 1993). More fruit injury has occurred along the borders than in the center of blocks in many pheromone-treated orchards (A.L.K., unpubl. data). Whether this "edge effect" is due to poor pheromone coverage, immigration of mated females, or both remains largely hypothetical (Pfeiffer et al. 1993). Milli & Dickler (1993) using a portable electroantennogram showed that pheromone concentration was lower along the edge than in the center of treated orchards. Dispersal of female codling moth has been reported by numerous authors using catches in bait pans (Steiner 1940) or light traps (Worthley & Nicholas 1937), or the distribution of fruit injury (Wildbolz & Mani 1959, White et al. 1973). However, the effect of sex pheromones on the behavior and specifically the movement patterns of females into or between pheromone-treated orchards is unknown.

Herein we report several studies that were conducted in 1989-90 to provide data on the emission characteristics of three components of codling moth's sex pheromone from a sealed polyethylene tube dispenser, and to provide data on the extent and distance of female dispersal (based on the incidence of fruit injury) into and between pheromone-treated plots.

Materials and Methods

Dispenser Characteristics. Translucent polyethylene tube dispensers manufactured by Shin-Etsu Chemical (Tokyo, Japan) were obtained from Pacific Biocontrol Limited (Davis, Calif.). Each dispenser contained an average of 87% active ingredient (AI) (63:31:6 blend of (E,E)-8,10-dodecadien-1-ol (E8, E10-12:OH), 1-dodecanol (12:OH), and 1-tetradecanol (14:OH); and 13% inert ingredients, i.e., UV inhibitors and antixoidants. Dispensers in 1989 had a 1.22 mm internal diameter (ID) and contained 157 mg AI; in 1990, dispensers had a 1.11 mm ID and contained 171.2 mg AI.

Dispensers aged in the field for emission characterization were placed in the upper third of apple trees and shaded by foliage each year. Temperature data were recorded with a Type T thermocouple connected to a 21XL data logger (Campbell Scientific, Logan, UT). New dispensers and dispensers collected once or twice during the first three weeks and then once every two weeks up to 144 d in 1989 and 126 d in 1990 were placed in plastic seal-top bags, returned to the laboratory, and kept at -15°C.

Methods used to determine the emission rate (μg per h) of dispensers were similar to those reported by Brown et al. (1992). Samples were analyzed on a Hewlett Packard 5880 GC (Hewlett Packard, Mountain view, CA) equipped with a HP 7673 automatic sampler and 60 m × 0.32 mm ID Supelcowax capillary column (Supelco Inc., Bellefonte, PA). Recovery rates of standards averaged 97% for 12:OH, 94% for 14:OH, and 102% for E8,E10-12:OH across both years.

Emission rates were determined at three temperatures, 15, 22.5, and 30°C on all sampling dates in 1989 and for new dispensers and dispensers aged 66 and 126 d in 1990. Using these data, a multiple regression model similar to that reported in Brown et al. (1992) was developed to estimate the emission rate (μg/h) of each component from a dispenser as a function of accumulated degree hours (DH) above 0°C and the instantaneous temperature (°C) with data for each year (equation 1).

$$\ln(\text{emission rate}) = \text{intercept} + k_1/\text{temperature} + k_2(\text{DH}/1{,}000) \qquad (1)$$

1989 Field Trial. Twelve 0.4 ha plots were established within a 10 ha apple orchard situated near Zillah, WA. Trees were 10 years old, spaced 3.6 × 5.5 m, mean canopy height = 3.5 m, and each plot contained two adjacent rows of 'Golden Delicious' interplanted among eleven rows of 'Delicious'. Rows ran east to west. Plots were laid out in three columns of four plots running east to west (Fig. 1a). This orchard was used by Howell et al. (1992) to study mating disruption of codling moth in 1987 and 1988. In 1988, cumulative fruit injury ranged from 0.06 to 1.63% in the various plots during the season. However, trees were inspected 2-5 times during the 1988 season and an attempt was made to remove all injured fruit prior to harvest.

Plots in 1989 were treated with either: one of three rates of pheromone dispensers alone, 1000 (n = 2), 2000 (n = 6), or 4000 dispensers per ha (n = 2); 2000 dispensers per ha plus nine applications of 8.96 kg/ha of ryania (Penick-Bio UCLAF Corp., Lyndhurst, NJ) and three applications of 0.56 kg/ha of Dipel® (Abbott Laboratories, North Chicago, IL) (n = 1); ryania and Dipel without pheromone (n = 1); and an untreated check (n =1). No other insecticides were applied to any plot in this study. Due to the small size of the plots, their proximity, and lack of adequate replication, no statistical tests were used to compare the efficacy of these various treatments.

Dispensers were placed in plots from 26 April to 1 May following the capture of the first moth in a sex pheromone trap baited with a red rubber septa loaded with 1 mg of E8, E10-12:OH (Trace Inc., Salinas, CA). Dispensers were hung in the highest part of each tree. All trees were examined every two weeks for injured fruit (injury included both stings and

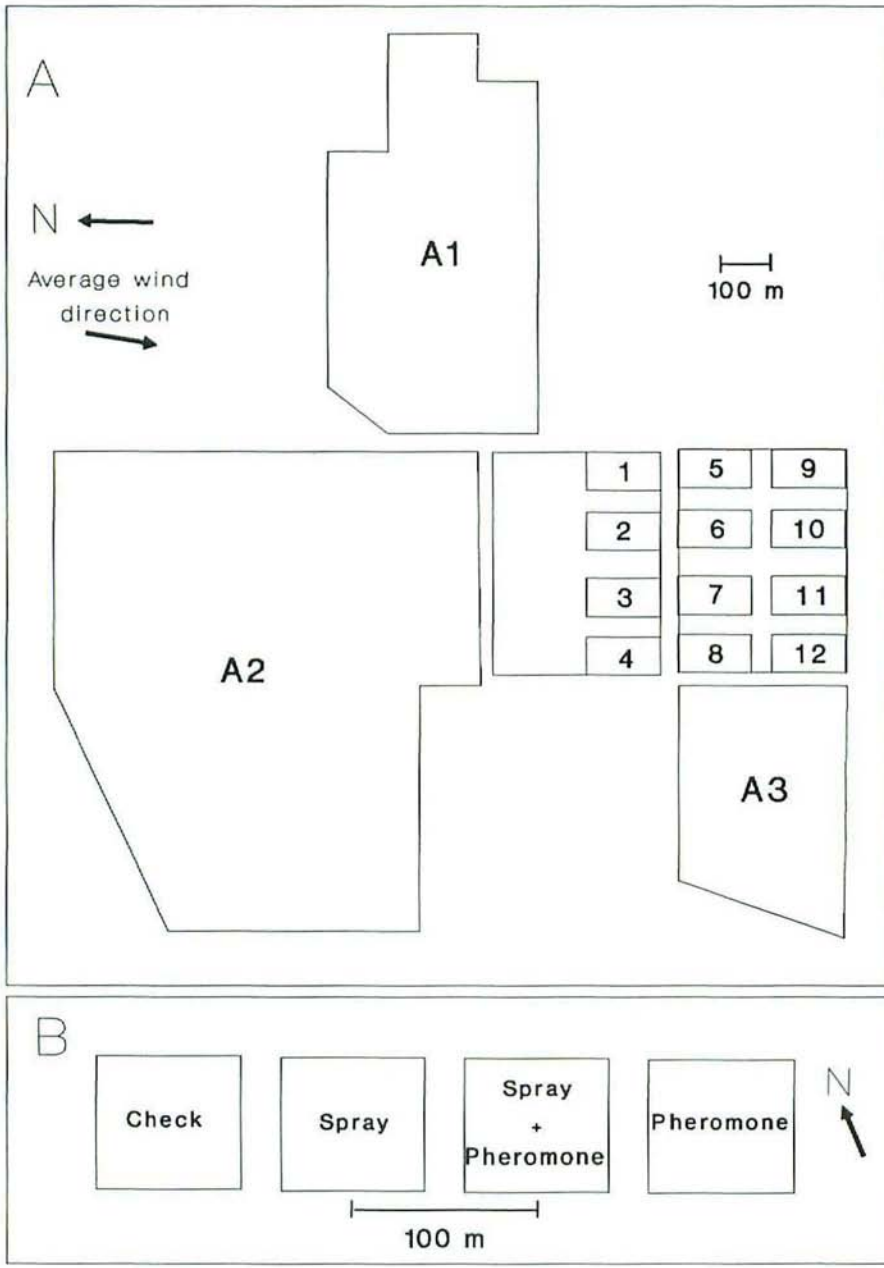

Fig. 1. The arrangement of experimental plots used to evaluate pheromone dispenser for mating disruption of codling moth (A) in 1989 in an apple orchard situated near Zillah, WA and (B) in 1990 in an apple orchard situated near Tieton, WA.

entries) by crews of 2-3 field scouts. Injured fruits were marked to prevent being recounted later in the season, and all injured fruit were removed prior to harvest. Wind direction and speed were monitored using a cup-anemometer (WM-III, Climatronics Corp., Bohemia, NY). Monitoring traps were placed in three surrounding apple blocks during the first generation flight (Fig. 1a).

The spread of fruit injury during second generation in 1989 was examined by measuring the distance of all trees in the six plots treated with 2,000 dispensers per ha from the SW edge of orchard A_1 (Fig. 1). The proportion of trees in these plots within arbitrary distance classes of 30 m with greater than 0, 1, 2, 3, 4, and 5 injured fruits was determined, respectively. These data were fit to a number of equations relating insect dispersal with distance (Taylor 1978) and the best model was selected based on the highest coefficient of determination (Kvalseth 1985).

1990 Field Trial. The experimental use of the tube dispenser was studied in another apple orchard (8 ha) with a mixed planting of 'Delicious' and 'Golden Delicious' situated near Tieton, WA. Trees in this orchard were >20 years old, 4 m in height, and spaced 4.0 × 7.6 m (329 trees/ha). Four 1 ha plots (A-D) were established from west to east based on treatments applied during the first generation, of codling moth (rows ran west to east) (Fig. 1b). During first generation, plot A was left untreated; plot B received 2 sprays of azinphosmethyl (Miles Chemical, St. Louis, MO) timed 21 and 40 d after the first moth catch, 'biofix' plot C received one spray of azinphosmethyl timed 21 d after 'biofix' plus pheromone dispensers; and plot D received only pheromone dispensers. Sprayed borders (ca. 25 m) were maintained (two sprays timed 21 and 40 d after 'biofix') during the first generation around each plot. Sprayed borders on the northern edge of the orchard were maintained (every 19-21 d) throughout the season. Azinphosmethyl (0.84 kg AI/ha) was first applied to borders (ca. 3 rows) and plots B and C on 26 May and to plot B and borders on 5 July. Additional spray applications at the same rate were made to the northern border of all plots on 27 July and 24 August.

Pheromone dispensers were applied at a rate of 2,000 per hectare, in groups of 2 or 3 dispensers (5 per tree) in the tops of trees in plots C and D on 21 May. This late application of pheromone ('biofix' of adult emergence was established as 16 April) corresponded to 40% moth emergence (Brunner et al. 1982).

First generation codling moth population density was assessed by three persons; two persons with mobile hydraulic ladders and one person from the ground for all trees from 11-16 July. All injuries were marked but not removed. All fruit from 24 randomly selected trees which had been searched were removed on 14 July and examined for codling moth injuries to measure searching efficiency in each cultivar.

A second placement of pheromone dispensers were applied in all plots on 24-25 July; 2,000 dispensers per hectare in plots A and B, and 1,200 dispensers per hectare in plots C and D. This reduced rate of dispensers in plots C and D was chosen to generate an approximate uniform emission rate of E8, E10-12:OH in all plots based on the expected emission rate of the older dispensers placed in plots C and D in May estimated by equation 1.

Second generation codling moth larval populations in each plot were sampled from 10-12 September for all trees in rows 4, 6, 8, 10, and 12. Apples on the ground beneath these trees were also sampled. All fruit from 110 trees were removed and examined for codling moth injuries to assess the efficiency of this sampling effort and to estimate crop load. Data on the number of codling moth injuries per tree for each generation were adjusted based on the sampling efficiency for each cultivar. Percent fruit injury was based on average crop load of each cultivar.

Results and Discussion

Dispenser Characteristics. New dispensers, in both years, released ca. 27 μg/h E8, E10-12:OH at 22.5°C and 6,000 ml/min aeration in the laboratory (Tables 1 and 2). The blend of E8,E10-12:OH emitted from new dispensers varied from 1.00:1.02 in 1989 to 1.00:0.78 in 1990 (Tables 1 and 2). Initial emission rates of 14:OH were only 3-4% of E8, E10-12:OH in both years. Aging dispensers in the field changed the ratio of 12:OH to E8, E10-12:OH emitted over time, e.g. 5.4:1.0 after 130 d in 1989 and 3.7:1.0 after 126 d in 1990. Similarly, the emission rate of 14:OH relative to E8,E10-12:OH increased and was 58% and 27% as high as E8,E10-12:OH after 130 d in 1989 and after 126 d in 1990, respectively.

The importance of the blend change that occurred during the season on the efficacy of mating disruption is unclear. Rothschild et al. (1988) provided only a small amount of field data to support their claim that the three component blend was superior to E8,E10-12:OH alone. Instead, they cited laboratory studies such as those of Arn et al. (1985), Einhorn et al. (1986), and Bartell et al. (1988) which found that 12:OH alone or together with 14:OH enhanced the activity of E8, E10-12:OH. However, two studies have recently contradicted these findings. McDonough et al. (1993) found that the three-component blend was not more attractive than E8, E10-12:OH to male moths in flight tunnel tests. In addition, McDonough et al. (1994) showed that the three component blend did not increase short-range communication disruption of moths in the field relative to E8, E10-12:OH alone. These latter two studies were conducted with a component ratio similar to that emitted by a female. In contrast, Arn et al. (1985) showed that an increase in the ratio of 12:OH relative to E8, E10-12:OH enhanced the blend's attractiveness. Thus, the change in pheromone blend ratios emitted by the tube dispenser over time could affect the efficacy of this dispenser in mating disruption. The impact of varying the ratios of these three pheromone components on mating disruption should be investigated.

The isomeric purity of 8,10-12:OH changed as dispensers aged (Tables 1 and 2). Initially dispensers released ca. 94% of the EE-isomer, but over time the percentage of this isomer was reduced and the blend approached an equilibrium mixture of the four geometrical isomers (ca. 61% EE, 20% EZ, 14% ZE, and 5% ZZ [McDonough et al. 1993]). These results were similar to those reported by Brown et al. (1992) for another translucent polyethylene dispenser, especially when their dispenser was aged in direct sunlight.

Table 1. Emission rates of E8, E10-12OH, 12:OH, and 14:OH and isomeric purity of E8,E10-12:OH at 22.5°C and 6,000 ml/min aeration from a sealed polyethylene tube dispenser aged in an apple orchard near Zillah, WA, during 1989, n=5.

Days in field	Emission rate E8, E10-12OH (μg/h) (SEM)	% EE isomer	Pheromone blend (E8, E10-12OH:12:OH:14:OH)
0	27.2 (2.1)	94.4	1.00:1.02:0.03
18	18.2 (2.6)	91.0	1.00:1.18:0.04
32	14.2 (2.0)	90.7	1.00:1.29:0.05
46	10.0 (0.6)	86.7	1.00:1.76:0.06
60	8.7 (1.3)	88.3	1:00:1.76:0.07
74	10.7 (3.73)	90.0	1.00:1.98:0.10
88	4.9 (1.28)	79.4	1.00:3.06:0.17
102	4.1 (1.22)	74.1	1.00:3.42:0.20
116	2.6 (0.80)	75.6	1.00:4.44:0.42
130	1.7 (0.41)	73.9	1.00:5.39:0.58
144	0.9 (0.28)	72.3	1.00:7.61:0.82

McDonough et al. (1993) found that the equilibrium mixture of the four isomers of 8,10-12: OH was much less attractive to males in a flight tunnel assay than E8,E10-12:OH alone. In field tests, the equilibrium mixture also improved the level of short-range communication disruption versus E8,E10-12:OH alone (McDonough et al. 1994). Larger-scaled field tests are needed to assess the potential of these nonpheromone semiochemicals for mating disruption. In addition, with the tube dispenser, studies are needed to clarify the effects that may occur on the behavior of codling moth and the efficacy of mating disruption from these temporal changes in isomeric blend.

The coefficients for the multiple regression model for dispenser emission rates for 1989 and 1990 are listed in Table 3. No significant differences were found for the coefficient of each component between years (overlapping 95% CL) except for 12:OH which had a slower emission rate in 1989 than in 1990. The effect of temperature on the emission rate of pheromone was similar to that reported by Brown et al. (1992) (i.e., emission rate of E8,E10-12:OH nearly tripled with an increase of 9.5°C). The emission rate of E8,E10-12:OH as a function of accumulated degree hours was ca. 28% lower from the tube dispenser than for the dispenser studied by Brown et al. (1992). Emission rate of 12:OH from the tube dispenser as a function of accumulated degree hours in 1990 was similar to Brown et al. (1992) but was significantly lower in 1989. No difference in the release rate for 14:OH was found between the two dispensers.

Table 2. Emission rates of E8, E10-12OH, 12:OH, and 14:OH and isomeric purity of E8,E10-12:OH at 22.5°C and 6,000 ml/min aeration from a sealed polyethylene tube dispenser aged in an apple orchard near Zillah, WA, during 1990, n=3-5.

Days in field	Emission rate E8, E10-12OH (μg/h) (SEM)	% EE isomer	Pheromone blend (E8, E10-12OH:12:OH:14:OH)
0	26.7 (5.4)	94.3	1.00:0.78:0.04
10	15.4 (0.8)	89.5	1.00:0.91:0.06
18	16.0 (1.1)	92.0	1.00:0.83:0.04
29	13.0 (1.0)	92.6	1.00:0.78:0.06
43	8.8 (1.7)	88.4	1:00:1.03:0.07
57	8.6 (1.7)	88.9	1.00:0.98:0.08
69	6.2 (1.1)	85.6	1.00:1.28:0.09
84	2.6 (0.2)	84.9	1.00:2.37:0.19
98	3.5 (0.4)	83.9	1.00:1.80:0.17
126	1.3 (0.5)	82.3	1.00:3.69:0.37

Emission levels of E8,E10-12:OH estimated under standardized laboratory conditions at dusk during both years are shown in Fig. 2. The tube dispenser in 1989 was estimated to have released 32.9 to 0.2 μg/h at dusk over the season (Fig. 2a). During 1990, the dispenser was estimated to have released 15.6 to 3.5 μg/h following the first application in plots C and D, between 7.9 to 0.6 μg/ha after 25 July in plots C and D, and between 31.2 to 2.3 μg/h in plots A and B after 24 July (Fig. 2b). Following the split application of dispensers on 24-25 July in all plots, levels of pheromone emitted at dusk were estimated to have ranged from 61.7 to 4.5 mg/ha/h in plots A and B and 52.5 to 4.0 mg/ha/h in plots C and D.

These estimated emission rates are based on standardized laboratory conditions and do not include the unknown effect of variation in wind speed. Brown et al. (1992) found that the emission rate of codling moth pheromones from a similar polyethylene dispenser was independent of aeration velocity over the range tested. Suckling (pers. communication) found that natural variation in the wind velocity in an orchard experienced by dispensers placed vertically throughout the canopy did not affect the emission rate of pheromone from a similar dispenser. Furthermore, the size of the potential error associated with our estimates of the total concentration of pheromone released by 1,000 dispensers per ha is likely reduced by this large sample size. Further developments in our knowledge of atmospheric pheromone concentrations in orchards is dependent on the development of real-time measurement methodologies (Milli & Dickler 1993).

Table 3. Equation coefficients for models predicting the emission rate of sex pheromone components from polyethylene tube dispensers as a function of temperature (°C) and accumulated degree hours above 0°C in 1989 and 1990. ln (emission rate) = intercept + k_1/temperature + k_2 (degree hours /1000).

			Coefficients (SE)		
Year	Compound	Intercept	k_1	k_2	R^2
1989	E8,E10-12:OH	5.83 (0.10)	-51.89 (1.92)	-0.051 (0.001)	0.94
	12:OH	5.78 (0.08)	-52.20 (1.40)	-0.018 (0.001)	0.92
	14:OH	2.45 (0.09)	-52.10 (1.78)	-0.018 (0.001)	0.86
1990	E8,E10-12:OH	5.46 (0.27)	-47.10 (5.43)	-0.050 (0.003)	0.85
	12:OH	5.16 (0.15)	-48.66 (3.12)	-0.024 (0.002)	0.87
	14:OH	2.29 (0.19)	-47.58 (3.82)	-0.015 (0.002)	0.77

Field Trial 1989. Catches in sex pheromone traps placed in three adjoining apple orchards (A_1 - A_3) averaged <2 moths per week during the beginning of first generation flight. Orchards A_2 and A_3 were situated 200 m north and 50 m west of the pheromone study orchard, respectively, and were treated conventionally for codling moth (six alternate-row sprays of azinphosmethyl during the season). Injury levels in these orchards were <0.1% at harvest. In contrast, orchard A_1, situated 25 m NE from the edge of plot 1, was treated with ryania, Dipel, and codling moth granulosis virus. Codling moth injury in 'Golden Delicious' in this orchard was evaluated during packing and exceeded 20% (A. L. K., unpubl. data).

Percent fruit injury in the untreated plot in our study was 0.64% and fruit injury ranged from 0.05 to 1.75% in the pheromone-treated plots (Table 4). No clear pattern was seen with respect to the number of pheromone dispensers applied per ha and levels of fruit injury (Table 4). The percentage increase in fruit injury between generations increased 4 to 5-fold in most plots, except in plots 10, 11, and 12 situated the furthest from orchard A_1 (Fig. 1) where it remained similar between generations (Table 4). Approximately, 50% of the injured fruits in plots 1, 5, and 9 were found in those 3-6 trees per row nearest block A_1. Plotting the data from only the plots treated with 2,000 dispensers per ha as the proportion of trees (y) with various number of injured fruits within 30 m distance classes from the SW corner of block A_1 showed that a clear gradient of injury occurred from the eastern to the western edge of the orchard (Fig. 3). Two of the equations fit to these data, y = 0.851 - 0.0022 (distance) (R^2 = 0.83) for trees with > 0 injuries, and the equation with the maximum R^2, ln (y) = -0.083 + 23.618/distance (R^2 = 0.97) for trees with more than 4 injuries are shown in Fig. 3. Fifty percent of the trees with >0 and >4 injuries were positioned < 225

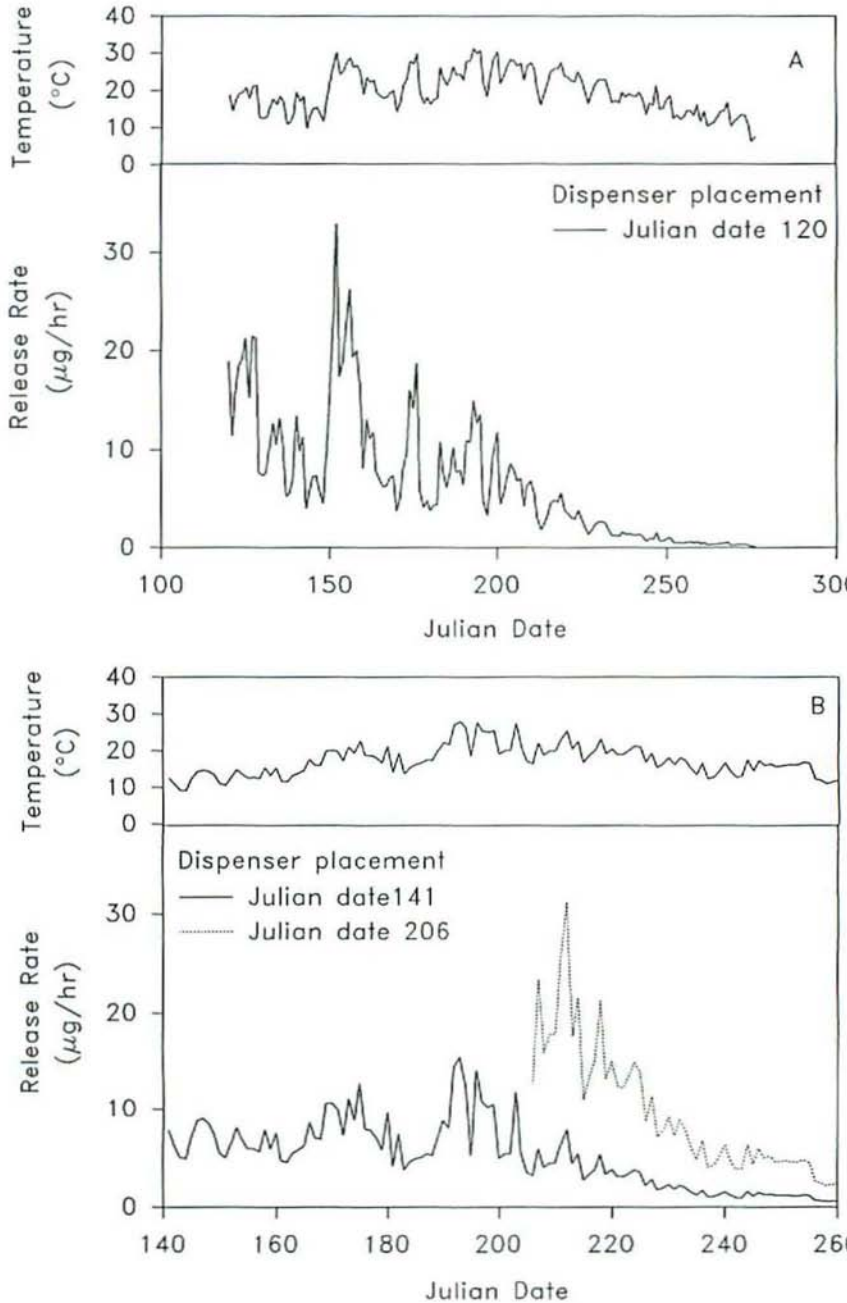

Fig. 2. Air temperatures and calculated emission rates (μg/h) of E8, E10-12:OH from a sealed polyethylene tube dispenser at dusk (2100-2200 hrs), for 1989 (A); 1990 (B).

Table 4. Fruit injury by codling moth in 0.4 ha plots treated with various densities of a sealed polyethylene tube dispenser in 1989 in an apple orchard near Zillah, WA.

		Percent fruit injury		
Plot	# dispensers	1st gen.	2nd gen.	Total
1	2000[a]	0.21	1.06	1.27
2	0[a]	0.05	0.21	0.26
3	2000[a]	0.02	0.08	0.11
4	0	0.23	0.41	0.64
5	4000	0.09	0.68	0.77
6	2000	0.06	0.27	0.33
7	1000	0.02	0.06	0.08
8	4000	0.00	0.05	0.05
9	1000	0.31	1.44	1.75
10	2000	0.09	0.15	0.25
11	2000	0.04	0.04	0.09
12	2000	0.04	0.03	0.07

[a] Plots were sprayed with 9 applications of 8.96 kg/ha ryania and 3 applications of 0.56 kg/ha Dipel.

and 75 m from the SW corner of block A1, respectively (Fig. 3). Measured from the center of block A_1 this was reflect a mean dispersal distance of 275 - 425 m (assuming a uniform distribution of emergence sites of moths in block A_1 and an insignificant moth population density developing within these plots).

Field Trial 1990. Sampling efficiency for counting codling moth injuries with persons on two mobile ladders and a single person on the ground was low, especially for 'Delicious.' The percentage of all codling moth injuries found on trees in July and September samples were only 31% and 40% for 'Delicious' and 55% and 63% for 'Golden Delicious,' respectively. Sampling efficiency was significantly, and negatively correlated with crop load (r^2 = 0.11, P = 0.03).

A 50-fold range in the mean number of injured fruit per tree during first generation was established among the four plots (Table 5). The delayed application of pheromone combined with the lack of any insecticides in plot D contributed to this plot having the highest population density. The population density during the first generation in the untreated plot A was also high (Table 5). The relatively higher population in plot D versus A was likely due to its proximity to a wood pile from a recently cut orchard that may have harbored overwintering codling moth larvae. The higher population density in the eastern versus the western plots was supported by relatively higher catches of males in pheromone-baited traps prior to the placement of pheromone dispensers (14.8 versus 8.3 moths per trap per wk).

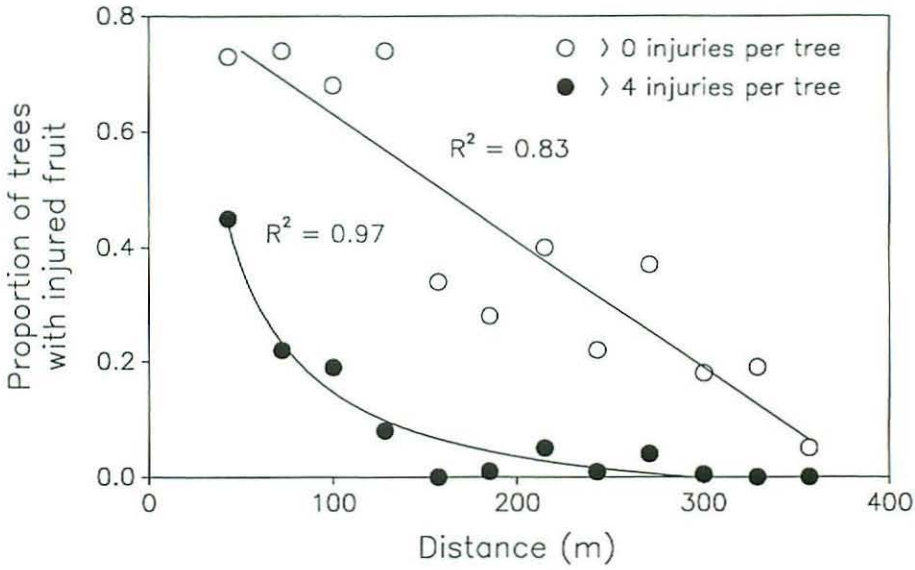

Fig. 3. Proportion of trees within 30 m distance classes from the SW corner of block A_1 with > 0 and > 4 injured fruits at harvest, 1989.

The use of mating disruption during second generation in all four plots was not sufficient to maintain commercially acceptable levels of fruit injury (<0.1%) (Table 5). The percentage of fruit injured at harvest was less than 1% for 'Delicious' in all plots except plot D (4.0%). In contrast, levels of injury for 'Golden Delicious' were greater than 1% in all plots except plot B (0.9%) (Table 5). This preference by codling moth for 'Golden Delicious' versus 'Delicious' was also found by Howell et al. (1992).

Increases in fruit injury in plots B and C which occurred between generations in 1990 (ca. 250% increase in plot B for both cultivars and ca. 850% and 2400% increase in 'Delicious' and 'Golden Delicious' in plot C, respectively [Table 5]) were affected by the movement of females out of plot D. The area of high codling moth density (>20 or >40 injuries per tree for 'Delicious' and 'Golden Delicious', respectively) increased from 50 m to 200 m in width from first to second generation (Fig. 4).

Our data from 1989-90 on the spread of codling moth infestation in pheromone-treated orchards are consistent with previous studies of the distribution of oviposition by females immigrating into uninfested, nonpheromone-treated orchards, i.e., > 90% of eggs oviposited on trees <100-300 m from their release point (Wildbolz & Mani 1959, White et al. 1973). Recent development of a passive trap (Weissling & Knight 1994) will allow us to more directly study the dispersal behaviors of virgin and mated females and males in the presence of pheromone and refine the deployment of mating disruption-based control strategies for codling moth.

Table 5. Estimated number of codling moth injuries per tree for each generation and percent fruit injury at harvest in four 1-hectare experimental plots in 1990 in an orchard situated near Tieton, WA. All plots were treated with sealed polyethylene tube pheromone dispensers during the second generation.

Plot/Initial Treatment[a]	Cultivar	Estimated mean number of codling moth injuries per tree (± SE)		% injured fruit
		1st Generation	2nd Generation	
A/check	'Delicious'	0.58 ± 0.36	0.95 ± 0.28	0.26
	'Golden Delicious'	5.72 ± 1.13	2.90 ± 0.76	1.75
B/2 sprays	'Delicious'	0.12 ± 0.06	0.43 ± 0.18	0.09
	'Golden Delicious'	1.13 ± 0.23	4.24 ± 1.14	0.93
C/1 Spray	'Delicious'	0.24 ± 0.07	2.29 ± 0.73	0.40
+ pheromone	'Golden Delicious'	0.40 ± 0.11	10.11 ± 2.19	1.75
D/pheromone	'Delicious'	10.73 ± 2.03	12.81 ± 2.40	4.01
	'Golden Delicious'	28.18 ± 3.98	50.58 ± 7.57	14.14

[a] Sprays of 0.84 kg AI azinphosmethyl per ha were applied on 26 May and 5 July. Pheromone dispensers (2,000 per ha) were applied to plots C and D on 21 May. On 24-25 July 2,000 dispensers per ha were applied to plots A and B and 1,200 dispensers per ha were applied to plots C and D.

Mating disruption with the polyethylene tube dispenser for high codling moth population densities has been shown not to be effective when used alone without insecticides (Pfeiffer et al. 1993). Clearly, the experimental design used in these field experiments in 1989-90 preclude an evaluation of the efficacy of this dispenser. However, the moderate percentage increase in codling moth density between generations that occurred in both orchards in plots not exposed to moth immigration suggests that the pheromone treatment had an important effect in limiting the rate of population growth of codling moth (Tables 4 and 5). The tube dispenser (Isomate-C) was subsequently registered in the United States in 1991 at a rate of 1000 dispensers per ha. Adoption of this product will likely depend on its cost and performance relative to the available broad-spectrum insecticides. Despite its registration and anticipated grower adoption, a range of both basic and applied studies will be needed to optimize its performance in managing orchard populations of codling moth (Knight 1992).

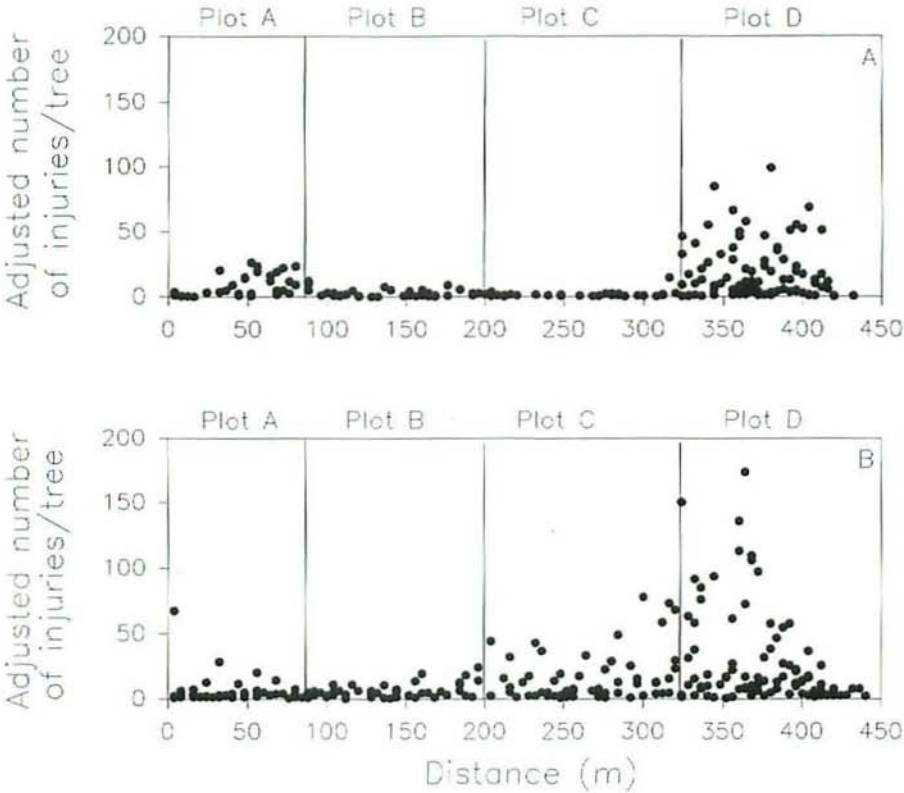

Fig. 4. Adjusted number of injured fruit per tree during first (A) and second (B) generation of codling moth as a function of distance from the western edge of the Tieton orchard, 1990.

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Effects of Soaps, Oils, and Plant Growth Regulators (PGRs) on *Neoseiulus cucumeris* (Oudemans) and PGRs on *Orius insidiosus* (Say)[1]

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ABSTRACT Direct and residual toxicity of selected oils, a soap, azadirachtin, and plant growth regulators were evaluated on a candidate for thrips management, *Neoseiulus cucumeris* (formerly *Amblyseius cucumeris*) and plant growth regulators were evaluated for a second candidate for thrips management, *Orius insidiosus*. These predators and compounds must be compatible for incorporation into a management program. The plant growth regulators chlormequat, daminozide, and paclobutrazol were compatible with both *N. cucumeris* and *O. insidiosus* in both direct and residual experiments. *Neoseiulus cucumeris* was compatible with residues of all insecticide materials at the 1 and 2% rates. Exposure to 4% Uni-Par® oil residues resulted in 90% *N. cucumeris* mortality at 48 h. Mortality of *N. cucumeris* at 48 h following residual exposure to 4% Sunspray Ultrafine® oil was 64%. Insecticidal soap residues were more compatible than oils with only 25% *N. cucumeris* mortality following a 4% application. However, *N. cucumeris* was not compatible with direct application of oils or 4% insecticidal soap.

KEY WORDS Biological control, *Neoseiulus cucumeris, Amblyseius cucumeris, Orius insidiosus*, greenhouse pests, plant growth regulators, integrated pest management, predators

Ongoing problems with pesticide resistance, registration, increased regulations, and concerns over worker safety, contamination of water, and pesticide residues are forcing growers to reduce the use of conventional insecticides on ornamental crops. Alternatives to conventional pesticides include pesticides which are more environmentally friendly (e.g. soaps and oils), improved cultural practices, and the use of natural enemies. There have been several studies conducted on the compatibility of conventional insecticides, fungicides, and herbicides with predators and parasites (e.g. Croft & Whalon 1982, Hassan & Oomen 1985, Ledieu 1985). The IOBC/WPRS Working Group 'Pesticides and Beneficial Organisms' has developed a summary of the side-effects of conventional pesticides against a wide variety of natural enemies (Hassan 1985). However, little information is available on the

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compatibility of soaps, oils, and plant growth regulators with natural enemies. Soaps and oils have been used for the management of pests of horticultural crops (Osborne 1984, Butler & Henneberry 1991, Johnson 1991) but more information is needed on the compatibility of natural enemies with these compounds. Osborne and Petitt (1985) utilized an insecticidal soap and a predatory mite, *Phytoseiulus persimilis* Athias-Henriot, as compatible components in the management of the two-spotted spider mite on greenhouse-grown foliage plants.

There is a need for similar information on the compatibility of insecticides with natural enemies of other pests of ornamentals, especially thrips. Thrips, specifically the western flower thrips, *Frankliniella occidentalis* (Pergande), have become important pests of greenhouse crops in the last decade. One mite predator, *Neoseiulus cucumeris* (Oudemans)(formerly *Amblyseius cucumeris*), has shown promise as a biological control of thrips in the greenhouse (Gillespie 1989, Ramakers & van Lieburg 1982). A minute pirate bug, *Orius insidiosus* (Say), is a general predator which also is a potential biological control for thrips (Fransen & Tolsma 1992, van den Meiracker & Ramakers 1991, Oetting & Beshear 1991).

The purpose of this study was to address the impact of some common pesticides used in greenhouse horticulture including: soaps, oils, a plant derivative insecticide azadirachtin, and plant growth regulators on natural enemies. Two predators with potential for control of western flower thrips, *N. cucumeris* and *O. insidiosus*, were included in this study. Since many growers are showing an increased interest in the use of these pesticides and plant growth regulators as a regular part of the management of ornamental crops, especially greenhouse crops, any predator introduced into the greenhouse must be compatible for smooth integration into a plant health management program.

Materials and Methods

Survival rates of two predators, *N. cucumeris* and *O. insidiosus*, were evaluated after exposure to plant growth regulators and *N. cucumeris* was evaluated after exposure to insecticides. The *N. cucumeris* were obtained from a commercial source (Applied Bio-Nomics Ltd., Sidney, B.C., Canada) and were maintained in culture using the rearing methods described by Ramakers (1983). The *O. insidiosus* were collected locally and maintained in culture using the methods described by Isenhour and Yeargan (1981) or in a greenhouse on chrysanthemums.

The chemicals tested against these two predators were four insecticides without residual activity and four plant growth regulators. The insecticides were: two horticultural oils Sunspray Ultrafine® (Mycogen Corp., San Diego, CA) and Uni-Par® (Uniroyal Chem., Brea, CA), an insecticidal soap (Impede®, Mycogen Corp.), and azadirachtin 0.3% (Margosan-0®, Grace Sierra, Milpitas, CA). The standard dosage of all insecticides was 1% of formulation in the test solution. The plant growth regulators and standard dosages were: ancymidol (A-Rest®, DowElanco, Indianapolis, IN) 60 ppm, chlormequat (Cycocel®, American Cyanamid Co., Wayne, NJ) 3,000 ppm,

daminozide (B-Nine®, Uniroyal Chem.) 5,000 ppm, and paclobutrazol (Bonzi®, Uniroyal Chem.) 40 ppm. Each chemical was tested at one, two, and four times the standard dosage.

The methods to test the effect of chemicals on predators were modified from standard methods developed by the International Organization for Biological Control (Hassan, 1985). Immature minute pirate bugs and late stage immatures and adults of *N. cucumeris* were used in these experiments. A minimum of 100 individuals of *N. cucumeris* and 50 *O. insidiosus* were used in every treatment combination. Experiments were conducted to investigate the impact of direct and residual effects of the chemicals on these predators.

In direct effect experiments, the test unit for *N. cucumeris* consisted of a 2 cm diam × 4 cm tall glass container closed with parafilm. The glass container was coated with the test solution and allowed to dry. A 1.5-cm disk from a chrysanthemum leaf was dipped in the test solution for 5 s, and placed immediately (direct effect) or air dried (residual effect) and placed in the container, as a test surface and a shelter. Five predatory mites and several *Acarus siro* L. (the host used for rearing) were placed on the leaf disk with a camel-hair brush. The test unit for *O. insidiosus* was a 2 cm diam × 4 cm tall glass container covered with 120-mesh screen, the leaf disk was 2 cm, and no prey was provided; otherwise, the experiment was conducted the same as with *N. cucumeris*.

Mortality of predators, placed on wet chrysanthemum leaf disks immediately following application of the test solution, was determined 24 h after application. In residual effect experiments, chemicals applied to the glass and leaf disk were allowed to dry about 1 h before introduction of predators. Survival was determined 24 and 48 h after application.

Data were analyzed by using SAS procedures (SAS Institute 1985). Data for predator survival were subjected to arcsin transformation for analysis of variance by the GLM procedure and mean separation using LSD ($P \leq 0.05$). Mortality for all treatments was determined and corrected for natural mortality as determined in the non-chemical treatment. Results were ranked in toxicity categories according to the standard used by the IOBC working group "Pesticides and Beneficial Organisms." The reduction in beneficial capacity (toxicity) was calculated as percentage reduction in predator population in treated compared to untreated treatments. The reduction levels were then categorized: (1) harmless=reduction <50%, (2) slightly harmful=reduction 50-79%, (3) moderately harmful=reduction 80-99%, and (4) harmful=reduction 99%.

Results and Discussion

Direct, residual, host feeding, and ovicidal toxicity are often tested to determine the effect of insecticides on predators. Because of the nature of soaps, oils, and plant growth regulators, only direct and short-term residual toxicity were considered to impact the incorporation of these two predator systems into a pest management program. There are many reports on the effects of conventional chemicals on predatory mites in the genus *Amblyseius*

using different techniques in evaluating toxicity. Methods of evaluating toxicity include: introducing mites on treated leaves placed on a wet cotton pad in an open petri dish to test residual toxicity (Streibert 1981), adhering mites to a slide with double-stick tape and dipping the slide in the test solution for direct toxicity (Rock 1979), placing mites in a tight-fitting plastic petri dish where the test solution was swirled briefly in the container (Thistlewood *et al.* 1992), and using a cell with a treated leaf on the bottom and a glass cover (Overmeer & van Zon 1981). We tested the leaf on a wet cotton pad (Streibert 1981), but the saturated cotton was not sufficient to keep the mites on the leaf. The result was inadequate recovery of mites in the water check treatments to obtain any meaningful data. Similar results have been reported by other investigators (Thistlewood *et al.* 1992). The slide dip assay can only be used for direct toxicity. In our experiments, we chose to use a modification of the methods of Overmeer & von Zon (1981) and Thistlewood *et al.* (1992) as a test chamber.

Soaps and oils are contact insecticides that must be deposited on the target pest to be effective. The result is a minimal impact on surviving individuals and individuals not exposed to the direct spray. All of the insecticide treatments were compatible with *N. cucumeris* release after application (Table 1). The residual results were all harmless at the 1% rate. The mortality was higher with the oil treatments than with soap in both the direct and residual experiments. Mortality was the lowest following the soap treatment at all rate levels. The only treatment that resulted in mortality in the moderately harmful range was Uni-Par oil at 4%.

The impact of direct application of oils to *N. cucumeris* was moderately harmful to harmful (Table 1). However, *N. cucumeris* was not as susceptible to insecticidal soap; only the 4% application rate was in the moderately harmful range. Azadirachtin was the least harmful of the tested insecticides to this mite in direct-exposure tests. However, this material is an insect growth regulator and the impact of direct exposure may not have been expressed within the test period.

The plant growth regulators were compatible with both *N. cucumeris* and *O. insidiosus* in both direct and residual experiments (Tables 2 & 3). The only treatment that resulted in *N. cucumeris* mortality over 50% was 20,000 ppm daminozide, four times the standard application rate, applied as a direct treatment (Table 2). All other treatments caused less than 50% mortality. The highest level of *O. insidiosus* mortality was 34% following direct treatment with 160 ppm paclobutrazol (Table 3).

Insecticide and plant growth regulator treatments utilized moderately affected the predators *N. cucumeris* and *O. insidiosus*. However, the level of mortality of these predators would be acceptable in a program using these chemicals for thrips management. Both predators could be used in conjunction with the plant growth regulators tested with limited detrimental effect. There would be more impact expected on populations of *N. cucumeris* than on *O. insidiosus* based on these test results. However, there would be sufficient survival of both predators for reestablishment. The application of soaps or oils should not affect mites released after application. In many programs, much of the thrips management with this mite is by augmentative release.

Table 1. The effects of the application of pesticides on the mortality of *Neoseiulus cucumeris*.

		Residual Effects						Direct Effects		
		24 h			48 h			24 h		
Treatment	dosage[a]	Surv.[b]	Corr. Mort.[c]	Tox.[d]	Surv.[b]	Corr. Mort.[c]	Tox.[d]	Surv.[b]	Corr. Mort.[c]	Tox.[d]
Sunspay	0	3.5 b	–	–	2.3 b	–	–	1.3 b	–	–
Ultrafine	0.5	–	–	–	–	–	–	0.1 a	92	3
Oil	1	1.8 a	49	1	1.0 a	44.6	1	0.2 a	85	3
	2	2.1 a	40	1	1.4 a	53.3	2	0.0 a	100	4
	4	2.0 a	43	1	1.3 a	64.4	2	0.0 a	100	4
Uni-par oil	0	3.9 c	–	–	3.1 c	–	–	2.1 b	–	–
	0.5	–	–	–	–	–	–	0.2 a	92	3
	1	2.5 b	36	1	1.6 b	47	1	0.4 a	81	3
	2	1.8 a	54	2	1.3 b	57	2	0.0 a	100	4
	4	0.8 a	79	2	0.2 a	94	3	0.0 a	100	4
Insecticidal	0	2.3 b	–	–	1.2 a	–	–	2.0 c	–	–
Soap	0.5	–	–	–	–	–	–	1.3 c	35	1
	1	2.2 b	4	1	1.2 a	0	1	0.8 b	60	2
	2	2.3 b	0	1	1.2 a	0	1	0.5 ab	75	2
	4	1.5 b	35	1	0.9 a	25	1	0.2 a	90	3
Azadirachtin	0	3.0 b	–	–	1.7 b	–	–	1.9 b	–	–
(Margosan-O)	0.5	–	–	–	–	–	–	1.1 a	42	1
	1	2.9 b	3	1	2.0 b	0	1	0.9 a	53	2
	2	2.2 a	27	1	1.6 b	6	1	1.1 a	42	1
	4	2.0 a	33	1	1.0 a	41	1	1.0 a	47	1

[a] Dosage expressed as percent of formulation.
[b] Means within a column followed by the same letter are not significantly different among rates within a treatment, LSD ($P < 0.05$).
[c] Mortality with treatments corrected to account for mortality in the 0 rate.
[d] Toxicity categories: 1 = harmless (reduction < 50%), 2 = slightly harmful (reduction 50-79%), 3 = moderately harmful (reduction 80-99%), and 4 = harmful (reduction > 99%).

Table 2. The effects of the application of plant growth regulators on the mortality of *Neoseiulus cucumeris*.

		Residual Effects						Direct Effects		
		24 h			48 h			24 h		
Treatment	dosage ppm	Surv.[a]	Corr. Mort.[b]	Tox.[c]	Surv.	Corr. Mort.	Tox.	Surv.	Corr. Mort.	Tox.
chlormequat	0	2.5 a	–	–	1.6 a	–	–	2.8 a	–	–
	1,500	–	–	–	–	–	–	2.4 a	14	1
	3,000	2.7 a	0	1	1.9 a	0	1	2.2 a	21	1
	6,000	2.3 a	8	1	1.4 a	13	1	2.4 a	14	1
	12,000	2.3 a	8	1	1.6 a	0	1	2.2 a	21	1
daminozide	0	3.1 a	–	–	1.8 a	–	–	2.1 c	–	–
	2,500	–	–	–	–	–	–	1.9 bc	9	1
	5,000	2.9 a	6	1	1.2 a	33	1	1.2 ab	43	1
	10,000	2.9 a	6	1	1.8 a	0	1	1.2 ab	43	1
	20,000	3.2 a	0	1	1.9 a	0	1	0.7 a	67	2
paclobutrazol	0	2.8 a	–	–	1.8 a	–	–	2.5 b	–	–
	20	–	–	–	–	–	–	2.1 ab	16	1
	40	2.7 a	4	1	1.7 a	6	1	2.2 ab	12	1
	80	2.7 a	4	1	1.1 a	39	1	1.8 ab	28	1
	160	2.8 a	0	1	1.5 a	17	1	1.6 a	36	1

[a] Means within a column followed by the same letter are not significantly different among rates within a PGR treatment, LSD ($P < 0.05$).
[b] Mortality with treatments corrected to account for mortality in the 0 rate.
[c] Toxicity categories: 1 = harmless (reduction < 50%), 2 = slightly harmful (reduction 50-79%), 3 = moderately harmful (reduction 80-99%), and 4 = harmful (reduction > 99%).

Table 3. The effects of the application of plant growth regulators on the mortality of *Orius insidiosus*.

		Residual Effects						Direct Effects		
		24 h			48 h			24 h		
Treatment	dosage	Surv.[a]	Corr. Mort.[b]	Tox.[c]	Surv.	Corr. Mort.	Tox.	Surv.	Corr. Mort.	Tox.
ancymidol	0	–	–	–	–	–	–	4.0 a	–	–
	1	–	–	–	–	–	–	4.1 a	0	1
	2	–	–	–	–	–	–	4.1 a	0	1
	4	–	–	–	–	–	–	4.2 a	0	1
chlormequat	0	4.9 a	–	–	4.1 a	–	–	4.0 a	–	–
	3,000	4.9 a	0	1	4.1 a	0	1	3.3 a	13	1
	6,000	4.2 b	14	1	3.4 a	17	1	4.0 a	0	1
	12,000	3.8 b	23	1	4.1 a	0	1	3.7 a	8	1
daminozide	0	4.6 a	–	–	4.3 a	–	–	3.9 a	–	–
	5,000	4.7 a	0	1	4.4 a	0	1	3.5 a	10	1
	10,000	4.6 a	0	1	4.1 a	5	1	3.5 a	100	1
	20,000	4.7 a	0	1	4.3 a	0	1	3.2 a	18	1
paclobutrazol	0	4.9 a	–	–	4.1 a	–	–	3.8 a	–	–
	40	4.7 a	4	1	3.9 a	5	1	3.9 a	0	1
	80	4.8 a	2	1	4.5 a	0	1	3.3 ab	13	1
	160	4.7 a	4	1	4.0 a	2	1	2.5 b	34	1

[a] Means within a column followed by the same letter are not significantly different among rates within a PGR treatment, LSD ($P < 0.05$).
[b] Mortality with treatments corrected to account for mortality in the 0 rate.
[c] Toxicity categories: 1 = harmless (reduction < 50%), 2 = slightly harmful (reduction 50-79%), 3 = moderately harmful (reduction 80-99%), and 4 = harmful (reduction > 99%).

Azadirachtin is an insect growth regulator requiring a longer period to determine direct/residual effects of applications. Although azadirachtin was included in this experiment to determine if there were any direct or residual effects, our inability to maintain the mite for more than 2 days under test conditions provided insufficient data on long-term residual effects.

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Effect of Bovine Blood Plasma and Erythrocyte Diets on Adult Horn Fly, *Haematobia irritans* (L.) (Diptera: Muscidae), Mortality and Oogenesis[1]

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ABSTRACT Egg production of horn fly, *Haematobia irritans* (L.), adults fed a diet of erythrocytes was significantly less than flies fed the standard laboratory diet of citrated bovine blood, but this difference is inconsequential for colony production. Flies fed erythrocyte diets resorbed fewer oocytes in the ovaries than flies fed a bovine blood plasma diet. Adult mortality did not differ significantly among flies fed the plasma diet and the erythrocyte diet. This work confirms that a requirement exists for erythrocytes or some component of erythrocytes in the horn fly diet for oogenesis to occur.

KEY WORDS Diptera, Muscidae, erythrocytes, plasma, resorption, oogenesis, horn fly, *Haematobia irritans*

The adult horn fly, *Haematobia irritans* (L.), is an obligate blood-sucking ectoparasite of cattle. Yearly loss in the United States attributed to the horn fly is estimated at $876 million (Kunz et al. 1991). Often, the study of horn flies is limited by the lack of effective rearing methods needed to produce large numbers economically and efficiently.

Horn flies were first reared successfully *in vitro* by Harris (1962). Prior attempts by McLintock & Depner (1957) to establish a colony on an adult diet of defibrinated and citrated beef blood failed because the wild flies stopped laying eggs after 2 or 3 days. No eggs were laid by second generation flies because ovarian maturation did not occur. One of the problems faced was microbial contamination of bovine blood, resulting in high adult mortality (Harris 1962). A subsequent success at mass-rearing horn flies was achieved by Schmidt et al. (1967). The initial adult diet for successful colonization of wild horn flies at the University of Florida consisted of bovine blood containing 7 g per 1800 ml sodium citrate, 1 g per 1800 ml of Kanamycin sulfate, and 500,000 units per 1800 ml Mycostatin (Greer 1975; Schmidt et al. 1976). The cows were injected with papain before slaughter (Greer 1975).

Galun (1986) grouped blood feeding arthropods into three categories according to their feeding response to blood fractions. These were: (1) those that recognize blood through properties of the plasma and ingest plasma as avidly as whole blood,

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(2) those that require components limited to the cellular fractions, either red blood cells or platelets, and do not ingest plasma unless specific cell components are added, and (3) those that are intermediate, feeding on plasma but to a lesser extent than on whole blood, and requiring cellular components for optimal response. It is not clear into which of the above categories the telmophagous horn fly falls and what effects the various blood components have on reproduction and mortality. The objective of this work was to compare the effects of the standard adult diet, a bovine plasma diet and an erythrocyte diet on horn fly egg production and mortality. An increased understanding of the dietetics of the horn fly is indispensable for successful *in vitro* rearing, and possibly could lead to the development of an artificial adult diet for wild horn fly colonization.

Materials and Methods

Horn fly adults were obtained from the laboratory colony at the University of Florida, Gainesville (Bolton 1980; Greer 1975). Standard colony rearing methods were modified from those of Greer (1975) as follows: A larval medium was made from a mixture of 1370 g of cattle manure (frozen at -20°C for at least 48 hours to kill all naturally occurring parasites), 546 g pelletized peanut hulls (High Springs Milling Co. Ltd., High Springs, Fl.) and 258 g dry mix (44% all-purpose flour, 33% fish meal, 18% alfalfa meal and 5% baking soda). Peanut hulls were presoaked in 700 ml of water for 30 minutes, and then crushed by hand. The dry mix was added to the peanut hulls and mixed thoroughly before the manure was mixed in. Horn fly eggs (0.5 ml) were added to 1400 g of medium which was maintained for seven days in an environmental chamber (Percival®, Boone, IA) at 27 ± 3°C and 75 ± 5% RH with continuous light supplied by two fluorescent tubes. Pupae were separated from the medium by water flotation and dried on paper towelling. Dry pupae were held in a screen-covered aluminum cage (51 × 26 × 27 cm) in the environmental chamber until adults eclosed.

Adults were collected with a modified Hoover® 2836 vacuum, anesthetized by chilling in a freezer at -2°C for about 10 min, and sexed. Twenty females (24 h old) and ten males (48-72 h old) were transferred into 120 ml clear plastic screw top specimen containers (Baxter, Deerfield, IL) (4.5 cm diameter 5 8.5 cm high). Tops and bottoms of containers were removed and replaced with 32 mesh nylon cloth through which the flies could feed (Fig. 1).

Diets. Whole beef blood (standard laboratory diet) obtained from freshly slaughtered cows was used as a control. One liter of blood was collected in a plastic container in which 3.96 g of sodium citrate had been mixed with 13.2 ml of water. Next, 0.24 g of Kantrex® powder (Apothecon, Princeton, NJ) and 0.022 g of Mycostatin® (E. R. Squibb & Sons, Inc., Princeton, NJ) powder were added to the 1 liter of citrated bovine blood to control microorganisms and prevent spoilage. The blood was stored at 4°C until needed.

To prepare the plasma diet and erythrocyte diet, the standard colony blood diet was centrifuged at 500 g (International Equipment Co., Needham, MA) for 30 min. The supernatant (plasma) and bottom layers (erythrocytes) were removed separately with 5 ml syringes, put into containers and stored at 4°C until needed.

The diets (or treatments) were administered twice daily by placing 2 × 2 cm cotton quilt batting pads saturated with the respective diet on top of each modified specimen container (Fig. 1). Each diet was replicated four times in each of five trials. Egg production and mortality were measured and recorded daily. The files were maintained in the environmental chamber for 15 d, after which all surviving female flies were dissected in phosphate buffered insect Ringer's solution (Smith & Butler 1991). Ovaries were observed under a Nikon® microscope and photographed with a Zeiss photo III scope.

Data were analyzed by analysis of variance (ANOVA), and means were separated with Duncan's multiple range test (SAS Institute, 1985). $P = 0.05$ unless otherwise stated.

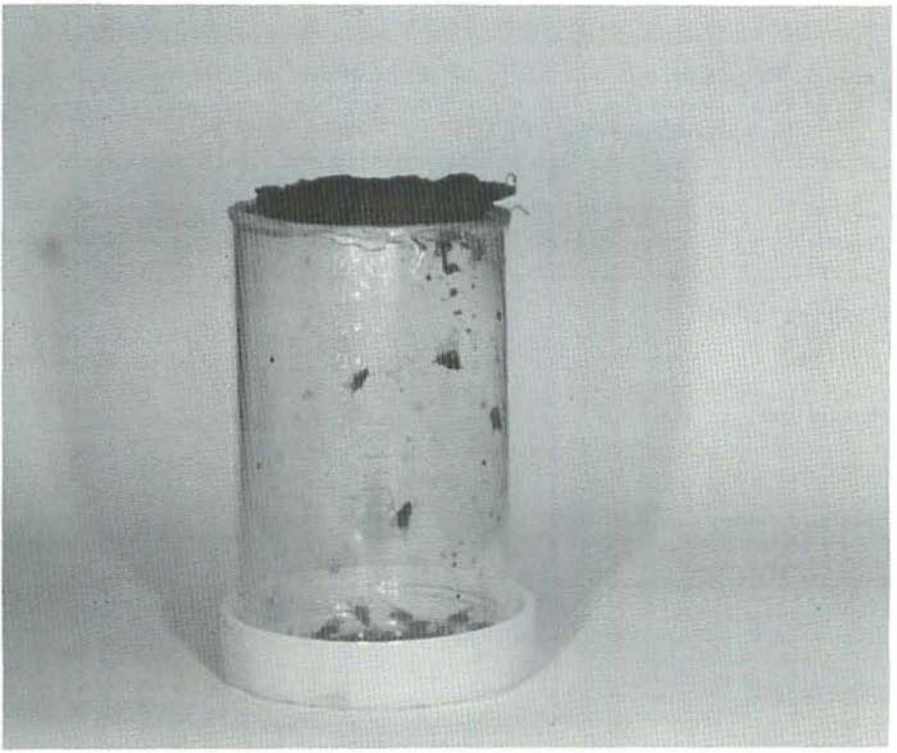

Fig. 1. Horn flies in the modified specimen container.

Results

Egg production was highest for flies fed the standard colony diet, and significantly lower for flies fed the erythrocyte and bovine blood plasma diets (F = 628.83; df = 2) (Table 1). However, the numerical difference in egg production between flies fed the standard colony diet and the erythrocyte diets was slight and, in terms of maintaining the horn fly colony, probably of no consequence. Differences in mortality between flies fed the erythrocyte and colony diets and between flies fed the erythrocyte diet and plasma diet were not significant. However mortalities of flies fed the colony diet and flies fed the plasma diet were significantly different (F = 4.01). Despite the significant differences, the values for mortality of the three diets were closely grouped (Table 1).

Table 1. Mean percent mortality, oviposition and ovarian resorption per replicate of *Haematobia irritans* fed bovine plasma, erythrocyte and standard colony diets.

Treatments	Mean % mortality (± SD)[a]	Mean number eggs per replicate (± SD)	% resorbed ovaries (± SD)
Erythrocyte diet	37.5 (6.5) ab	308 (18) b	1.3 (2.5)
Plasma diet	43.8 (6.3) a	71 (12) c	80.0 (4.1)
Standard colony diet (Control)	35.0 (4.0) b	346 (14) a	0.(0)

[a] Column means followed by the same letter are not significantly different (n = 3; df = 2 P = 0.05; Duncan's Multiple Range Test [SAS Institute 1985]).

Microscopic examination for ovarian development in the flies fed the plasma diet showed a high rate of oocyte resorption with some ovarioles showing multiple resorption (Fig. 2). In contrast, flies fed either the bovine erythrocyte fraction or the standard diet showed little or no ovary resorption. Further, the ovaries of plasma-fed flies without resorbed ovarioles had relatively smaller ovaries compared with the flies fed either the erythrocyte or the standard colony diet.

Fig. 2. Four resorbed ovarioles of horn fly fed plasma diet.

Discussion

Spates and DeLoach (1980) reported that all blood-sucking insects utilize erythrocytes as a nutritional source because 50% of blood meal protein is contained in the erythrocytes. Also, Kapatsa et al. (1989) found that adult *Stomoxys calcitrans* require erythrocyte membrane components in their diets for normal oogenesis. Fleas also need a factor, probably heme, for vitellogenesis to occur (Telfer 1965). When fleas were fed a diet of plasma and albumin only, oocyte resorption occurred. Our data also suggest that the component of the blood more critically needed for egg production in horn flies is the erythrocyte portion. The resorption of oocytes we observed in horn flies fed the plasma diet indicates that plasma is incapable of supplying sufficient nutrients to the developing egg. In contrast, horn flies fed the erythrocyte fraction showed egg development comparable to that of the control group fed standard laboratory diet. Although the erythrocyte portion extracted from the standard diet seems to meet the nutritional requirement for basically normal egg production in the horn fly, egg production was reduced somewhat.

The erythrocyte and plasma diets did not affect mortality significantly, indicating that bovine blood plasma and erythrocytes had no adverse effect on adult horn fly survival. This is true for a number of substances which do not affect survival but which prevent oogenesis in hematophagous flies (Pappas & Fraenkel 1977).

Significant achievements have been made in the development of semi-defined, nutritionally adequate, synthetic diets for blood-feeding insects (DeLoach & Spates 1984; Kabayo et al. 1985). These diets have contributed to the understanding of nutritional requirements of the tsetse fly, *Glossina* sp., and the stable fly, *Stomoxys calcitrans*. The major components of these diets are hemogloblin and albumin. Our work shows that some component of erythrocytes, possibly hemoglobin, is essential for oogenesis in the horn fly. If a supplement can be found that will enhance horn fly oogenesis, perhaps an artificial diet can be developed.

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Adaptation of Wheat Curl Mite (Acari: Eriophyidae) to Resistant Wheat in Kansas[1]

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ABSTRACT Wheat streak mosaic (WSM) was the most important disease of wheat, *Triticum aestivum* L., in Kansas from 1987 to 1991. The incidence of WSM is reduced in the wheat cultivar TAM 107, which has resistance to the wheat curl mite, *Eriophyes tulipae* Keifer, vector of the WSM virus. Our objectives were to determine whether *E. tulipae* could overcome the resistance of TAM 107 in the laboratory and to look for evidence of a resistance-breaking strain on TAM 107 in the field. *E. tulipae* was able to overcome resistance after being reared on TAM 107 for 2 mo. (ca. 8 generations) under laboratory conditions. One of 10 1992 field collections of *E. tulipae* from spikes of TAM 107 was adapted to that cultivar. Thus, *E. tulipae* can develop a resistance-breaking strain in both field and laboratory, but more information is needed on its prevalence and distribution in the field.

KEY WORDS Wheat curl mite, Acari, Eriophyidae, *Eriophyes tulipae* Keifer, Wheat streak mosaic virus, Vector, Resistance, Adaptation.

Wheat streak mosaic (WSM) was the most important disease of wheat (*Triticum aestivum* L.) in Kansas from 1987 to 1991 with an average annual loss of 5.5 million hectoliters (15.5 million bushels) (Harvey et al. 1994). It is vectored by the wheat curl mite, *Eriophyes tulipae* Keifer (Slykhuis 1955). Resistance to *E. tulipae* in wheats having translocations from rye (*Secale cereale* L.) effectively reduced field infections of wheat streak mosaic virus (WSMV) (Martin et al. 1984, Harvey & Martin 1988, Harvey et al. 1990, Conner et al. 1991). *E. tulipae* resistance is being utilized in the wheat cultivars TAM 107, TAM 200, and Century. These cultivars derive their resistance from 'Gaucho,' a resistant triticale (X *Triticosecale* W., cv. Trujillo) (Sebesta et al. 1994). Different physiological strains of *E. tulipae* have become adapted to species that were initially poor hosts (del Rosario & Sill 1965), so *E. tulipae* might become adapted to the resistance of TAM 107, which is now the most popular wheat cultivar grown in western Kansas.

The objectives of this study were to determine whether *E. tulipae* could adapt to or overcome the resistance of TAM 107 in the laboratory and whether resistance-breaking *E. tulipae* strains or biotypes have developed on TAM 107 in the field.

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Materials and Methods

Test 1 was initiated to determine whether *E. tulipae* could overcome the resistance of TAM 107 under laboratory conditions. Three collections of *E. tulipae* were made from 'Arkan' wheat at Hays, Kansas: the seedling stage in November 1990, the heading stage in May 1991, and volunteers during March 1992. *E. tulipae* collections were increased in the greenhouse on Arkan seedlings for 1 mo before being transferred to TAM 107. Thirty-three Arkan seedlings, each infested with 100-500 *E. tulipae* were placed on each flat of TAM 107 seedlings in the greenhouse. Each flat contained 11 rows of TAM 107 with 25 four-leaf stage seedlings per row. Three excised-infested Arkan seedlings were placed on each row of TAM 107 and removed after 2 d, when the mites had transferred to the growing wheat. Two months after infestation, the youngest leaf was removed from 33 infested TAM 107 seedlings (3 seedlings/row). The infested leaves were cut into 3-cm sections and placed in 0.5 dram shell vials. After 6 h, the mites crawled from the drying leaves to the vial rims, where they were picked up individually on the tip of a hair glued to a dowel and released on the youngest leaves of the test plants. Only adult or 2nd instar nymphs that displayed normal movements immediately after transfer were evaluated. Mite transfers were made with the aid of a stereo microscope (15X). The test plants were 2-leaf stage seedlings growing in poly-cast 2.5 × 14 cm. tubes (Stuewe and Sons, Inc., Corvallis, OR) containing a standard greenhouse soil mixture. Ten seedlings each of Arkan and TAM 107 were infested with *E. tulipae* from each of the three collections at the rate of 5 *E. tulipae*/seedling. Infested seedlings were randomized into supportive holders set in trays filled with water and held in a growth chamber at 27°C with a 12L:12D photoperiod for 10 d. Plants then were excised and dissected to record the numbers of *E. tulipae* per plant. The unselected *E. tulipae* controls were treated the same as described above, except they were reared continuously on Arkan.

Test 2 was designed to estimate the time required for *E. tulipae* to become adapted to TAM 107 in the laboratory. Arkan leaves infested with 100-500 *E. tulipae*, which had been collected from the field, were attached with spring-loaded hair clips to each of 100 TAM 107 and Arkan seedlings growing in poly-cast tubes and held in growth chambers as described for test 1. The clips were removed 2 d after infestation, when the mites had transferred to the growing plants. At 2 wk intervals for 8 wk after infestation, 20 infested plants each of TAM 107 and Arkan were used as sources of *E. tulipae* to infest the TAM 107 and test plants using the same methods described for test 1.

Test 3 was designed to determine if resistance-breaking strains of *E. tulipae* occur in the field. Wheat spikes in the milk stage were collected at random from one plot each of TAM 107 and the susceptible cultivar Karl from each of 10 western Kansas County wheat cultivar demonstration plots on 19 and 20 May and 3 June 1992. 'Karl' was used as a susceptible check because it was available at all locations and is similar to TAM 107 in maturity and degree of leaf pubescence. Pubescence may affect numbers of *E. tulipae* infesting wheat in the field (Harvey & Martin 1980). Five spikes of each cultivar from each county were cut into 1-cm sections and scattered on

2-leaf stage seedlings of Karl and TAM 107 growing in pots. The 15-cm pots were divided into two sections, with 8 seedlings each of Karl and Tam 107 occupying opposite halves of the pots. The seedlings then were covered with cages for 2 wk before the numbers of *E. tulipae* infesting the TAM 107 and Karl seedlings were recorded. Data are presented as mean numbers of *E. tulipae* per wheat spike then transferred to Karl and Tam 107 seedlings in the greenhouse.

Test 4 was to verify results from test 3, which indicated that *E. tulipae* collected from Graham County might differ in reaction to TAM 107. Ellis, Rush, and Graham were the only counties from which sufficient numbers of *E. tulipae* were obtained from spikes of TAM 107 to do the test. *E. tulipae* obtained directly from spikes of TAM 107 and Karl without being increased in the laboratory, were transferred to seedlings of TAM 107 and Karl. Methods were the same as described for test 1.

E. tulipae numbers were subjected to analysis of variance, and treatment means were separated by the Student-Newman-Keuls (Steel & Torrie, 1960) multiple range test and treatment variance was partioned with orthogonal contrasts at $P = 0.05$.

Results and Discussion

Three field collections of *E. tulipae* from susceptible Arkan wheat, made in different yr and from different stages of growth, each readily reproduced on the resistant TAM 107 after being reared on that cultivar for 2 mo (ca. 8 generations) (Table 1). Another *E. tulipae* field collection partially overcame the resistance of TAM 107 after being reared on that cultivar for only 6 wk (Table 2). Slykhuis (1955) & del Rosario & Sill (1965) found that *E. tulipae* from *Agropyron smithii* Rydb. adapted to wheat with great difficulty, whereas Painter & Schesser (1954) easily colonized wheat with *E. tulipae* from naturally infested *A. smithii*. On the other hand, del Rosario and Sill (1965) rather easily established *E. tulipae* obtained from *Setaria viridis* (L.) Beauv. on wheat, but Staples & Allington (1956) had little success making this transfer, and Connin (1956) and Orlob (1966) were not able to establish *E. tulipae* obtained from *S. viridis* on wheat. Evidently the potential for *E. tulipae* adaptation varies among mites collected from different locations, years, and hosts.

The 1992 *E. tulipae* collections from wheat spikes of Karl and TAM 107 obtained from 10 counties indicated that more *E. tulipae* transferred from Karl than from TAM 107 (Table 3). *E. tulipae* transferring from both Karl and TAM 107 were generally more numerous on Karl than on TAM 107; however, *E. tulipae* numbers obtained from several of the collections, especially from TAM 107, were probably too small to show meaningful differences. The Graham County collection had the largest numbers of *E. tulipae,* and these mites transferred to and developed on TAM 107 about as well as on Karl (Table 3). Only the collections from TAM 107 in Graham, Ellis, and Rush counties provided enough *E. tulipae* to do another test in which the mites were transferred directly from the spikes to TAM 107 and Karl seedlings. TAM 107 had fewer *E. tulipae* than Karl, except for the TAM

Table 1. Number of wheat curl mites (WCM) on seedlings of TAM 107 and Arkan 10 d after being infested with 5 WCM per plant from mite colonies collected on 3 different dates and reared for 2 mo on TAM 107 or Arkan.

Cultivar		Mean[a] number of WCM per plant		
Rearing host	Test host	1990[b]	1991	1992
TAM 107	TAM 107	58.9 a	50.1 a	71.5 a
	Arkan	57.4 a	45.8 a	76.0 a
Arkan	TAM 107	11.5 b	9. 2 b	6.3 b
	Arkan	61.6 a	53.6 a	68.8 a

[a] Means within a column followed by the same letter are not significantly different at the 0.05 level of probability (Student-Newman-Keuls' multiple range test). All three orthogonal contrasts in the 2 × 2 factorial design are significant.

[b] Year WCM originally collected. Arkan seedlings in November 1990, spikes in May 1991, and volunteer in February 1992.

Table 2. Number of wheat curl mites (WCM) on TAM 107 and Arkan seedlings 10 d after being infested with 5 WCM per plant from mite colonies reared on TAM 107 and Arkan for 2-wk intervals up to 8 wk.

Cultivar		Mean[a] number of WCM per plant			
Rearing host	Test host	2 wk[b]	4 wk	6 wk	8 wk
TAM 107	TAM 107	13.8 b	18.9 b	39.7 a	53.7 a
	Arkan	58.9 a	48.3 a	55.0 a	47.2 a
Arkan	TAM 107	10.2 b	7.0 c	11.0 b	10.6 b
	Arkan	51.8 a	39.8 a	48.7 a	56.5 a

[a] Means within a column followed by the same letter are not significantly different at the 0.05 level of probability (Student-Newman-Keuls' multiple range test). All three orthogonal contrasts in the 2 × 2 factorial design are significant.

[b] Number of wk mites were reared on either TAM 107 or Arkan before transfer to test plants.

Table 3. Populations of wheat curl mites (WCM) on seedlings of Karl and Tam 107 infested in the greenhouse with mites from spikes of Karl and Tam 107 from 10 county wheat cultivar demonstration plots, 1992.

	Mean number of WCM per spike transferring to and developing on seedlings in the greenhouse			
	Karl [a]		TAM 107 [a]	
County of Collection	Karl [b]	TAM 107 [b]	Karl [b]	TAM 107 [b]
Ellis	48.8	4.0	14.7	3.8
Graham	102.1	12.6	74.8	66.8
Kearney	1.9	0.1	1.6	0.2
Kiowa	17.4	0.7	0.1	0.0
Lane	0.5	0.0	0.3	0.0
Rush	34.5	7.1	15.3	1.6
Scott	10.3	0.2	3.9	0.3
Seward	17.7	0.7	14.0	0.8
Stanton	111.5	1.9	4.6	1.2
Stevens	8.2	0.1	0.2	0.0

[a] WCM source collected in May and June, 1992.
[b] Mean number of WCM per spike which transferred to seedlings.

107 collected from Graham County (Table 4). Apparently, at least one of the 10 collections of *E. tulipae* was adapted to and had overcome the resistance of TAM 107. When *E. tulipae* from Ellis, Graham, and Rush counties were transferred directly from wheat spikes to Karl and TAM 107, only those mites obtained from TAM 107 in Graham County readily developed on TAM 107 (Table 4).

Loss of resistance was expected, because resistance-breaking strains of *E. tulipae* developed within 2 mon of being reared on TAM 107 in the greenhouse. Also, *E. tulipae* may complete a generation in 7 d (Slykhuis 1955) and with its long period of development on wheat in the field it has many generations to overcome the resistance of its host. The numbers of field collections were too small and limited in distribution to provide a reliable estimate of the prevalence and distribution of the resistance-breaking strain. However, resistance is likely to be lost in proportion to the amount of resistant wheat grown; TAM 107 and TAM 200 were grown on 49 percent of the western Kansas wheat hectareage in 1993. *E. tulipae* populations were too low in 1993 to obtain additional data, but the effectiveness of resistance should be monitored in the future to determine the need to deploy new sources of resistance.

Table 4. Number of (WCM) on Karl and TAM 107 seedlings 10 d after being infested with 5 WCM per plant from wheat spikes from 3 county wheat cultivar demonstration plots in 1992.

Cultivar		Mean[a] number of WCM per plant		
WCM[b] source	Test[c] host	Ellis	Graham	Rush
TAM 107	TAM 107	9.2 b	53.3 a	7.9 b
	Karl	47.8 a	49.5 a	50.6 a
Karl	TAM 107	5.4 b	8.3 b	6.4 b
	Karl	36.3 a	44.3 a	52.9 a

[a] Means within a column followed by the same letter are not significantly different at the 0.05 level of probability (Student-Newman-Keuls' multiple range test). All three orthogonal contrasts in the 2 × 2 factorial design are significant.
[b] WCM collected from wheat spikes during June, 1992.
[c] WCM transferred to wheat seedlings from spikes.

Information also is needed on the WSMV vectoring efficiency of *E. tulipae* that have overcome the resistance of TAM 107. Del Rosario and Sill (1965) found that *E. tulipae* from *A. smithii* Rybd. were less efficient vectors of WSMV, even after becoming adapted to wheat, than *E. tulipae* originating from wheat.

Research is needed to determine the capability of *E. tulipae* to overcome other sources of resistance (Thomas & Conner, 1986; Whelan & Hart, 1988; Harvey & Martin, 1992) that have not been deployed in the field but are being advanced in wheat breeding programs.

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Alternatives to Pyrethroids for Control of *Helicoverpa zea* (Boddie) and *Heliothis virescens* (F.) on Cotton in South Carolina[1]

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ABSTRACT Eleven non-pyrethroid insecticides were compared with a pyrethroid standard during 1991 and 1992 at both Florence and Blackville, South Carolina, to determine if suitable alternatives are available for management of *Helicoverpa zea* (Boddie) and *Heliothis virescens* (F.) on cotton, *Gossypium hirsutum* (L.). Treatments were sulprofos, profenofos, methomyl, thiodicarb, and acephate each applied alone and in combination with an ovicide, amitraz. *Bacillus thuringiensis* variety *kurstaki* Berliner was only applied in combination with amitraz. The pyrethroid l-cyhalothrin applied alone and an untreated control were used for comparisons. *L*-cyhalothrin was the most effective insecticide and resulted in the highest cotton yields and greatest economic return above insecticide cost at both locations in 1991 and 1992. Thiodicarb was the most effective alternative, indicating that cotton could still be produced successfully if it becomes necessary to replace the pyrethroids. However, yields would be slightly lower and treatment costs would be higher. The use of amitraz could not be economically justified in 1991 or 1992.

KEY WORDS Pyrethroids, *Heliothis virescens, Helicoverpa zea,* cotton, ovicides

Cotton, *Gossypium hirsutum* (L.), production in South Carolina has increased dramatically in recent years. From 1989 to 1991 this crop increased over 77%, from 118,000 to 210,000 acres harvested (Hardee & Herzog 1992). The elimination of the boll weevil, *Anthonomus grandis* (Boheman), as an economic pest in South Carolina is a major reason for the resurgence (Bacheler 1991). Another reason for this increase is the availability of the pyrethroid class of insecticides. The bollworm, *Helicoverpa zea* (Boddie), and the tobacco budworm, *Heliothis virescens* (F.), are the primary insect pest species on cotton in South Carolina. *H. virescens* is the dominant species during June. However, as *H. zea* flights move out of corn in early July and into cotton, it becomes the dominant pest species for the remainder of the season. Pyrethroids are generally applied once or twice during June for control of *H. virescens* and two or

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more times during July and August for control of *H. zea* (Turnipseed et al. 1991). Prior to the advent of the pyrethroids, recommended control practices often failed to provide satisfactory control of these species. Pyrethroids, on the other hand, provide effective, economical control (Allen et al. 1989, DuRant 1984, Newell et al. 1991).

Two disadvantages of the use of pyrethroids are the reduction in populations of natural enemies of arthropod pests (House et al. 1985, Hood 1991) and the potential for development of resistance to this class of compounds (Campanhola & Plapp 1989, Graves et al. 1991, Martinez-Carrillo et al. 1991, Plapp et al. 1989). Resistance to these chemicals in populations of *H. virescens* has been widely reported, but South Carolina has yet to experience this phenomenon (Graves et al. 1991, Plapp et al. 1989, M. E. Roof personal communication 1993). Also, no significant resistance problems have been encountered in *H. zea* (Clower et al. 1992). Another problem farmers may face in the future is the ban of this class of pesticides by regulatory agencies, or voluntary termination of the sale of pyrethroids by manufacturers due to impending regulatory pressure. To ensure the continued success of cotton production in South Carolina, farmers need information on alternative control strategies. If effective, economical alternatives are available, farmers can reduce the threat of pyrethroid resistance in arthropod pests while maintaining control.

The insecticides used in this study have been evaluated alone (DuRant 1979, Luttrell et al. 1989, Mullins et al. 1989, Smith 1990), but their cost-effectiveness alone and in combination with amitraz season-long has not been compared with pyrethroids. Reported herein are results of a two-year study comparing the cost-effectiveness of six non-pyrethroid insecticides applied alone and in combination with amitraz throughout the growing season with that of a standard pyrethroid during July and August against populations that consisted primarily of *H. zea,* but also included *H. virescens.*

Materials and Methods

Season-long applications of 11 non-pyrethroid insecticide treatments were compared with a pyrethroid standard and an untreated control in field studies during 1991 and 1992. Insecticides ([AI/ha]) were sulprofos (Bolstar 6EC [emulsifiable concentrate], Mobay Chemical Corp., Kansas City, MO.) (1.12 kg), profenofos (Curacron 8EC, Ciba-Geigy Corp., Greensboro, NC) (0.84 kg), methomyl (Lannate L 1.8 [water soluble], E. I. du Pont de Nemours and Co., Wilmington, DE.) (0.504 kg), thiodicarb (Larvin 3.2 AF [aqueous flowable], Rhone-Poulenc Ag. Co., Research Triangle Park, NC) (0.84 kg), and acephate (Orthene 75S [soluble powder], Valent U.S.A. Corp., Walnut Creek, Calif.) (0.84 kg) applied alone and in combination with an ovicide, amitraz (Ovasyn 1.5 EC, NOR-AM Chemical Co., Wilmington, DE.) (0.14 kg). *Bacillus thuringiensis* var. *kurstaki* Berliner (Dipel ES, Abbott Laboratories, North Chicago, IL.) (19.8 billion International Units [BIU]) was only applied in combination with Ovasyn. The pyrethroid *l*-cyhalothrin (Karate 1 EC, Zeneca, Wilmington, DE.) (0.028 kg) applied alone, and an untreated control were used for comparisons. As pest pressure increased or control was inadequate,

rates of all materials except Ovasyn and Karate were increased as follows: Larvin (1.008 kg), Curacron (1.12 kg), Bolstar (1.68 kg), Lannate (0.75 kg), Dipel ES (29.64 BIU) and Orthene (1.008 kg). Because control was adequate, Karate was not applied with other treatments on 23 July at Blackville during the 1991 season and Karate, Larvin, and Larvin + Ovasyn were not applied with other treatments on 31 July at Florence and Blackville in 1992.

Tests were conducted simultaneously at the Pee Dee Research and Education Center in Florence, SC and at the Edisto Research and Education Center in Blackville, SC. The cotton cultivar 'Deltapine 90' was planted on 30 April (Florence) and 9 May (Blackville) in 1991 and on 11 May (Florence) and 12 May (Blackville) in 1992. Agronomic practices recommended for cotton production in South Carolina were followed. Each plot consisted of eight 15.2-m rows, spaced 96.5 cm apart and plots were arranged in a randomized complete-block design with four replications.

All plots were treated with aldicarb (Temik 15 G [granular], Rhone Poulenc) (1.2 [1991], 0.8 [1992] kg [AI]/ha) in furrow. Prior to planting, 560 kg/ha of a 3-9-18 (N/P/K) fertilizer with 3% Zn, 2% S, 1% Mg plus 0.45 kg B/ha were applied broadcast and incorporated. Herbicides were trifluralin (Treflan 4 EC, Elanco Products Co., Indianapolis, Ind.) (0.84 kg [AI]/ha) pre-plant incorporated, fluometuron (Cotoran 4 L [liquid], Ciba-Geigy) (1.71 kg [AI]/ha) pre-emergence, and monosodium methoanearsonate (MSMA 4 EC) (2.24 kg [AI]/ha) post-emergence directed.

Insecticidal treatments were applied during daylight hours, using a high clearance sprayer (John Deere 6000). Treatments were initiated in July when egg counts, primarily of *H. zea*, exceeded 10/100 terminals, followed by another treatment 5-7 d later. The treatments were continued as needed, based on a threshold of 3 small larvae/100 terminals.

Treatments were evaluated every 5-10 days or 48-72 h after treatment. Fruit damage, larvae, and eggs were counted from 25 plants randomly selected from the four center rows of each plot. Secondary pests such as aphids, mites, thrips, and armyworms were monitored weekly.

Beneficial arthropod species such as big-eyed bugs (*Geocoris* spp.), hooded beetles (*Notoxus* spp.), ladybird beetles, spiders, and lacewings were monitored 48-72 h after each treatment. Using a 38 cm clipboard, 10 plants/plot (2-3/row) from the four center rows were beat over a plastic pan 27.94 cm wide by 34.97 cm long by 13.97 cm deep) and arthropods were counted from the pan. Secondary pests such as plant bugs (*Lygus* spp.) and cotton fleahoppers (various spp.) were also monitored using this technique. The four center rows of each plot were machine-picked at harvest maturity to determine yields.

Data were analyzed using an analysis of variance and treatment means were separated using the Student-Newman-Keuls mean separation test ($P < 0.05$). All calculations were performed using the ANOVA-2 and RANGE procedures of MSTAT (Power 1985). Returns to treatment/ha (lint yield-untreated control lint yield multiplied by lint price - cost of control) were calculated using 35% lint turnout, $1.50/kg lint price, an estimated application cost of $5.00/ha per application, and 1992 insecticide retail prices. The cost of amitraz, which received full registration early 1993, was

estimated at $7.48/ha. Means were taken for the four replications in each test and again averaged for both years and both locations and presented in Table 1.

Results

The combined means from both years and locations for all treatments are presented for populations of large larvae, % boll damage, beneficial arthropod populations, yield, insecticide cost, and returns to treatment (Table 1). *L*-cyhalothrin, thiodicarb, and thiodicarb + amitraz were the most effective treatments against populations of large larvae of *H. zea*. Populations of large larvae were used since they represented the best gauge of insecticide performance and related closely to fruit damage and yields. Orthene was the least effective treatment. *L*-cyhalothrin, thiodicarb, and thiodicarb + amitraz were the most effective treatments against damage to cotton bolls. The untreated control had the greatest boll damage and the highest number of beneficial arthropods. All treatments significantly reduced populations of beneficial arthropods compared with the untreated control. Use of *l*-cyhalothrin resulted in significantly higher yields than all other treatments. Thiodicarb and thiodicarb + amitraz plots had the second highest yields. Overall, all treatments resulted in yields significantly higher than the untreated control. Returns to treatment were highest with *l*-cyhalothrin, thiodicarb being the second most cost-effective treatment. All treatments except acephate produced significantly higher returns to treatment compared to the untreated control. Although differences were not always significant, the use of amitraz in combination with the other insecticides caused consistently lower densities of large larvae and % boll damage, and higher yields compared with the insecticides alone. However, the increased yields did not compensate for the increased costs of amitraz. Overall, *l*-cyhalothrin was the most effective treatment in every category followed by thiodicarb, while Dipel ES + amitraz and acephate were significantly less effective and the poorest performing alternatives. Dipel ES is generally more effective against *H. virescens* than *H. zea* which may partially account for its poor performance (Bacheler 1991). The other insecticides were intermediate between thiodicarb and acephate and additional data are not presented for these materials.

1991. On 8 July, densities of eggs exceeded established thresholds of 10/100 plants at both locations and peaked at above 80/100 plants one week later. Egg densities remained high through July and early August before declining in late August. Treatments were initiated at both locations on 9 July (Fig. 1). With the exception of *l*-cyhalothrin and acephate, rates were increased on 23 and 25 July at both locations because control was inadequate. *L*-cyhalothrin was not applied with other treatments on 23 July at Blackville because control was effective. Densities of large larvae in acephate plots increased to above 80/100 plants on 22 and 25 July at Florence and Blackville. Peak populations of large larvae were higher in acephate plots than in control plots at both locations. *L*-cyhalothrin and thiodicarb maintained acceptable control throughout the season, being well

Table 1. Effects of treatments on *Helicoverpa zea* (Boddie) and *Heliothis virescens* (F.) larval densities, boll damage, beneficial arthropod populations, yield, insecticide costs, and returns to treatment on cotton at Florence and Blackville in 1991 and 1992.[a,b]

Treatment	rate (kg[AI]/ha)	No. large larvae/100 plants	% Boll damage	Beneficials/ 100 plants[c]	Yield kg/ha	Cost per application ($/ha)[d]	Returns to treatment ($/ha)[e]
Sulprofos	(1.68)	6.8 ef	4.3 de	3.5 b	918 d	27.40	580 d
Sulprofos + amitraz	(1.68 + 0.14)	5.3 fgh	3.6 de	3.6 b	953 cd	34.88	573 d
Profenofos	(1.12)	9.2 d	5.7 d	2.6 cd	932 cd	32.45	571 d
Profenofos + amitraz	(1.12 + 0.14)	8.4 de	4.5 de	2.9 c	983 c	39.93	604 d
Methomyl	(0.75)	7.0 ef	6.6 d	3.8 b	785 e	30.85	361 e
Methomyl + amitraz	(0.75 + 0.14)	5.7 fg	6.0 d	4.0 b	749 e	38.33	262 f
Thiodicarb	(1.008)	4.1 ghi	3.5 de	3.5 b	1081 b	36.18	783 b
Thiodicarb + amitraz	(1.008 + 0.14)	3.3 hi	4.0 de	3.5 b	1041 b	43.66	679 c
Acephate	(1.008)	19.4 a	14.7 b	2.4 de	566 g	23.90	78 gh
Acephate + amitraz	(1.008 + 0.14)	13.5 b	11.0 c	2.8 cd	692 f	31.38	217 f
Dipel ES + amitraz	(29.64BIU + 0.14)	11.6 c	13.5 b	4.0 b	603 g	24.38	118 g
l-cyhalothrin	(0.028)	2.5 i	1.8 e	2.0 e	1167 a	20.83	1010 a
Untreated		13.9 b	18.3 a	5.8 a	421 h	0	0 h

[a] Means within a column followed by the same letter do not differ significantly ($P > 0.05$; Student-Newman-Keuls test [Power 1985]).
[b] Means from Florence and Blackville in 1991 and 1992 presented.
[c] Beneficial arthropods include: big-eyed bugs (*Geocoris* spp.), hooded beetles (*Notoxus* spp.), lady beetles, spiders, and lacewings.
[d] Represents 1992 retail prices. Includes application cost of $5.00 / ha.
[e] Represents kg/ha of lint per treatment minus the untreated control lint yield multiplied by $1.50 and minus the number of applications, multiplied by application cost (chemical cost/ha/application).

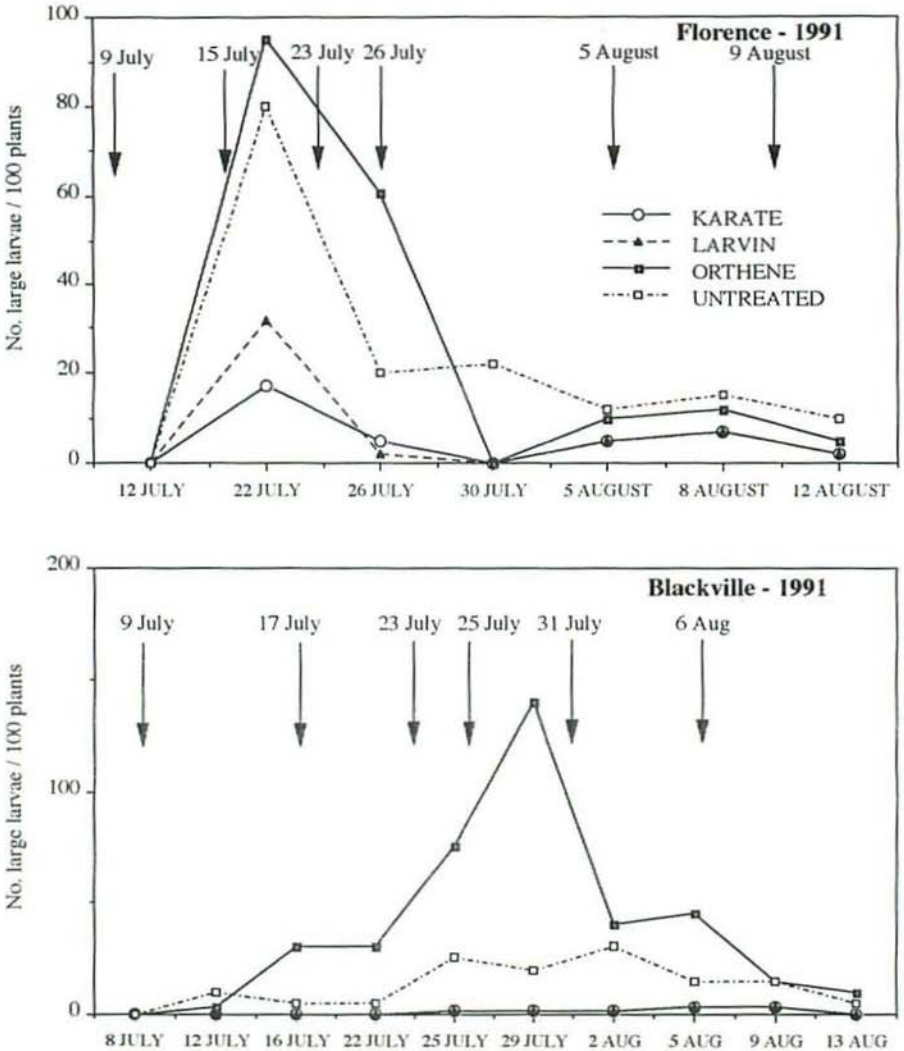

Fig. 1. Effects of selected treatments against populations of large larvae of *H. zea* and *H. virescens* on cotton at Florence and Blackville in 1991. Treatment dates are indicated by arrows.

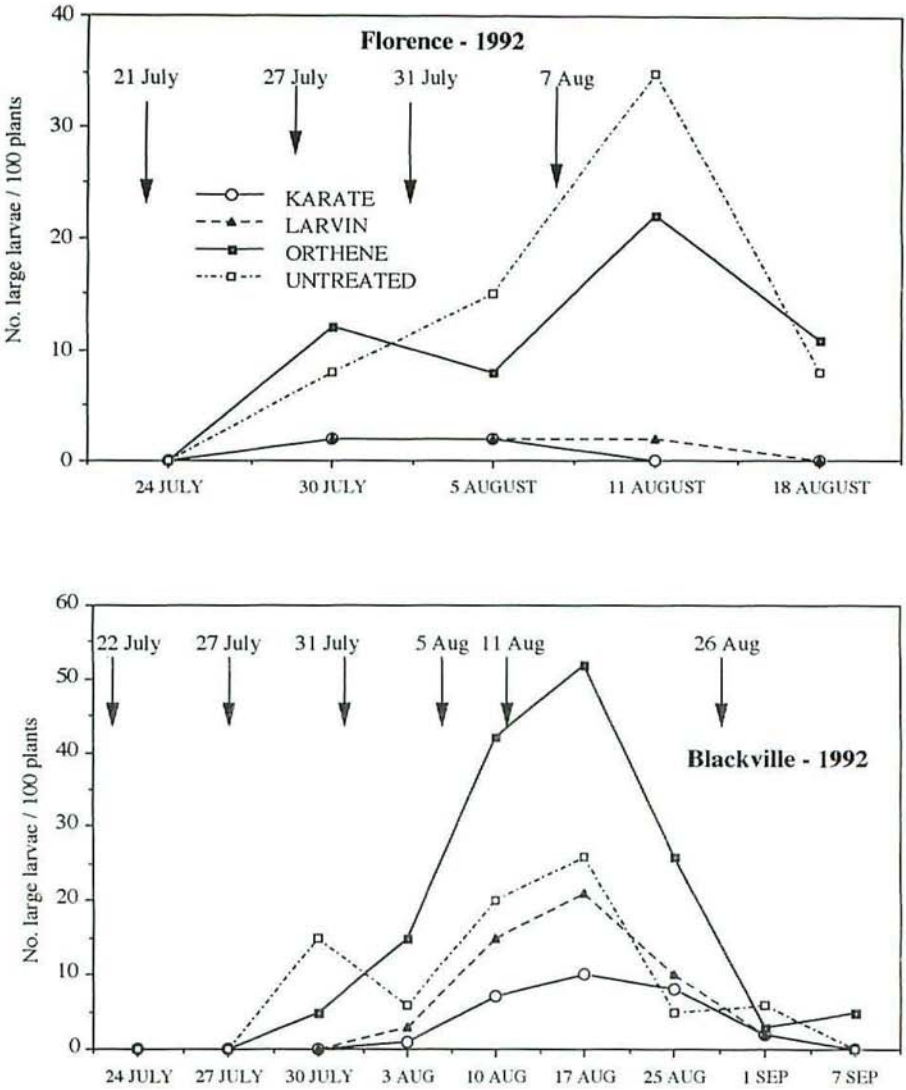

Fig. 2. Effects of selected treatments against populations of large larvae of *H.zea* and H. *virescens* on cotton at Florence and Blackville in 1992. Treatment dates are indicated by arrows.

below the levels of acephate and the untreated control. All other treatments, even at increased rates, failed to maintain populations at the levels of *l*-cyhalothrin and thiodicarb. Populations of large larvae generally decreased during August. However, populations of large larvae remained above the untreated control in the acephate treated plots at Blackville.

1992. On 21 July, densities of eggs exceeded established thresholds at both locations and peaked at above 70/100 plants one week later. Egg densities remained high through early August before declining in late August. Treatments were initiated on 21 and 22 July at Florence and Blackville, respectively (Fig. 2). Insecticide rates were increased only at Blackville on 31 July and 5 and 11 August due to inadequate control. *L*-cyhalothrin, thiodicarb, and thiodicarb + acephate were not applied with other treatments on 31 July at either location because control was effective. Densities of large larvae increased to above 20/100 plants in the acephate plots and 35/100 plants in the untreated control on 11 August at Florence. Densities of large larvae increased to above 50/100 plants in the Acephate plots and 20/100 plants in the untreated control on 17 August at Blackville. Peak populations of large larvae were higher in acephate plots than in control plots at Blackville. At Florence, *l*-cyhalothrin and thiodicarb were efficacious throughout the season, maintaining populations well below the levels of acephate and the untreated control. However, at Blackville, only *l*-cyhalothrin maintained populations of large larvae well below the untreated control for the entire season. Even at increased insecticidal rates and additional applications, all other treatments were less effective than *l*-cyhalothrin. Populations of large larvae decreased for the remainder of the season in the untreated control. As in 1991, populations of large larvae in acephate plots at Blackville remained above the untreated control through August. It could be speculated that acephate-treated plots may have had an attractant effect on female moths or some unidentified natural control mechanism was disrupted, but the reason is unknown.

Conclusions

Karate was clearly the most effective insecticide against *H. zea* and *H. virescens* at both locations during 1991 and 1992. Thiodicarb (carbamate class of insecticide) was an effective alternative in both tests during that same time frame. Sulprofos (organophosphate class), profenofos (organophosphate class), methomyl (carbamate class), acephate (organophosphate class), and Dipel ES + amitraz were not comparable to thiodicarb or thiodicarb + amitraz for regular, season-long control. However, the use of thiodicarb resulted in a much lower return to treatment compared with *l*-cyhalothrin. Moreover, the use of amitraz with thiodicarb or with any other insecticide did not justify the cost.

The pyrethroid *l*-cyhalothrin continues to be effective against *H. zea* and *H. virescens* in South Carolina. With the small numbers of *H. virescens* encountered during July and August and the lack of resistance in *H. zea,* the pyrethroids should remain effective season-long against *H. virescens* and *H. zea* in South Carolina cotton. Also, the performance of thiodicarb alone

appears promising as an alternative. This performance is possibly due to its low impact to beneficial arthropods and high efficacy against *H. zea* and *H. virescens*. If the pyrethroids are taken off the market or if resistance develops in South Carolina, an alternative is available for cotton production although costs will be higher.

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Influence of Snakeweed Foliage on Engorgement, Fecundity and Attachment of the Lone Star Tick (Acari: Ixodidae)[1, 2]

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ABSTRACT Nymphal lone star ticks, *Amblyomma americanum*, were allowed to engorge on domestic rabbits that had received diets containing 0, 5 or 10% perennial snakeweed foliage. Tick attachment was reduced 39 and 33% on rabbits ingesting 5 and 10% snakeweed foliage, respectively. Adult ticks reared from engorged nymphs showed no treatment differences in survivability, engorgement weight or hatchability of egg masses. In a study conducted on sheep, adult ticks, confined in cells to an area with half of the skin surface treated with methylene chloride extracts of snakeweed foliage, attached significantly less often to treated skin compared to cells half-treated with acetone. When confined in cells to an area totally treated with snakeweed foliage extracts, a mean of 12.5, 4.5 and 0 ticks (out of 40 ticks per cell) attached to skin treated with acidic, basic or neutral extracts, respectively, compared to a mean of 16.7 in acetone-treated cells.

KEY WORDS Acari, *Amblyomma americanum*, phytochemicals, *Gutierrezia* spp.

There are 22 species of ticks that infest cattle in the United States, and they are responsible for an estimated $399 million in losses annually to the cattle industry (Byford et al. 1992). Losses are caused by exsanguination, injection of toxins that can cause paralysis, damaged hides, "tick worry" and disease transmission (Drummond et al. 1981).

Traditional tick control measures usually consist of acaricidal treatment of hosts or reduction of tick habitat, but the presence of some species of plants on cattle ranges or pastures reportedly helps to reduce tick populations. Two tropical grasses, *Melinis minutiflora* Beauv. and *Andropogon gayanas* Kunth, reduce numbers of

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larval ticks, possibly by exposing questing larvae to dessication (Thompson et al. 1978). Also, some tropical legumes in the genus *Stylosanthes* have glandular trichomes that produce toxins which are lethal to larval ticks (Sutherst et al. 1982). Other plant species produce secondary chemicals that have direct activity against ticks; for example, hexane extracts of *Commiphora erythraea* Engler (a relative of myrrh) show acaricidal and repellent activity against several species of ixodid ticks (Carrol et al. 1989). However, indirect effects of phytochemicals against ticks (i.e. effects on engorgement success and fecundity of ticks engorging on animals feeding on specific plants) apparently have not been reported.

Perennial snakeweed, particularly broom snakeweed, *Gutierrezia sarothrae* (Pursh.) Britt. and Rushby, and threadleaf snakeweed, *G. microcephala* (D. C.) Gray, infests rangeland in the western half of North America from southern Canada to northern Mexico. Snakeweed foliage contains numerous phytochemicals, including saponins, flavonoids and terpenoids (Smith & Flores-Rodriguez 1989) which are toxic to many species of mammals (Mathews 1936, Smith & Flores-Rodriquez 1989). Although snakeweed is unpalatable to livestock, it is often ingested in varying amounts by mammalian herbivores, especially when more palatable forage is unavailable (Pieper 1989). It seems probable that ingestion of snakeweed foliage by mammals could have an indirect effect on blood-feeding ectoparasites. In addition, the chemical constituents of snakeweed foliage may demonstrate direct acaricidal or repellent properties. The terpenoids alpha-pinene and beta-pinene, which have been isolated from snakeweed leaf and stem tissue, are toxic to insects, fungi and bacteria (Barbosa & Letourneau, 1988), but direct effects of snakeweed foliage extract on ticks have not been reported.

Preliminary studies showed no significant direct mortality to adult lone star ticks, *Amblyomma americanum* (L.), either treated topically with, or exposed to filter papers treated with acidic, basic or neutral extracts of snakeweed foliage. (R. J. M., unpublished data). The objective of this study was to characterize engorgement and fecundity of lone star ticks allowed to engorge as nymphs on a host that had ingested snakeweed foliage, and the effect on attachment behavior of adult ticks exposed to skin treated with snakeweed foliage extracts.

Materials and Methods

Snakeweed (mixed *G. sarothrae* and *G. microephala*) foliage was collected at a site 17 km east and 5 km south of Lordsburg, New Mexico. The terminal 7 to 10 mm of snakeweed plants, bud to pre-bloom stage, were hand-clipped, then frozen within 4 h. Frozen snakeweed foliage was ground through a 2-mm mesh screen in a Wiley mill (Arthur H. Thomas Co., Philadelphia, Pa.), allowed to air dry for 36 h at ambient temperature (≈ 21°C) and stored frozen until used.

Twelve female New Zealand white rabbits, six to eight months of age and weighing 3806 ± 140 g, were purchased from a commercial supplier and individually housed in cages (15 × 15 × 30 cm) made from hardware cloth

6.3 mm mesh). Caged rabbits were placed by pairs into tick tubs. Tick tubs are cubical (32 cm per side) open-topped fiberglass containers, with an electric heat coil along the rim to prevent tick escape.

Each pair of rabbits (2 tubs per treatment) was randomly allocated to receive a diet of 0, 5 or 10% snakeweed foliage mixed with pulverized Purina Rabbit Chow (Purina Mills, St. Louis, Mo.) and 5% commercial corn syrup (to improve diet palatability). Experimental diets were fed to coincide with the nymphal tick feeding period, and tap water was provided free choice.

During the feeding of experimental diets each rabbit was infested with 175 nymphal lone star ticks. On each day following infestation, detached ticks in each tub were counted, weighed, sealed with cellophane wrap in half-liter cardboard ice cream cartons and placed in rearing tubs. Rearing tubs are identical in construction to tick tubs but have no heat coil. Water was added to rearing tubs to a depth of 3 cm and a sheet metal shelf was supported 2 cm above the water surface. A pane of glass was placed over the top of tubs to maintain a constant environment of 26°C and 98% R. H.

After ticks had molted to the adult stage, they were allowed to mate and engorge on sheep. Two ewes were sheared, washed, placed in stanchions and fitted with six tick holding cells (three per side). Cells were prepared by gluing one end of a piece of 8" (20.3 cm) orthopedic stockinet to the fleece stubble and skin, forming a circular boundary the same circumference as the stockinet. The other end of the stockinet was twisted and bound with a rubber band to confine ticks in the cell. Twenty ticks, 10 males and 10 females, were placed into each cell. Detached female ticks were collected daily, weighed and placed individually into 20-ml scintillation vials until oviposition and subsequent hatching of larvae were completed.

After egg masses hatched, vials were frozen to kill larval ticks and hatching rate of eggs was determined. Contents of an egg mass vial were spread evenly in a single layer over the bottom of a glass Petri dish and the dish placed on 1 × 1 cm counting grid. Five diagonal grid squares were selected across the dish and the number of hatched and unhatched eggs within selected squares was recorded.

Snakeweed foliage extracts were obtained through partition extractions, using methylene chloride as the extraction solvent. Dried and ground snakeweed foliage was mixed in a laboratory blender for 2 min. with an equal volume of methanol:water (80:20) solution, then the mixture was vacuum filtered and the filtrate added to an equal volume of saline solution (10% NaCl). To obtain the neutral extract, the snakeweed/methanolic solution was adjusted to pH 7.0 with concentrated HCl, placed in a separatory funnel and extracted twice with equal volumes of methylene chloride. The retained snakeweed/methanolic solution was then adjusted to pH < 2.0 with concentrated HCl and extracted twice to yield the acidic components. To obtain the basic components, the retained solution was adjusted to pH > 12.0 with concentrated NaOH and extracted twice. The methylene chloride solvent was allowed to evaporate out of all extractions, leaving paste-like mixtures of extracted components.

To test effects of snakeweed foliage extracts on tick attachment, four cells were attached as previously described to each side of three ewes (six cells per

treatment). Cells on each sheep were randomly allocated to receive neutral, acidic, basic or control (acetone only) treatments. Snakeweed foliage extracts were thinned with acetone to a paint-like consistency, then treatments were applied with a small paintbrush to 1/2 of the skin surface of selected cells. Twenty pairs of adult lone star ticks were placed into each cell and allowed to attach. Since no individual male ticks were observed attached alone, the attachment site data (i.e., mean attached within cell and mean attached on treated skin) was the number of females observed after 36 h.

To determine if extracts would completely prevent tick attachment, the six control cells (half-treated with acetone only) were randomly assigned (two cells per treatment) to receive treatments of acidic, basic or neutral extract. Extracts were applied as before; however the entire skin surface of the cells was treated. Twenty pairs of adult ticks were placed in each cell, and the number of females attached after 48 h in treated cells was compared with the number attached in the control cells in the previous study.

Data on nymphal tick engorgement were subjected to analysis of variance (ANOVA) for a completely randomized design. Means were tested by LSD and for linear contrasts when F tests were significant ($P < 0.05$). Oviposition data for adult ticks reared as nymphs on snakeweed-fed rabbits were analyzed by two methods: A chi-square analysis with a Fisher's exact test was performed to determine treatment effects between ticks that laid no eggs, those that laid eggs that did not hatch and those that laid eggs which did hatch. For ticks which laid eggs that hatched, a separate, nested analysis was performed. The statistical model incorporated the effects of treatment, cell-within-treatment and day of detachment within treatment within cell (a model that included rabbit effects would have been preferred, so that possible host effects could be accounted for, but the experimental design did not allow for this).

Data on effects of snakeweed foliage extracts on attachment of adult ticks in half-treated cells on sheep were subjected to ANOVA for a randomized complete block design on log transformed responses. All analyses were done using SAS software (SAS Institute 1989).

Results

Engorgement success was significantly reduced ($P < 0.05$) in nymphal lone star ticks exposed to rabbits fed snakeweed foliage. Out of 350 nymphs per tub, a mean of 341.5 ± 4.5 ($\bar{X}$ ± SEM) nymphs survived the control treatment, compared to 208.5 ± 5.5 and 230.5 ± 17.5 nymphs (a reduction of 39 and 33%) that survived exposure to rabbits fed 5 and 10% snakeweed foliage, respectively.

Adult ticks reared as nymphs on snakeweed-fed rabbits showed no differences in survivability, engorgement weight or hatchability of egg masses between treatment groups. Thirty-three, 32 and 33 female ticks from the 0, 5 and 10% treatment groups, respectively, engorged on sheep. Mean engorgement weights were the same (90 mg, $P = 0.46$) for all three treatments. Seventeen, 23 and 24 engorged females (0, 5 and 10% treatment, respectively) laid viable egg masses, with similar mean hatching rates ($P = 0.23$) of 51.5, 71.9 and 75.0% in 0, 5 and 10% treatments, respectively.

When adult ticks were confined in half-treated cells, significantly fewer ($P < 0.05$) ticks attached to the extract-treated side than to the acetone-treated side in control cells. Mean attachment was 1.2, 0.8 and 0 ticks on basic, acidic and neutral extract-treated skin, respectively, versus 10.8 in the control cells (Table 1). These data mainly reflect the attachment of the 20 female ticks, since very few male ticks attached in any cell. Statistical analysis also revealed a significant ($P < 0.01$) sheep effect on adult tick attachment, with one of the ewes supporting 3- and 7-fold more ticks than the other two ewes.

Ticks confined in cells completely treated with acidic, basic and neutral extracts of snakeweed foliage showed reduced attachment. Means ($\bar{X} \pm$ SEM) of 12.5 ± 5.5, 4.5 ± 0.5 and 0 attached ticks were observed in cells treated with acidic, basic and neutral extracts, respectively, compared to a mean of 16.7 ± 4.6 attached ticks in acetone-treated control cells.

Table 1. Attachment of female *A. americanum* (20 per cell) on sheep after 36 h in cells with half of skin surface treated with acetone only, or with basic, acidic or neutral methylene chloride extracts of snakeweed foliage (*Gutierrezia* spp.).

		Attachment within treated half-cells		
Treatment	Mean number of ticks attached within cells	Mean attached[a] (± SE)	% total	% reduction vs. control
Acetone	16.7	10.8 (± 2.0) a	65	–
Basic Extract	10.7	1.2 (± 0.5) b	11	89
Acidic Extract	17.0	0.8 (± 0.7) bc	5	95
Neutral Extract	15.5		0	100

[a] Values followed by the same letter in a column are not statistically different ($P < 0.05$); Fisher's Protected LSD on log transformed responses.

Discussion

Nymphal lone star ticks engorging on snakeweed-fed rabbits showed reduced attachment, but rabbits that ingested snakeweed foliage had reduced daily feed intake and reduced weight gain. Recent studies show that well-nourished animals can tolerate ingestion of greater amounts of snakeweed foliage than animals on a lower plane of nutrition (Smith et al. 1994a, 1994b). It would be important to know if reduced tick attachment

would still occur on animals fed a diet containing a high enough caloric content to negate the detrimental nutritional affects of snakeweed foliage. Results of our study suggest that snakeweed foliage, if ingested by potential hosts, could have an indirect, negative effect on tick populations. However, in view of the mammalian toxicity of snakeweed foliage compared with the relatively small effect on tick survivability, ingestion of snakeweed foliage likely causes more harm than good.

There appeared to be no latent effect on adult ticks that fed as nymphs on rabbits, but these results might be misleading. All engorged nymphal ticks were reared to the adult stage separated by treatment and by tub, but when these adults were placed on sheep they were distinguished only by treatment. Since it was impossible to trace an individual tick back to an individual tub, potential tub effects were lost.

The neutral fraction of snakeweed foliage extract was most effective in reducing tick attachment. No ticks attached to skin treated with this fraction. It is not known what components in the extracts caused these responses. Snakeweed foliage contains many allelochemicals that prevent the growth of competitive plants or retard herbivory, and one or any combination of these chemicals may cause reduced tick attachment. Further studies on individual components of snakeweed foliage extracts are needed to determine the chemicals responsible for reducing tick attachment.

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Monitoring and Control of European Corn Borer, *Ostrinia nubilalis* (Lepidoptera: Pyralidae), on Bell Peppers in Ohio[1]

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ABSTRACT Field studies were undertaken to document pod infestation by European corn borer (*Ostrinia nubilalis*) during the harvest season, to evaluate timings of insecticide applications, and to evaluate whether monitoring populations in traps is an appropriate basis for timing insecticide applications. Over a three year period at several locations, acephate was sprayed on 5-d to 14-d schedules, and pepper pods were evaluated during periodic harvests. Damage by *O. nubilalis* was usually highest in the first two harvests, when as few as 36% of the pods were undamaged in untreated plots. Later harvests were less affected by *O. nubilalis* but were sometimes infested by fall armyworm (*Spodoptera frugiperda*) or corn earworm (*Helicoverpa zea*). In 1990, when *O. nubilalis* populations were moderate in size, fewer infested pods and higher yields were found in plots treated on a 7-d schedule than on a 14-d schedule. In 1991, when populations were exceptionally high, damage was high even in plots sprayed every 7 d. In 1992, when populations were low to moderate, damage was light and no yield advantage resulted from a variable 5- to 10-d schedule versus a 7-d schedule. A 7-d schedule was suitable in years with average *O. nubilalis* activity, starting when blacklight traps consistently caught one or more moths per night. Pheromone traps appear to be an acceptable alternative to blacklight traps, but a pheromone-based threshold has not yet been tested. Management of European corn borer on peppers in Ohio must be supplemented in the later part of the season by management of fall armyworm and corn earworm.

KEY WORDS Peppers, Lepidoptera, Pyralidae, *Ostrinia nubilalis*, acephate, blacklight traps, pheromone traps

Production of peppers (*Capsicum annuum* L.) in Ohio expanded in the early 1990s, reaching 440 ha (1,100 acres) valued at $4.9 million in 1991. Much of the new acreage is planted with red bell peppers for the processing market and the remainder with green or red bell peppers for the fresh market. Red bell peppers are grown to full maturity when their red color and sweet flavor increase their value.

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Because processors have near-zero tolerance for insect-contaminated peppers, growers are acutely aware of the need to effectively manage European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae), which is the key pest of peppers in the midwestern USA.

Eggs of *O. nubilalis* are laid on the underside of pepper leaves and hatch in three to seven days. Within two to twelve hours after egg hatch, larvae enter pods by boring near the calyx. Larvae can also bore into stems and branches causing limb breakage. In Ohio, the first generation is active in June and usually does not attack peppers because at that time, pepper plants are small, do not yet have pods, and are less attractive than corn as a mating and egg-laying site for *O. nubilalis*. The second generation is active in August; in hot years, there may be a third generation in September. The second and third generations attack peppers because maturing corn is less attractive to *O. nubilalis* than peppers in late summer. Infestation of *O. nubilalis* larvae in peppers becomes apparent three to five weeks after peak captures of male and female moths in blacklight traps (Elliott et al. 1978).

O. nubilalis larvae in peppers are difficult to control with insecticides because they are exposed to sprays or residues for a short time before they bore into and are protected by the pod. Pepper growers use a protective management strategy for control of larvae by applying insecticides, with particular attention to covering the calyx end of pods. In the 1960s and early 1970s, the standard insecticide treatment for control of this pest on peppers was carbaryl or DDT applied every 3 days (Sleesman 1973). Since the mid-1970s, acephate has been commonly used; studies in Ohio showed excellent control of *O. nubilalis* with acephate used on a 5 to 8-d schedule (Sleesman 1974), a 10-d schedule (Sleesman 1975), and even on a 14-d schedule (Ladd et al. 1982). The standard practice currently in use is to apply foliar sprays of acephate, permethrin, or methomyl with a hydraulic boom sprayer weekly until harvest. Granular carbofuran was commonly used on peppers as a soil treatment until 1991, when a registration change restricted its use.

Ohio pepper growers interested in maximizing control of *O. nubilalis* but minimizing use of insecticides are seeking information about the appropriate time to start and stop spraying for *O. nubilalis* control and the best interval between sprays. A practice currently recommended for peppers in some areas is to begin insecticide treatment on a 7-d schedule once blacklight trap captures of *O. nubilalis* average five or more moths per night (Ghidiu 1992) or four or more female moths per night for three consecutive nights (Showers et al. 1989). Improvements in pheromone trapping techniques for *O. nubilalis* indicate that pheromone traps may be a suitable alternative to blacklight traps for use in pest management programs (Fletcher-Howell et al. 1983).

This study was undertaken to document pepper pod infestation by *O. nubilalis* during the harvest season, to evaluate various options for timing insecticide applications on peppers, and to evaluate blacklight and pheromone traps for monitoring Ohio populations of *O. nubilalis*.

Materials and Methods

Study locations. All experiments were conducted on Ohio State University research farms. Pepper plots were established at Columbus, in central Ohio, in 1990 and 1991; at Fremont, 160 km north of Columbus, in 1990 and 1992; and at Piketon, 120 km south of Columbus, in 1992. Moths were monitored at all sites where pepper plots were established, as well as at Fremont in 1991 and in Columbus in 1992.

Trapping. Adult populations of *O. nubilalis* were monitored with electric blacklight traps and pheromone traps from May until October. One blacklight trap (O. B. Enterprises Inc., Oregon, WI) per site was placed adjacent to farm buildings about 100 m from pepper plantings. Blacklight traps were emptied four to seven days per week.

Pheromone lures were placed in large cone-shaped traps made of plastic mesh ('Heliothis trap', Scentry Inc., Buckeye, AZ); cone traps have been shown to be superior to sticky cardboard traps for monitoring *O. nubilalis* (Webster et al. 1986). The 'Iowa' blend of pheromone components for *O. nubilalis* was supplied by Scentry Inc. (Buckeye, AZ) in 1990 and by Trécé Inc. (Salinas, CA) in 1991 and 1992. Previous studies showed that lures with the 'Iowa' blend (Klun et al. 1973) were more effective than the 'New York' blend (Kochansky et al. 1975) in five Ohio locations tested (C. W., unpublished data). The number of pheromone traps used per site was one in 1990 and 1991, and three in 1992. Traps were placed along the edge of pepper plantings. Traps were emptied weekly and lures replaced every four weeks.

Experimental design. In all plantings, four replicates of each treatment were arranged in a randomized complete block design. Pepper cultivars used were 'Resistant Giant 4' in 1990, 'Merced' in 1991, and 'North Star' in 1992; each of these was common in commercial fields that year. Peppers were transplanted on 24-25 May 1990, 17 May 1991, 26 May 1992 at Fremont, and 17 June 1992 at Piketon. Foliar spray treatments were applied in 380 to 475 liters water per ha (40 to 50 gal/acre) with hollow cone nozzles at a pressure of 4.2 to 5.5 kg/cm^2 (60 to 80 lb/in^2) delivered by a tractor-drawn hydraulic boom sprayer. Plot dimensions are specified below for individual sites.

Fully ripe red pods were harvested at 2 to 3-week intervals from the center two rows per plot. At the final harvest, scheduled just before the first predicted frost, green pods over 5 cm wide also were harvested. Pods that were too rotten to pick were not harvested. Harvested pods were counted, weighed, cut open, and rated for damage and presence of *O. nubilalis*. Presence of fall armyworm, *Spodoptera frugiperda* (Smith), and corn earworm, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae), in pods also was recorded.

Harvest data were subjected to analysis of variance (ANOVA) and means were compared by orthogonal contrasts using the JMP microcomputer program (SAS Institute 1989). Individual harvests were analyzed separately, and red pod harvests were also summed over each season and analyzed as a cumulative harvest. Percentage data were transformed by arcsine ($x^{0.5}$) before analysis to prevent variances from being a function of means (Sokal & Rohlf 1981).

Insecticides and rates. Acephate (Orthene 75S [soluble powder], Valent U.S.A. Corp., Walnut Creek, CA) was used at two rates: 1.12 kg product per ha (1.0 lb/acre) is referred to here as the low rate, and 1.46 kg/ha (1.3 lb/acre) as the high rate. Carbofuran (Furadan 15G [granular], FMC Corp., Philadelphia, PA) was used at two rates: 149 g product per 100 linear m of row (1.0 lb per 1,000 linear ft) is referred to here as the low rate, and 209 g per 100 m (1.4 lb per 1,000 ft) as the high rate.

Treatments, 1990. Different schedules of insecticide application were compared in four treatments: high intensity, low intensity, intermediate intensity, and an untreated control. In high intensity plots, carbofuran was sidedressed at the low rate 2 wk after planting and at the high rate 6 wk after planting. In high intensity plots, acephate was sprayed 4 wk after the second carbofuran application then every 7 d until mid-September, for a total of seven sprays. In low intensity plots, carbofuran was sidedressed at the low rate 4 wk after planting and at the high rate 10 wk after planting. In low intensity plots, acephate was sprayed 4 wk after the second carbofuran application then every 14 d until mid-September, for a total of two sprays. In the intermediate intensity treatment, plots were not treated with carbofuran but were sprayed with acephate every 14 d starting in late July, which was when catch of *O. nubilalis* in blacklight traps increased to consistently ≥1 moth per night. Intermediate intensity plots were sprayed four times at Fremont and five times at Columbus. In low intensity plots, acephate was used only at the low rate. In high and intermediate intensity treatments, the first acephate applications were at the low rate; the high rate of acephate was then used, starting in early August in Columbus and in late August at Fremont. Control plots were not treated with insecticides. At Fremont, plot size was 3.6 m by 4.8 m with four single rows per plot. At Columbus, plots were 3.0 m by 7.5 m with two twin-row beds per plot.

Treatments, 1991. Acephate sprayed every 7 d versus 14 d was evaluated again at Columbus but without the added factor of carbofuran applications. Carbofuran was deleted due to a registration change in early 1991 that restricted it to one application at planting at a rate of 75 g 15G product per 100 m of row (8 oz per 1,000 ft) for aphid control; this low rate was unlikely to control *O. nubilalis*. Pepper plots were treated with acephate at the high rate on three schedules, starting once *O. nubilalis* catch in the blacklight trap was consistently ≥ 1 moth per night. The high intensity plots were sprayed every 7 d for a total of 15 sprays, and the low intensity plots were sprayed every 14 d for a total of 8 sprays. The variable intensity plots were sprayed every 14 d when the blacklight trap was catching 1 to 5 moths per night, or every 7 d when the trap was catching > 5 moths per night. Variable intensity plots were sprayed 11 times. An untreated control treatment also was evaluated. Plot size was 3.0 m by 6.0 m with two twin-row beds per plot.

Treatments, 1992. Three treatments were evaluated at Fremont and Piketon in plots that were larger than in the previous two years. Plot size was 7.5 m by 15.0 m at Fremont with five twin-row beds per plot; plot size was 7.2 m by 12.0 m at Piketon with eight single rows per plot. In the untreated control treatment, no insecticides were used. In both the high

intensity treatment and the variable treatment, acephate was applied starting once pods were present and *O. nubilalis* catch in the blacklight trap was consistently ≥ 1 moth per night. The first treatments were in early July at Fremont, at the end of the first flight, and in late July at Piketon, at the start of the second flight. In the high intensity treatment, acephate was applied on a 7-d schedule. In the variable treatment, peppers were treated with acephate on a 10-d schedule when there were 1 to 5 moths per night in blacklight traps, or on a 5-d schedule when there were > 5 moths per night. Acephate in Fremont was applied at the low rate until mid-August and at the high rate thereafter; only the high rate was used at Piketon. Due to low moth catches in traps at Piketon, the threshold for the 5-d spray schedule was modified to 4 moths per night in the blacklight trap. At Fremont, both treatments were sprayed 10 times. At Piketon, there were 9 sprays in high intensity and 10 sprays in variable intensity treatments.

Results

Pest species. The predominant pest infesting harvested pepper pods was *O. nubilalis*, but *S. frugiperda* and *H. zea* were also important at times. An unidentified species (Lepidoptera: Tortricidae) was occasionally found in pods. In Columbus in 1990, *O. nubilalis* predominated in the first harvest, but equal numbers of *O. nubilalis* and *S. frugiperda* were found in the second harvest; *S. frugiperda* predominated in the remaining harvests, although mixed with substantial numbers of *H. zea* in the final harvest (Fig. 1). In 1991, *O. nubilalis* predominated in all harvests at Columbus (Fig. 1); *S. frugiperda* was present throughout the season and accounted for 6% of larvae found, while *H. zea* was present in the last three harvests and accounted for 5% of larvae found. In 1992, *O. nubilalis* and an unidentified Tortricid accounted for damage in the few peppers that were infested at both sites (Fig. 1). Damage caused by these species can be assumed to be proportional to the percentages of larvae found, but these proportions are approximate because many damaged pods did not contain a larva at harvest.

Blacklight trapping. Blacklight trap monitoring of *O. nubilalis* indicated that populations at Fremont were larger, in all years, than at Columbus or Piketon (Fig. 2), probably because corn production was more intensive in Fremont than in Columbus or Piketon. Peak catches ranged from 34 moths per week at Piketon in 1992 to nearly 3,000 per week in Fremont in 1991 (Fig. 2). Emergence in northern and southern Ohio in 1992 was surprisingly similar in timing despite a separation of 280 km; only one moth was trapped at Piketon one week before the first moth was trapped at Fremont. There were the normal two generations of *O. nubilalis* in 1990 and 1992 but three generations in 1991. In years with two generations, moths from the overwintering generation began emerging in mid-May and peaked in mid-June. There was a 3- to 4-week period from late June to late July when very few moths were active. Moths of the first summer generation began to emerge in late July, flight activity peaked in mid-August, and ended in early October.

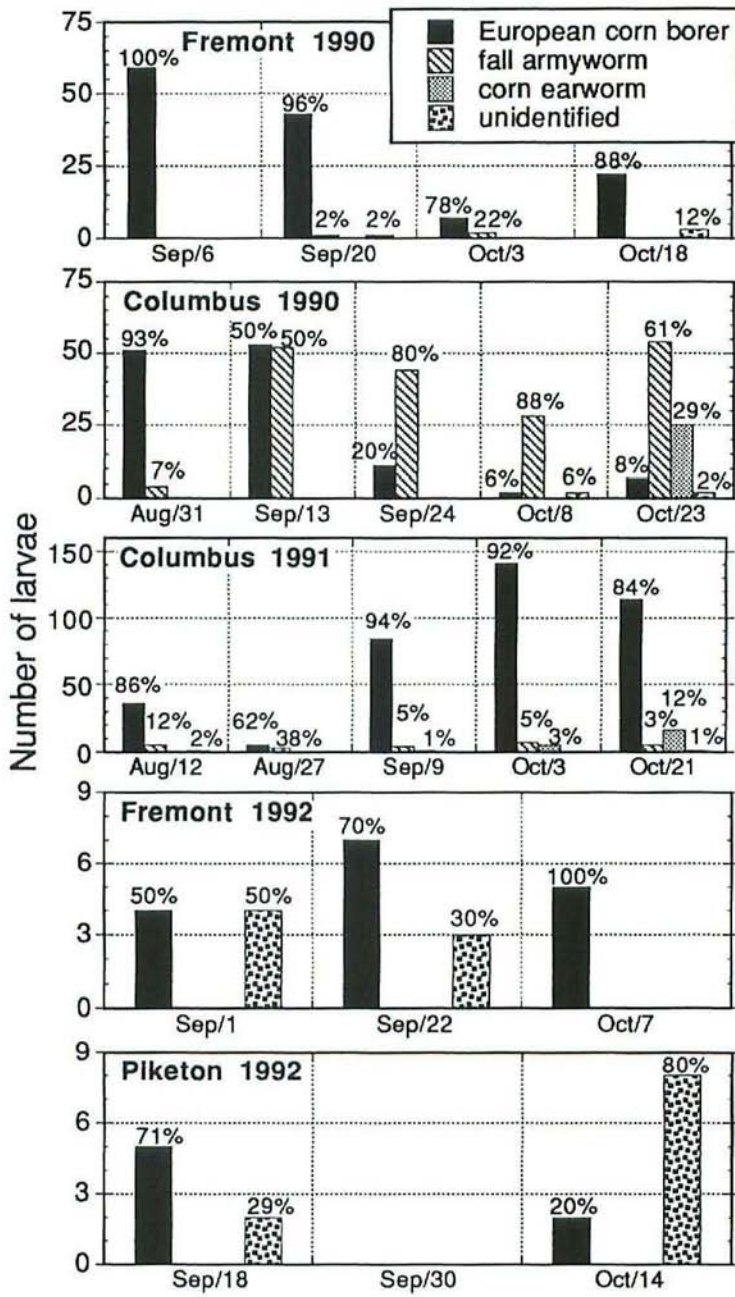

Fig. 1. Relative occurrence of species found in pepper pods at harvest. Sum of larvae found in all plots per harvest is plotted, and for each species, the percentage of total larvae found on each date is given above each bar.

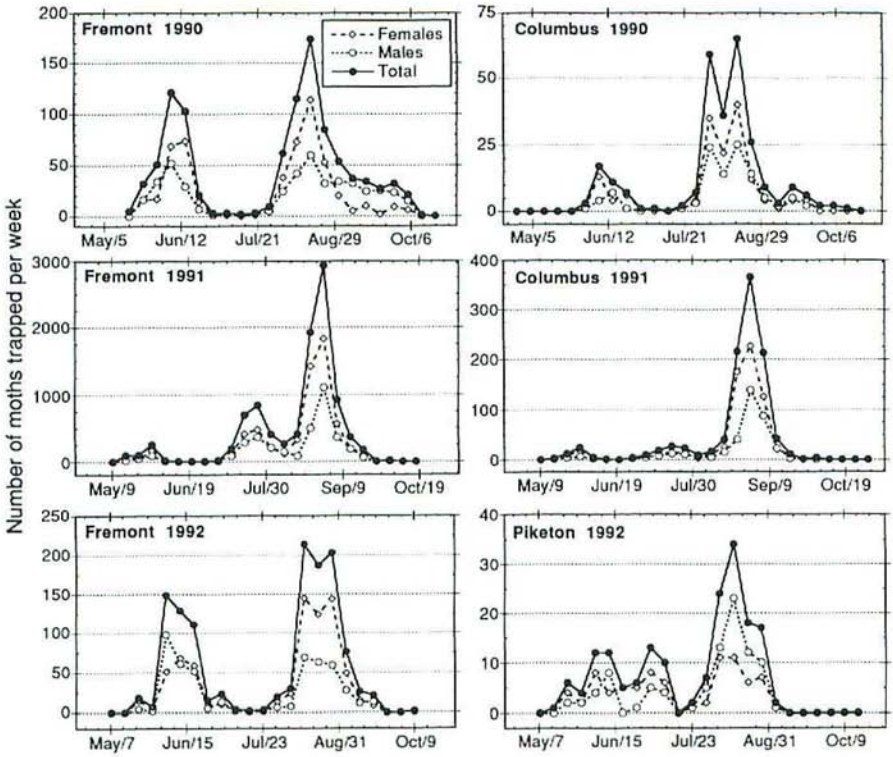

Fig. 2. Weekly catches of European corn borer (females, males, and total) adults in blacklight traps at three sites.

In 1991, development of *O. nubilalis* was accelerated due to higher than normal temperatures; blacklight traps showed peak flights in late May, late July, and late August (Fig. 2). Although there was not as sharp a drop in trap catches between the second and third flights as between the first and second flights, observations of degree-day accumulations were evidence that there was a third generation in 1991. If degree-days are accumulated once flight activity of the overwintering generation begins, an average of 1150 degree-days (base = 50° F) accumulate from the start of one generation's flight to the start of the next generation's flight (Showers et al. 1989). In Columbus in 1991, 1150 degree-days accumulated by the last week of June and 2300 degree-days accumulated by the third week of August; these two times coincided with when there was a sharp increase in the number of moths trapped. Observations of larval size provided further evidence that there was a third generation. In pods harvested on 12 August, late instars (20 to 25 mm long) predominated, which were assumed to be second generation. Pods harvested in a nearby field on 30 August (unpublished data) were infested by some late instars, but primarily by early instars (6 mm long), which were assumed to be third generation.

Pheromone trapping. Pheromone traps detected increasing *O. nubilalis* activity at about the same time as blacklight traps, and the number of male moths caught in pheromone traps was approximately the same as in blacklight traps in most weeks (Fig. 3), particularly in 1992 when more attention was paid to trap placement. The peak catch in pheromone traps tended to occur one to two weeks later than in blacklight traps, and catch in pheromone traps was more prolonged than in blacklight traps. Peak catch per week in pheromone traps was as low as 20 male moths at Piketon in 1992 and as high as 220 moths in Fremont in 1992. During the first half of a flight period, higher numbers of males were caught in blacklight traps than in pheromone traps, whereas the opposite trend was seen during the second half of a flight period (Fig. 3). In blacklight traps, there were slightly more females than males before the peak of a flight period, and slightly more males than females after the peak (Fig. 2). During the 3- to 4-week lull between major flight periods, pheromone traps caught 0 to 7 moths per week, just as the blacklight traps did. During the first week after this lull, pheromone traps caught between 3 and 12 male moths while blacklight traps caught between 9 and 24 total moths. During the second week after the lull, pheromone traps caught between 6 and 24 male moths while blacklight traps caught between 18 and 193 total moths.

Observations of *O. nubilalis* catch in pheromone traps indicated that trap placement was important, particularly the proximity of traps to vegetation. Traps placed within 30 cm of the plant canopy caught more than traps placed higher. If pheromone traps were placed over bare ground, as sometimes happened when fields were cultivated or lanes were mowed, then they usually had fewer moths than traps placed over vegetation. When traps were consistently placed close to vegetation in 1992, trap catch was more similar to that in blacklight traps (Fig. 3).

Infestation and treatment effects, 1990. At Fremont, *O. nubilalis* infestation in pepper pods was highest in the first two harvests, when only 36% and 41% of pods in untreated plots were undamaged, respectively (Fig. 4). Infestation in untreated plots was lower (59% undamaged) in the small third harvest, and lowest in the final harvest (100% undamaged red pods; 79% undamaged green pods). Damage was surprisingly high in high intensity plots; the most likely explanation is that spray penetration was insufficient in the tall and dense canopy. The percentage of undamaged pods was significantly higher in high intensity plots than in untreated plots in all harvests ($P < 0.05$; individual P values shown in Fig. 4), except for the final harvest of red pods. Analysis of the cumulative harvest showed that damage in low and intermediate intensity treatments was similar to untreated control plots, although damage trends in these treatments were inconsistent among individual harvests.

Similar differences were found in yield at Fremont. Yields were significantly higher in high intensity plots than in untreated plots in the second and fourth red pod harvests and in the final green pod harvest (Fig. 5). No treatment differences were found in the first, third, or cumulative harvests. Yields in low and intermediate intensity treatments were similar to untreated controls (Fig. 5).

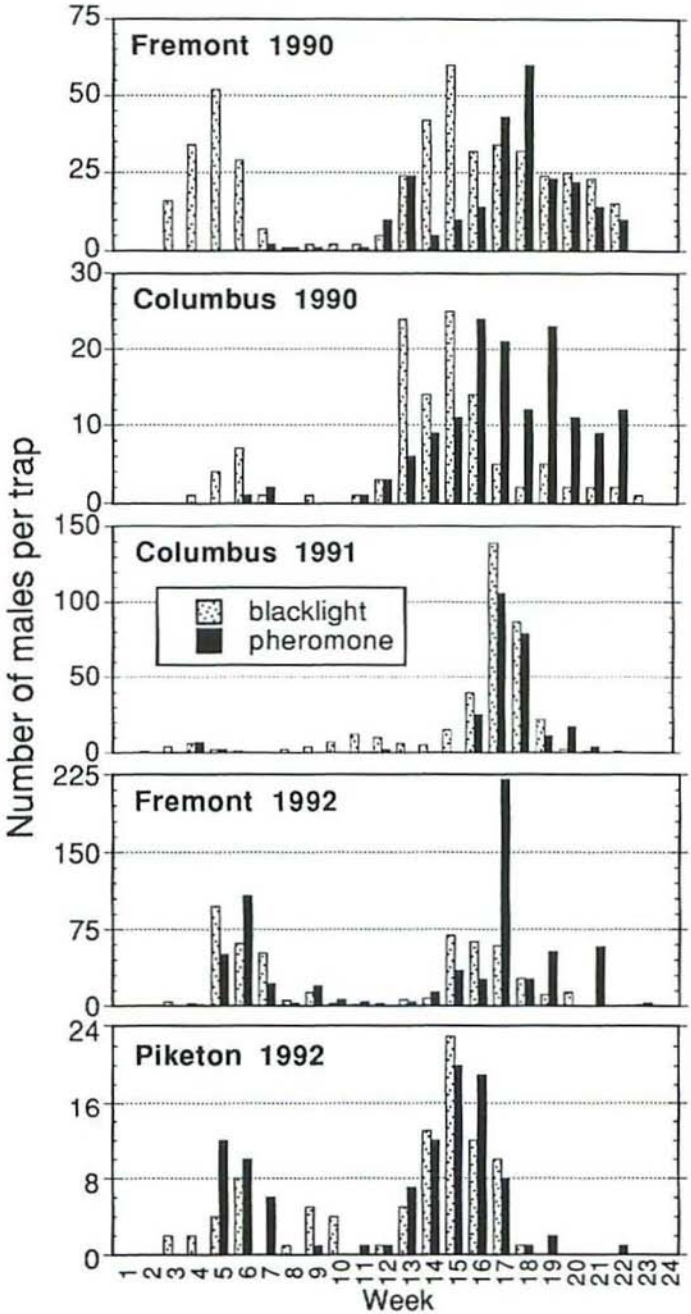

Fig. 3. Weekly catches of European corn borer, males only, in blacklight and pheromone traps at three sites, mid-May to mid-October.

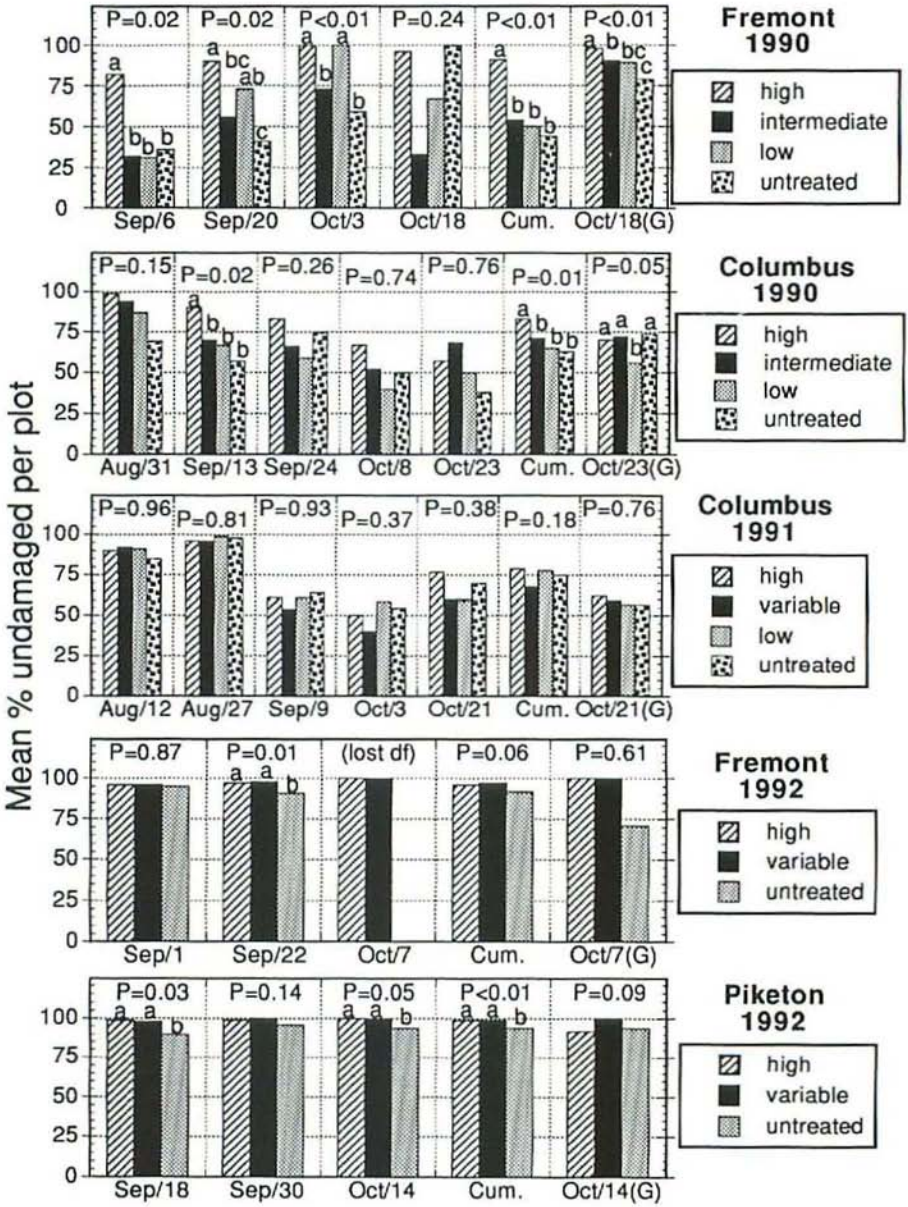

Fig. 4. Mean percentage of pepper pods undamaged by insects on periodic harvest dates and in cumulative harvests; pods harvested were red except for dates marked 'G' for green pod harvest. Within each group of columns, P value for treatment effect from ANOVA is shown at top of graph; where $P \leq 0.05$, treatments marked by different letters are significantly different from each other.

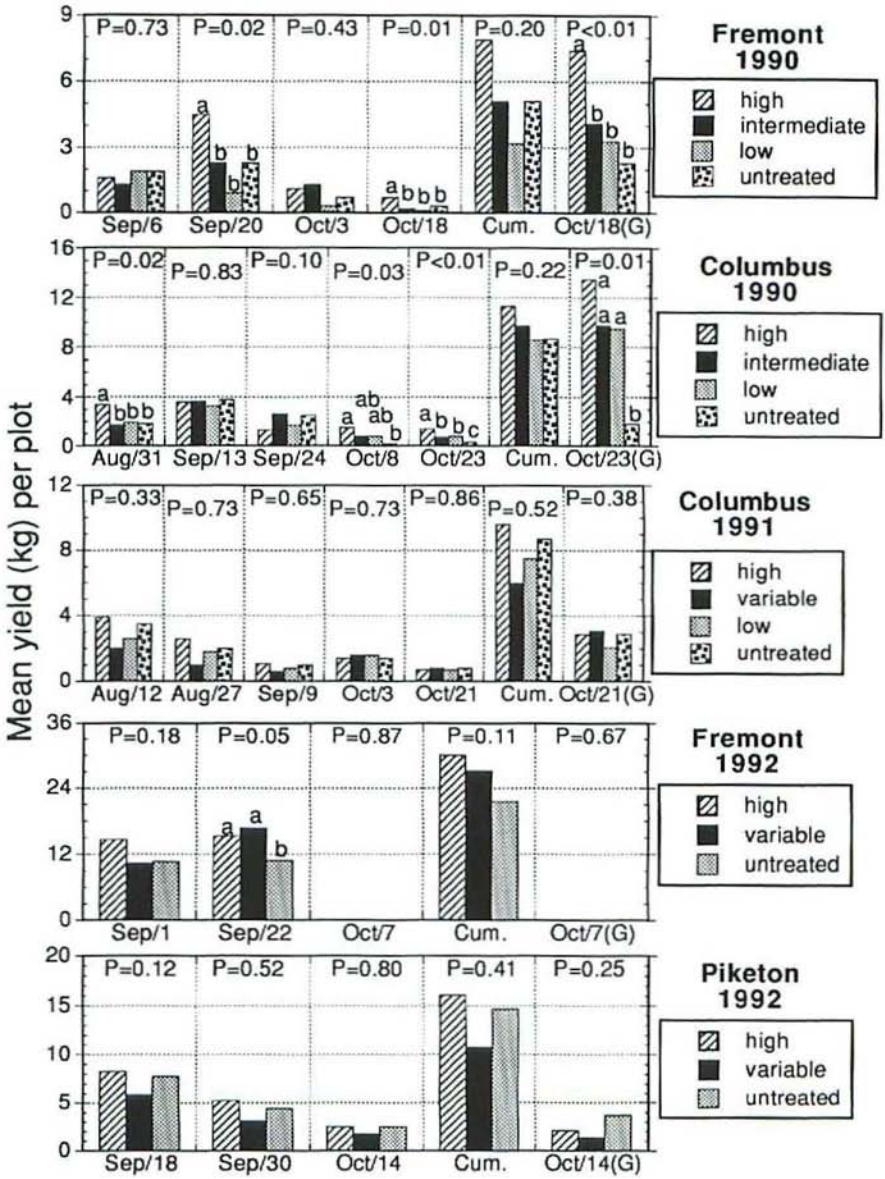

Fig. 5. Mean yield (kg) of pepper pods per plot on periodic harvest dates and in cumulative harvests; pods harvested were red except for dates marked 'G' for green pod harvest. Within each group of columns, P value for treatment effect from ANOVA is shown at top of graph; where $P \leq 0.05$, treatments marked by different letters are significantly different from each other.

At Columbus in 1990, damage was apparent throughout the harvest period, with only 38 to 75% of pods undamaged in untreated plots. There were more treatment differences in yield than in percentage undamaged pods, due to the number of insect-infested pods that were too rotten to harvest. The percentage of undamaged pods was significantly higher in high intensity plots than untreated plots in the second harvest and the cumulative harvest (Fig. 4). Yield in high intensity plots was significantly higher than in untreated plots in the first, fourth, fifth, cumulative red, and green pod harvests (Fig. 5). Damage and yields in low and intermediate intensity treatments were intermediate between high intensity plots and untreated plots.

Infestation and treatment effects, 1991. Damage in the first harvest was due to late instars of second generation *O. nubilalis*. Damage was light in the second harvest (Fig. 4); these pods were developing during the period between the second and third generations. Damage in the last three harvests was due to third-generation *O. nubilalis*. Damage was most severe in the fourth harvest when only 40 to 59% of pods were undamaged. There were no significant treatment effects on percentage undamaged pods (Fig. 4) or yield (Fig. 5) on any harvest date or for cumulative red pod harvests.

Pods and plants were small throughout the 1991 planting, most likely due to drought conditions soon after transplanting. At all harvests, damage was surprisingly high in high intensity plots, probably due to unusually high levels of *O. nubilalis* activity in July and August (Fig. 2); higher than normal temperatures and low rainfall apparently contributed to good survival of pests. Damage was surprisingly low in untreated plots, especially in the first harvest; this may have been due to pepper harvest starting early, at a time when corn was still attractive to *O. nubilalis*. Small plot size and drift of acephate from treated plots were other possible confounding factors.

To follow up on observations in 1990 that some of the late-season damage was restricted to the cap and stem portions of pepper pods, which are discarded during processing, damage in 1991 was recorded separately for the cap and stem versus the remainder of the pod. The percentage of total damage that was to caps only was 2% in the first harvest, 9% in the second and third harvests, 10% in the fourth harvest, 26% in the final harvest of red pods, and 25% in the final harvest of green pods.

Infestation and treatment effects, 1992. Field trials were strongly influenced by weather in 1992, especially from mid-July to mid-August when heavy rains prevented timely insecticide applications. At Fremont, peppers in high intensity plots were sprayed an average of every 10 d during the 14-wk period when a 7-d schedule was called for, while peppers in the variable plots were sprayed every 14 d during the 4-wk period when a 10-d schedule was called for, and every 10 d during the 8-wk period when a 5-d schedule was called for. The 1992 summer was unusually cool, which caused emergence of *O. nubilalis* to be about one week later than normal. Cool wet weather promoted rapid disease development at Fremont, where pepper plants collapsed from *Phytophthora* blight after the second harvest, thus leaving few harvestable pods in the final harvest.

Pepper harvests at both locations in 1992 showed little insect damage even in untreated control plots. At Fremont, peppers in both high intensity and variable intensity plots were significantly less damaged (Fig. 4) and higher yielding (Fig. 5) than in untreated plots in the second harvest, but there were no treatment differences in the first, third, or cumulative harvests. The lack of differences between high intensity and variable treatments at Fremont is not surprising because they were treated the same number of times although not on the same dates. At Piketon, a treatment effect was apparent in the percentage of undamaged pods in the first, third, and cumulative red pod harvests, when peppers in high intensity and variable plots were significantly less damaged than untreated peppers (Fig. 4); there was no effect of treatment on yield (Fig. 5). Although no advantage of variable over high intensity sprays was observed, it must be considered that treatments were not as timely as planned due to wet field conditions.

Discussion

Monitoring. Blacklight trap monitoring of *O. nubilalis* populations was useful for describing seasonal trends as well as differences among years and among locations. Several trends were apparent in data from blacklight traps over the three year period. A catch of zero to seven moths per week, or an average of zero to one moth per night, represented low density populations; this was typical in the 3- to 4-week period between the first and second flights, usually from late June to late July. A catch of more than 35 moths per week, or an average of five moths per night, represented high populations typical during the 3- to 5-week period of peak flight. A catch of intermediate numbers, 8 to 34 moths per week, was typical of the 1- to 2-week periods before and after peak flights. A key question for pepper management is how important are these intermediate population levels. Although guidelines for management of *O. nubilalis* on pepper in some areas call for insecticide treatment once blacklight trap captures reach an average of five or more moths per night (Ghidiu 1992) or four or more female moths per night for three consecutive nights (Showers et al. 1989), a more conservative approach was taken in my study by starting treatments when the moth catch reached the intermediate category, i.e., when moth catch consistently exceeded one moth per night. With my results showing that only 82 to 90% of pods were undamaged in high intensity treatments in the first harvests in some trials, even when sprays were based on this more conservative threshold, it is unlikely that Ohio pepper growers would be willing to use the higher thresholds unless further research can demonstrate their effective use under Ohio conditions.

Although blacklight traps are appealing for research purposes because they can document activity of female as well as male moths, pheromone traps appear to be an acceptable alternative for growers who wish to monitor *O. nubilalis* populations. Monitoring with target-specific pheromone traps is far less time-consuming than blacklight traps, which require sorting of target species from nontarget species. Pheromone traps also are less expensive. Care must be taken in placing pheromone traps close to

vegetation rather than over bare ground. The importance of pheromone trap placement relative to vegetation when monitoring *O. nubilalis* was also observed by Fletcher-Howell et al. (1983). Traps should be set up as soon as plants begin to flower, to target any lingering moths of the overwintering generation and moths of the one or two summer generations. Pheromone traps appear to be more reliable for detecting the beginning and peak of activity periods than for monitoring the end of activity periods. The slight lack of synchrony in catch of *O. nubilalis* males in blacklight and pheromone traps observed in this study was similar to that documented by Oloumi-Sadeghi et al. (1975), who found that peak capture of males in a sticky cardboard type of pheromone trap occurred after peak capture of males and females in blacklight traps and after peak egg-laying on corn.

An alternative to traps as an *O. nubilalis* monitoring tool is field scouting. Twenty pepper plants per plot were scouted weekly in 1992 with *O. nubilalis* egg masses as the primary target, but presence of other pests and natural enemies was also recorded (C. W., unpublished data). Disadvantages of scouting were that pepper plants were brittle and difficult to examine without breaking stems, and egg masses were difficult to locate. Scouting peppers was beneficial for aphid detection during early summer, but was of questionable value for management of *O. nubilalis*.

Control by Insecticides. Although the high intensity treatments provided better control of *O. nubilalis* and higher yields than other treatments in 1990, it was impossible to separate the relative contributions of carbofuran versus acephate with the experimental design used. It is likely that improved control was due to the 7-d schedule of acephate, and higher yields were due to carbofuran, which is known to have a general growth enhancing effect on various crops (e.g., Pless et al. 1971). A surprising result at both sites in 1990 was the ineffectiveness of a 14-d spray schedule, in contrast to the excellent control by acephate on a 14-d schedule reported by Ladd et al. (1982) for peppers grown in northeastern Ohio in 1980 and 1981. The *O. nubilalis* population pressure was much lower in the 1980-81 study, based on damage in untreated control plots, than in Fremont or Columbus in 1990. The poor control in plots treated every 7 d in 1991 led to the hypothesis tested in 1992 that a 5-d schedule may be needed during periods of peak moth activity. However, with the low levels of insect damage in 1992, even in untreated control plots, no advantage of a 5-d schedule was seen. A late planting of sweet corn near the pepper plantings at both sites in 1992 possibly acted as a trap crop and contributed to lower than expected damage to peppers, as has been suggested by Showers et al. (1989).

The difficulty in controlling this pest even with an intensified spray schedule suggests that components of the management system other than the spray schedule should be explored for improved control. A controlled droplet applicator may be a more effective delivery system than a conventional hydraulic boom sprayer for controlling this pest (Grafius et al. 1990). True systemic insecticides may be more effective than the limited systemic activity that characterizes acephate applied as a foliar spray.

One difference between the two study sites in 1990 was that there was little insect damage in the final harvest at Fremont, but there was

substantial damage in the final harvest at Columbus. Both sites were treated for the last time in mid-September. Presence of fall armyworm and corn earworm at Columbus but not at Fremont (Fig. 1) explains this difference in damage. These data indicate that potential damage by fall armyworm and corn earworm is great enough that maintaining insecticide applications until a week before the final harvest may be warranted at some sites. Pheromone traps have been an effective monitoring tool for corn earworm in Ohio sweet corn fields and can be suggested for pepper fields in September and October. Fall armyworm can be monitored in the adult stage by pheromone or blacklight traps, or in larval stages by scouting nearby plantings of sweet corn, a crop on which their feeding is easily detected. Further studies are needed to evaluate management tactics for these two pests in pepper fields.

Conclusions. Information on *O. nubilalis* activity obtained from traps was useful for the first management decision of the pepper-growing season, which is determining when to initiate a spray schedule. A level of < 1 moth per night in blacklight traps corresponded to a low density *O. nubilalis* population, and a threshold of ≥ 1 moth per night in blacklight traps was appropriate for initiating a spray schedule. Pheromone traps appear to offer an acceptable and less time-consuming alternative to blacklight traps; a threshold of > 1 male moth per night in pheromone traps could be tested in comparison with the blacklight threshold.

The second pest management decision is determining how often to spray. This study showed that a 7-d insecticide spray schedule was suitable for control in peppers in Ohio in years with average *O. nubilalis* activity. Increasing the intensity of treatments during periods of peak moth activity and decreasing the intensity of treatments during periods of low moth activity seems logical, but the levels of moth activity that correspond to high and low activity need to be defined and tested in large scale field experiments before any recommendation on variable schedules can be made.

The third pest management decision is determining when to stop spraying. Traps were useful for determining when activity of *O. nubilalis* moths tapered off to low levels, usually in late September. Sprays for *O. nubilalis* control could be discontinued at this point, but the potential exists for late-season damage by fall armyworm and corn earworm. Additional data is needed to develop guidelines for monitoring and control of these two pests of peppers.

Despite the status of European corn borer as the key pest of bell peppers, surprisingly few studies have been published on its damage and management. The data on pepper management options that were obtained in this three-year study will be valuable in helping pepper growers evaluate their insect management programs, but there is a need for additional information. The fluctuations in *O. nubilalis* populations and damage to peppers from year to year and from site to site suggest that a longer term study would be needed to refine the monitoring and control options explored here.

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NOTE

Impact of Indigenous *Beauveria bassiana* (Balsamo) Vuillemin on Banana Weevil and Rotten Sugarcane Weevil (Coleoptera: Curculionidae) Populations in Banana in Florida[1]

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The banana weevil, *Cosmopolites sordidus* Germar and the rotten sugarcane weevil, *Metamasius hemipterus sericeus* (Olivier) are pests of banana, (*Musa* sp.) in the Neotropics. For more than 40 years, *C. sordidus* was considered the only important pest of bananas in Florida (Wolfenbarger 1964) until the documented establishment of *M. h. sericeus* in 1984 (Woodruff & Baranowski 1985). The egg, larval and pupal stages of banana weevil occur in plant tissues near the soil line. Banana weevil larvae bore into corms causing death of young plants, the toppling of older plants and a general decrease in productivity. The rotten sugarcane weevil feeds in the pseudostem above the soil line. By means of their secluded life cycle, both of these weevils are protected from many potential natural enemies. Endemic natural enemies of these weevils include ants of the genus *Tetramorium* and a complex of generalistic predators, i.e., *Hololepta quadridentata* (Fabricius) (Histeridae) and *Propagalerita bicolor* (Drury) (Carabidae) (Roche & Abreu 1983, Bennett et al. 1985, Peña et al. 1990).

Entomopathogens could provide a promising, yet untested means of control of banana weevil and rotten sugarcane weevil in Florida. Entomopathogenic fungi, *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metchnikoff) Sorokin have gained considerable attention as potential control agents for weevils (Tedders et al. 1973, Boethel & Eikenbary 1979, Gotwald & Tedders 1983).

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Beauveria bassiana was found infecting *C. sordidus* and *M. h. sericeus* in Florida [J. E. Peña unpubl. data; identity confirmed by R. Humber (USDA-ARS Plant Protection Res. Unit)]. This fungus has also been found attacking *C. sordidus* and *M. hemipterus* in Guadeloupe, Cuba and Brazil where it is considered an effective naturally occurring control agent (Delattre & Jean-Bart 1978, Mesquita 1987, Castineiras et al. 1990). The objective of this research was to evaluate the impact of indigenous *B. bassiana* on *C. sordidus* and *M. h. sericeus* populations.

The experimental site was a 3 year-old banana field (15 ha) which was not irrigated. It was located 5 km south and 7 km west of Homestead, Dade County, Florida. Estimates of adult weevil seasonal abundance were made by trapping from September 1989 through July 1991. Each week 30 banana pseudostem disc traps (Viladerbo 1973) were placed in the field. Individual traps were spaced 8 m within the rows, 8 m between the rows and about 15 cm from a banana plant. Only those weevils present in each trap were counted. The level of fungal infection was estimated each week with 30 *C. sordidus* and 30 *M. h. sericeus* which were individually confined in 12 cm petri dishes. Each petri dish was lined with a P4 filter paper (Fisher Scientific), had 1 ml of water added, and sealed with Parafilm® (American Can. Co., Dixie Greenwich, CT) and kept for 30 d at 25 ± 2°C. Weevils were examined every other day for the presence of hyphal bodies and conidia which were easily observed with a dissecting microscope.

To determine the impact of weather conditions on disease incidence, records of daily rainfall and maximum-minimum temperatures from weather stations at Homestead from 1989-1991 were obtained from U. S. Weather Service. Accordingly, principal component analysis, using the FACTOR module of SAS (SAS 1985), were performed on the rainfall and maximum and minimum temperature records, using the average biweekly values for each month.

Non-Fungus Mortality. The prevalence of other parasites, on both weevil species was low during the entire 2.5 year sampling period. Two undescribed species of nematodes (Rhabditidae and Diplogasteridae) were collected from *M. h. sericeus* cadavers, but failed to cause weevil mortality when healthy individuals were exposed. Dissections revealed that both species of nematodes were carried as dauer juveniles (J_3) in the genital capsules of both sexes of healthy *M. h. sericeus*. Both of these nematodes appear to be commensally associated with *M. h. sericeus* and their appearance in host cadavers probably represents opportunism. A phorid fly, *Scarites* sp., emerged from one *C. sordidus* cadaver, but also failed to parasitize weevil adults when they were exposed to several adults of this species. Thus, nonfungus mortality of reared weevils was insignificant.

Prevalence of *B. bassiana*. In the field, dead weevils infected with *B. bassiana* were mostly found adhering to undersides of fallen banana pseudostems or corms and conidial sporulation was evident in almost every instance. The *B. bassiana* disease incidence in *C. sordidus* adults was consistently less than 10% between January and March and increased up to 34% between April and July (Fig. 1). The percentage of infected weevils decreased during the subsequent months. Infection peaks were observed for

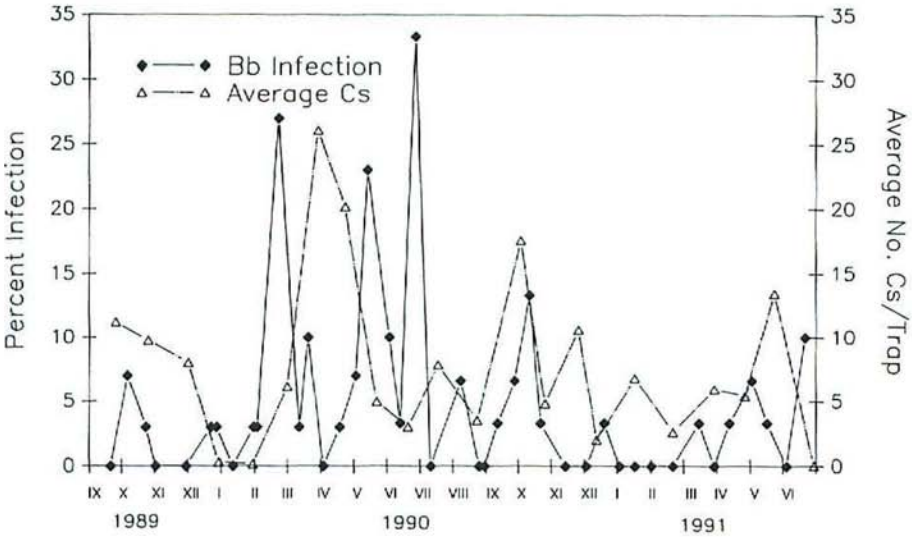

Fig. 1. Percentage of field-collected *Cosmopolites sordidus* (Cs) adults infected with *B. bassiana* throughout the sampling period in 1989-1991.

the months of April 1989, November 1990 and May 1991. *B. bassiana* disease incidence regularly followed an increase of population density for most of the months with the exception of June 1990 when percent infection was as low as 4% compared with an average of 34 *C. sordidus* per trap (Fig. 1).

The population of *M. h. sericeus* was consistently low, 5 weevil adults per trap during 1989 and 1990 and increased up to 10 adult weevils per trap during April 1991 (Fig. 2). *B. bassiana* infection occurred at low weevil densities during 1989 and 1990 and increased up to 70% between March and April 1991 when more than 10 weevils were captured per trap.

The differences in *B. bassiana* disease incidence between *C. sordidus* and *M. h. sericeus* may be due to several factors. First, the population of the newly introduced *M. h. sericeus* could be more susceptible to *B. bassiana* infection or to the strain(s) in Florida than the naturally occurring *C. sordidus* population, which was introduced into Florida more than 40 years ago. Second, *M. h. sericeus* are good fliers and disperse rapidly in banana fields, allowing contaminated individuals to disperse the pathogen to healthy weevils more readily than *C. sordidus* which does not fly and is limited to a few meters around their site of origin. *B. bassiana* disease incidence on *C. sordidus* was more correlated to precipitation (r = 0.16) and maximum temperature (r = 0.16) than *M. h. sericeus* (r = 0.02, precipitation and r = -0.08 for maximum temperature). According to these results, *B. bassiana* infection of *C. sordidus* depended more on favorable environmental conditions than its infection of

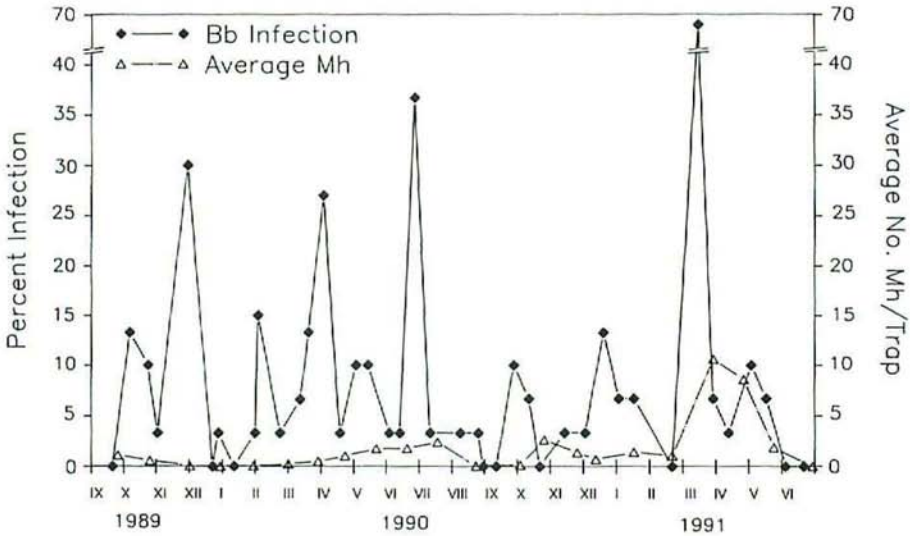

Fig. 2. Percentage of field-collected *M. h. sericeus* (Mh) adults infected with *B. bassiana* throughout the sampling period in 1989-1991.

M. h. sericeus. This study demonstrates that naturally occurring *B. bassiana* is an important mortality factor to adults in naturalized populations of *C. sordidus* and *M. h. sericeus* in southern Florida and that the potential for occasional epizootics exists. However, much more information is needed on the impact of this entomopathogen on larval and pupal mortality, and on adult longevity and reproductive potential of *C. sordidus* and *M. h. sericeus* in the field before pest management decisions can be made.

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Section E Symposium
1993 Entomological Society of America Annual Meeting, Indianapolis, Indiana

The Crisis in IPM: Is There a Solution to the Gap Between Theory and Practice?

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Introduction to the Symposium Proceedings

James S. Berry

J. Agric. Entomol. 12(4): 169-170 (October 1995)

Integrated Pest Management (IPM) is often seen as an innovative approach to managing agricultural pests in an ecologically and economically sound manner. The vision and hope for the effectiveness of IPM have even been proclaimed from the highest levels of the United States government. In practice, what is the current state of IPM? The term IPM has become a buzzword that often means no more than improved scouting and static thresholds based on pest density. Currently, IPM is basically business as usual where pest control has been refined with the use scouting and economic thresholds. This is far short of what is expected of IPM and far short of current technology. A paradigm shift is needed to change from a focus on control to a focus on integrated management of pests. This symposium was born out of a desire to focus nationwide attention on this situation and develop some renewed hope in moving IPM forward.

The following collection of papers was presented before a standing-room-only crowd of nearly one thousand people at the 1993 Entomological Society of America Annual Meeting. The amount of interest in this symposium indicates that many people are concerned about the current status and future direction of IPM. The authors of these papers believe that application of current knowledge and technology can be used to bridge the gap between IPM theory and practice. Integrated Pest Management is an important concept that offers great potential for agriculture. These papers evaluate the past, present, and future of IPM so that the gap between IPM theory and practice is placed in perspective to what must be done to bridge this gap.

Pedigo provides a historical perspective of IPM along with a clear definition of a management framework that relies on nonpesticidal preventatives and the use of therapeutics when the preventive measures fail. This paper also lays a solid foundation for the papers that follow by focusing on yield instead of pest density. Steffey shows that it is important to know what various stakeholders in agriculture expect from IPM. Then, IPM programs can be developed to meet these needs. The economists, Skold and Davis, revisit the concept of economic thresholds which is one of the cornerstones of IPM decision making. They point out weakenesses of mainstream thought and then lay a firm foundation for dynamic economic thresholds. Herbert discusses hindrances to IPM implementation and adoption. He then proposes a framework to improve adoption of IPM. Hutchins presents a private sector perspective. He focuses on the need for IPM to become a value-added service in a free market economy where efficient businesses prevail. Also, he identifies organizational hindrances to IPM research and adoption.

The two final papers describe computer and information technologies that can be applied to complex IPM problems. In both these papers computers manage information and simplify the decision making process for the user. First, Berry shows how computer technology, multi disciplinary research, and field practitioner involvement led to the successful development and implementation of IPM decision support software for the Grasshopper IPM Project. This software incorporates computer models that allows users to evaluate pest control strategies, innovative management options, and long-term strategies in light of dynamic economic analysis. In the second paper, Travis shows that expert systems can use complex information and present it in a way that facilitates IPM decision-making by the user. He also points out that agricultural legislation and regulation is impacted by the agricultural and non-agricultural community. Therefore, both groups need to understand IPM concepts.

The spirit of this symposium was not to present a definitive answer. Rather, these papers should be a starting point for returning to the biological and economic foundations of pest management. With a rejuvenated vision and expanded paradigm for IPM, pest management professionals and practitioners will be enabled to make new advances for agriculture.

Closing The Gap Between IPM Theory and Practice[1, 2]

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J. Agric. Entomol. 12(4): 171-181 (October 1995)

ABSTRACT Conflicting opinions regarding the progress of Integrated Pest Management (IPM) since its inception have prompted the need to review IPM trends and consider future directions of the concept. The major issues that have shaped agricultural policy in the United States help to explain IPM development and its present status. These issues are grouped as environmental issues, sustainable agriculture issues, farm economic issues, and ecological blacklash issues. Based on the original IPM paradigm, a gap between theory and practice has occurred, with a shift away from multiple-tactic programs and toward single-tactic, pesticide based programs. An alternative view of IPM is presented that emphasizes the use of nonpesticidal preventive tactics as a first line of defense against pests, followed by the use of therapeutics (curatives) only when preventives fail. The steps required to develop an integrated management program are presented, along with a discussion of closing the gap between IPM theory and practice.

KEY WORDS Integrated Pest Management, IPM, preventive pest management, IPM therapy, strategies, tactics, curative tactics, preventive tactics, theory, practice, alternatives

It has been over three decades since the first reference to the term pest management was made by Australian entomologists P. W. Geier and L. R. Clark (1961) and even longer since V. M. Stern and his coworkers conceptualized the practice of integrated control in their Hilgardia paper (Stern et al. 1959). Much as occurred since those modest beginnings, and today the approach is officially accepted at all levels of agriculture in the U. S. A., such as the United States Department of Agriculture, Cooperative Extension Service, food processing firms, and grower organizations. Indeed, a recent policy of President Clinton's administration is to achieve the goal of having 75% of farmers in the U. S. A. using Integrated Pest Management (IPM) techniques by the year 2000. This initiative is an attempt to reduce the use of high-risk pesticides (News Release 0815093 on September 21, 1993, of the U. S. EPA, FDA, and USDA).

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[2] Journal paper no. J-15805 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Project No. 2285, 3207, & 3183.

Yet, the IPM approach is being questioned by many people. After years of effort, some agriculturalists believe that IPM has failed to deliver on its promises and that the approach should be abandoned in favor of other schemes (Delucchi 1989) or at least that the direction of IPM development has significantly changed since its inception (Cate and Hinkle 1993).

With these conflicting opinions and many questions about the approach, a review of what has been said and done with IPM is in order. Therefore, it is the purpose of this paper to consider major trends and to suggest how IPM should proceed to achieve the goal of environmentally safe manipulation of pest populations and commodity protection. The emphasis of this theme is straightforward. If IPM is to meet the challenges faced by modern agriculture, more tactics will have to be integrated into IPM practice.

Issues Shaping Agricultural Policy in the U.S.A.

To understand the progress of IPM and its status today, it is important to consider the major issues that have shaped and continue to shape agricultural policy in the United States. The major issues can be grouped into four broad categories, environment, sustainable agriculture, farm economics, and ecological backlash (National Research Council 1989).

Environmental issues. The negative effects of agrichemicals have spawned much public concern through the years. This concern has evoked legislative action, such as pesticide use restrictions, cancellation of pesticides, and pesticide-user certification. Most public concern has focused on food safety, ground water contamination, and degradation of quality of nonagricultural environments. The environmental and food safety concerns have become more focused in recent years through environmental organizations (Cate and Hinkle 1993). These organizations can be counted upon to influence new legislation on pesticide use. Pesticide use and concern for the environment helped promote the rise of IPM to its present position and will further enhance its future.

Sustainable agriculture issues. Sustainable, or alternative, agriculture has been suggested as the wave of future agricultural production. With this paradigm, low-input crop production methods are practiced because of environmental quality concerns on the one hand and conservation of natural resources, such as soil, on the other. Most sustainable approaches mandate reduced energy-based inputs, including agrichemicals, and greater use of managerial skills.

The IPM concept is a forerunner of the sustainable agriculture paradigm and has become a central component of this approach to agricultural production. Further adoption of sustainable agriculture will continue to promote IPM practice, as it has in the past.

Farm economics issues. The farm situation today is an embattled one. Farmers are caught between rising production costs and flat, or falling, market values. The need to constantly increase yields to offset greater costs has nurtured the increased use of agrichemicals. Increased yields further reduce market values, in turn, creating a need for yet more agrichemicals (Perkins 1982). As a result, the public and environmental groups blame

farmers for environmental problems caused by overuse of agrichemicals. This situation has led to a continuing need to reduce costs and improve farm profits, while conserving natural resources.

IPM theory certainly addresses the economics of pest losses and, at the very least, offers the potential for cost reductions (Rajotte et al. 1987). The promise of lowered inputs for pest control will enhance the role of IPM in future production systems.

Ecological blacklash issues. As with other technologies, there has been a history of change in pest control practices. Some of the most profound changes have occurred because of failures in established, mainly pesticide-based programs (Perkins 1982). There are numerous examples of pest resistance to pesticides, pest resurgence, secondary pest outbreaks, and enhanced microbial degradation of pesticides (Pedigo 1989). In particular, resistance to pesticides is of major concern, presently reaching crisis proportions in entomology. At issue is how to alleviate these problems in an ecologically sound manner.

Here again, IPM explicitly deals with ecological backlash issues and suggests ways to alleviate associated problems. Indeed, avoiding ecological backlash is the very essence of IPM. This issue was and still is a primary catalyst in acceptance of IPM.

Therefore, IPM continues to play a central role in major agricultural issues. These issues have helped define IPM as it is known today. Moreover, perceptions and expectations of IPM have largely been determined by its involvement in these issues. However, are these perceptions of IPM correct and are the expectations of IPM realistic? To answer these questions, the IPM paradigm needs closer examination.

The IPM Paradigm

Much has been said and written about IPM. It has been idealized by entomologists, environmental groups, the food industry, politicians, and others. As an ideal, it is often presented as a cure-all and has come to represent almost any pest control activity that suits the occasion, management-based or not. For example, some lawn-care concerns use the term IPM to describe scheduled chemical applications, which are clearly not IPM practices.

Although specialists disagree on an exact definition of IPM, most accept that it has a unique set of goals that sets it apart from other pest technologies. Some of these goals include reducing pest status (not simply killing pests), accepting the presence of a tolerable pest density, conserving environmental quality, and improving user profits (Pedigo 1985). Not all bona fide IPM programs achieve all of these goals, although most set out to do so.

Commonly, IPM strategies to achieve these goals involve pest population assessment and prognosis, an economic analysis based on an understanding of crop responses to injury, intervention in the production system only when necessary, and the use of several selective and compatible tactics when intervening. In this list of strategies, the last is probably the most common

in IPM definitions. Indeed, integration of multiple tactics has been a central theme of IPM since its inception (Cate and Hinkle 1993). Even the name pest management (Geier 1966) has been changed to integrated pest management to emphasize this point. Because integrating multiple tactics has been a central theme, successful integration should be the main criterion for distinguishing bona fide IPM programs from programs that are IPM in name only.

The Gap Between IPM Theory and Practice

Considering that integrating multiple tactics in an ecologically sound manner is the primary tenet of IPM, it would seem that a gap has developed between theory and practice. From the late 1970's until the present, a primary emphasis has been placed on single-tactic programs, accompanied by a retreat from ecological principles (Cate and Hinkle 1993). This trend has resulted in a shift from the original pest management concept as envisioned by Geier and Clark (1961), Smith and van den Bosch (1967), and others.

The belief that the single-tactic program is prevalent in IPM practice is supported by a study evaluating the Cooperative Extension Service's National IPM Program (Rajotte et al. 1987). In that study, scouting was the most pervasive IPM practice of the farmers surveyed. IPM scouting usually refers to population sampling, assessment using a threshold, and application of a pesticide, when appropriate.

Granted, the scouting strategy is an improvement over the identify-and-spray approaches of the past. But, this strategy can hardly be considered a multiple-tactic strategy. Therefore, if multiple tactics and ecological considerations are the guiding principles of IPM, can pesticide-based single-tactic programs be considered IPM at all? Perhaps they can if IPM advances as phases, with the single-tactic program representing an early development phase. However, after more than 20 years of development, it would seem that IPM has stalled in this early phase.

Without question, the rate of development and acceptance of multiple-tactic programs has been slow, indeed, too slow to meet most expectations. Many reasons could be suggested for this delay, but two stand out, the immediate need to alleviate pest problems and the lack of a simple conceptual basis for combining multiple tactics.

The immediate need to solve existing pest problems most certainly has influenced the course and rate of IPM development. If problems are severe, a scouting-pesticide strategy can be developed quickly and delivered to farmers. Adoption of such programs allows the farmer to avoid future losses in short order. Once adopted, successful scouting-pesticide strategies are usually retained because the farmer has no incentive to change to multiple-tactic programs. Moreover, farmers are reluctant to take risks on new and more complicated programs if the scouting-pesticide strategy is effective. Even explanations of long-term advantages associated with multiple-tactic programs, such as avoiding pesticide resistance and secondary pest outbreaks, will not likely cause a shift to these programs.

The lack of a simple conceptual basis for integrating multiple tactics may have also been a factor slowing multiple-tactic development and acceptance. For at least two decades, mathematical modeling and systems analysis have claimed almost exclusive domain over the theoretical basis for integration. Modeling has been useful, but mainly from a research standpoint (Wilson 1989). However, there seems to have been no emergence of a clear set of principles to guide field-by-field integration. Without principles, integration may proceed from some serendipitous assemblage of tactics. Integration, however, should proceed from a logical base that will allow organization of IPM tactics in a meaningful and effective way. In searching for the principles of integration, other disciplines can be considered in which integration is a crucial part of the problem-solving process.

An Alternative View of IPM

One such discipline, which is roughly analogous to IPM, is human medicine. In this discipline, a broad range of tactics is used in managing diseases, and some of its most spectacular successes involve combining both preventive and curative procedures. In fact, the time-proven method of integrating tactics from preventive medicine and therapeutics is the cornerstone of modern medical practice. For example, specific diets and limiting exposure to carcinogens are recommended to reduce the risk of contracting cancer. But, if these preventives fail, therapy is applied in the form of chemotherapy or surgery.

Management of agricultural pests is not unlike management of many human diseases. This powerful dualistic concept of prevention and cure can be used to produce programs in which the integration of tactics is effective and practical. This idea is not new of course. Papers by Rabb (1978), All (1989), and Nyrop and Binns (1991) used the same concept. However, only All (1989) emphasized IPM prevention, and using the prevention/therapy-idea as a logical basis for integrating IPM tactics has not been explored to any great extent.

IPM Prevention

IPM prevention recently has been called Preventive Pest management (Preventive PM) and has been a major thrust of the Cooperative States Research Service (CSRS) North Central IPM granting program (Cate and Hinkle 1993). Preventive PM is, or at least should be, the ultimate form of IPM

Preventive PM implies that action should be taken against a pest before injury occurs. Therefore, the tactics are often employed without knowledge of pest presence or status at a particular point in time. For example, seeds of resistant plants are chosen and plans made in advance of the growing season, often long before any knowledge of a pest's economic importance in a particular growing season is known.

Lowering the pest's general equilibrium position. Prevention can be achieved by focusing on either the pest or the host. Very often it focuses on

the pest. As shown in Fig. 1, the ecological objective is to lower the pest's general equilibrium position (average density) and, subsequently, the average level of crop damage to a position below the economic damage level, which is where costs equal benefits (Stern et al. 1959).

Lowering the general equilibrium position can be accomplished either by prohibiting pest establishment or quickly limiting pest population growth when pest establishment occurs. Tactics for this purpose include many biological controls, crop rotations, sanitation and tillage, altering planting dates to prevent or reduce colonization, trap cropping, spatial arrangements of plants (e.g., row widths and adjacent crops), and cultivar selection for insect resistance (e.g., antibiosis, antixenosis).

Most of these tactics are compatible for integrating into the overall Preventive PM program. Seemingly, the least compatible tactic is the use of insects as biological control agents. Although the prevailing viewpoint is that these biological controls are compatible with other tactics (Hoy 1990), it would not seem so. This is because tactics used to suppress the pest also usually suppress natural-enemy populations, if in no other way than to reduce the natural enemy's food source. This should not be taken to imply that insects not be used in biological control, but rather that these agents are some of the most difficult to integrate into the management program. Therefore, special emphasis is needed for this integration.

Seemingly, if tactics work in a density-independent manner they tend to be compatible for inclusion in the pest management program. Conversely, if effectiveness of the tactic is promoted by pest density, as with many insect natural enemies and disease-causing organisms, then the tactic becomes less compatible when used in conjunction with other density-reducing tactics (Quisenberry and Schotzko 1994).

Prospects for natural enemy compatibility have improved in recent years with more efficient rearing procedures and methods of agumentation. Consequently, there will be a greater potential for augumentation, thereby making the natural enemies less density-dependent for effectiveness in management. Genetic improvements through conventional selection and bioengineering to produce natural enemies resistant to insecticides and other tactics also will enhance compatibility.

Raising the level at which economic damage occurs. The other area of prevention focuses on the crop itself. In this instance, attempts are made to manage the loss from the pest rather than managing pest density. In other words, the goal here is to reduce the level of injury per pest.

The ecological objective of this approach is to raise the level at which economic damage occurs (Fig. 2). Here, the manager looks for ways to make the crop less vulnerable to a developing pest population. For most crops, this could mean irrigating or increasing nutrient inputs to increase plant vigor, changing planting dates to present a less vulnerable stage to a pest, and/or selecting tolerant cultivars.

Tolerance to pest injury is a tactic often ignored by plant breeders, entomologists, and others, though it may be the most sustainable tactic that can be used. Advantages of tolerance are two-fold. First, tolerance is completely compatible with insect natural enemies. It allows higher pest

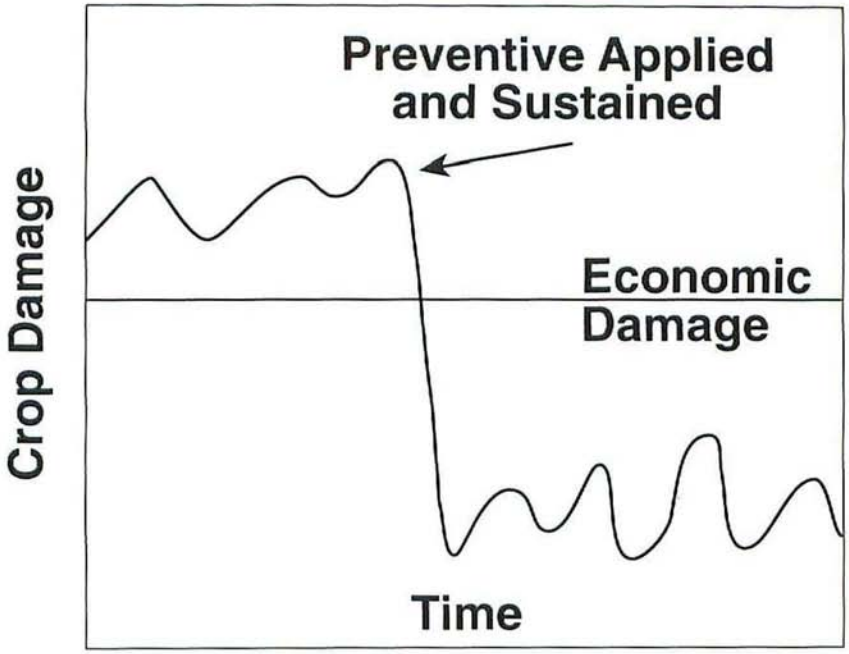

Fig. 1. Preventive pest management in which the ecological objective is to lower the general equilibrium position of a pest population, with subsequent reduction in the average level of crop damage.

densities without significant yield loss and, therefore, is conducive to factors acting in a density-dependent manner. Second, because no mortality pressure is placed on the pest population, there is little chance for development of resistance to the tactic. Indeed, because of the latter, tolerance may be the premier IPM tactic. However, much more must be known about tolerance mechanisms in plants and modes of inheritance of these before this approach can be more widely adopted.

Pesticides not recommended as a preventive tactic. In seeking preventive tactics, pesticides are not recommended for Preventive PM. They have been used widely for prevention, and many farmers still use them in this way today. However, the use of pesticides in regularly scheduled applications frequently has resulted in pesticide resistance and other forms of ecological backlash (Pedigo 1989). Therefore, this approach cannot be considered part of a sustainable IPM program.

IPM Therapy

Although Preventive PM should form the basis and first line of defense in the ideal IPM program, prevention alone is usually not adequate. IPM therapy also is necessary in most IPM programs. Therapy seeks to cure an acute or chronic crop disorder. It differs from Preventive PM in that a pest

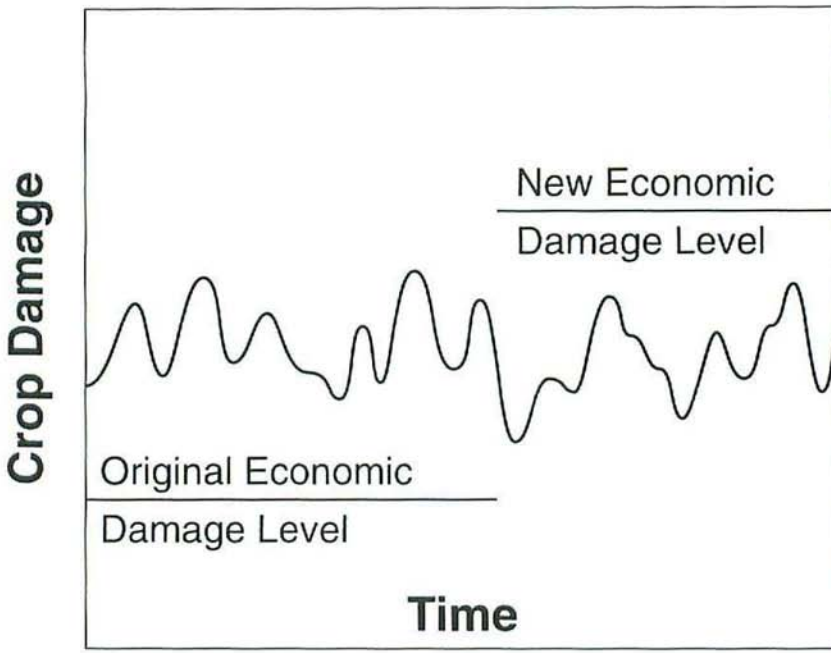

Fig. 2. Preventive pest management where the ecological objective is modify crop susceptibility to pest injury resulting in an increase of the level at which economic damage occurs.

population is present, and injury is occurring when management decisions are made. In other words, therapy is applied after pest sampling is conducted, and an assessment of pest status indicates that economic damage is imminent. Although therapy is considered distinct from prevention, there still is a preventive aspect to it. This is because future loses must be prevented by use of a therapy; otherwise, the therapy would not be economically feasible.

Therapy often constitutes the first phase of IPM development because therapeutic programs can be formulated quickly to alleviate ongoing problems. From an IPM developmental standpoint, therapy may be the final phase of program development for some occasional pests. In such instances, the general equilibrium position of the pest is suppressed naturally, and there may be no need for preventives because nature supplies them. Here, all that may be needed is an infrequent "correction" of population density to achieve the management goal. With these occasional pests, the judicious use of pesticides may be all that is required because such use is effective and usually would not result in ecological backlash. Examples of such situations include spider mite and grasshopper outbreaks associated with drought in the upper Midwest.

Use of therapeutics in IPM. The ecological objective of therapy is to interrupt ongoing pest population growth and associated injury. The goal of therapy can be achieved either by dampening pest-population peaks or by truncating increasing injury by altering crop exposure to the pest. Dampening pest-density peaks is usually accomplished by proper application of a pesticide to kill pests and/or early harvest to reduce crop exposure. An example of the latter approach is found with dense populations of alfalfa weevil, *Hypera postica* (Gyllenhal) (Coleoptera: Curculioidae), in alfalfa stands with advanced growth. In this instance, early cutting, which terminates further foliage loss, is often economically advantageous (Wedberg et al. 1980).

For key insect pests, therapeutics is envisioned as being used in conjunction with a Preventive PM program (Fig. 3). Here if the preventives fail, therapy serves as a "correction" in the system. In this IPM system, population sampling and consultation of economic thresholds are the primary activities to determine need for the correction.

Several tactics are available for use in IPM therapy. Some of these include selective traditional pesticides, fast-acting nonpersistent biological controls such as microbial insecticides, early harvest, and mechanical removal of pests (e.g., hand picking, pruning infested branches). Of these tactics, traditional pesticides currently are the most practical for IPM therapy.

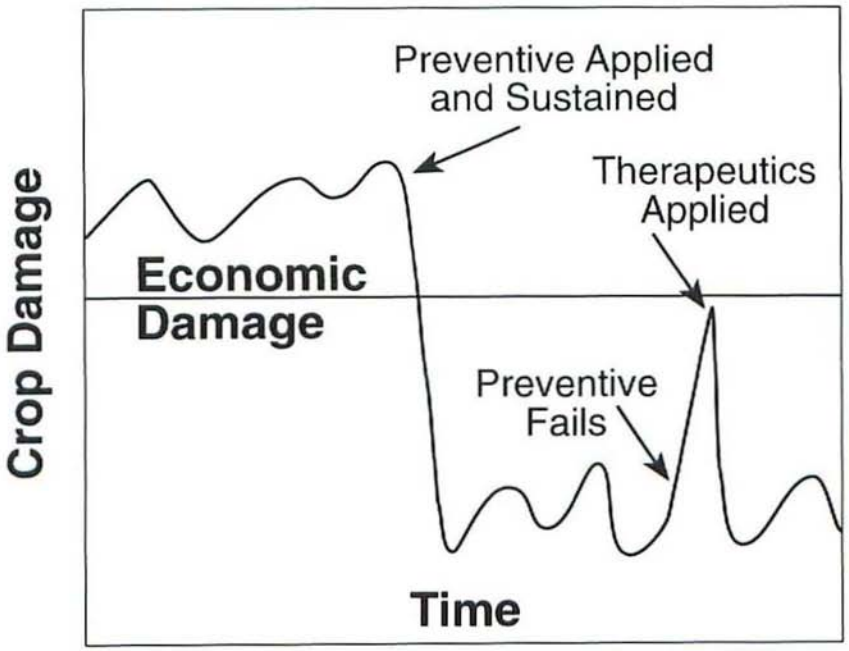

Fig. 3. Use of a pest management program integrating both preventive and therapeutic tactics. Therapy is applied only when preventives fail.

Development of an Integrated Management Program

When IPM is perceived as being composed of both preventive and therapeutic practices, developmental objectives for new programs become sharper, and a much better scheme for combining several tactics emerges. In other words, the establishment of principles for combining tactics becomes clear. These principles suggest that preventive tactics, based on an understanding of pest ecology and pest-plant relationships, be combined as a first-line of dense in the IPM program. Further, should the preventives fail, therapeutic tactics can be incorporated as a second-line of defense.

To develop an integrated program having both preventive and therapeutic elements, a number of steps can be envisioned. The first step would involve identifying potential preventive and therapeutic tactics. A therapeutic program may need to be developed first for early relief from the problem. Following this, tactics need to be tested individually for practicality and efficacy. With this information, mathematical models or, more simply, conceptual models of potential systems can be formulated. Field experiments with the system then can be conducted to determine costs, compatibility of tactics, and overall system effectiveness. Finally, successful programs should be delivered to growers that offer on-farm flexibility and can be tailored to suit individual production practices.

In developing new IPM programs, a special focus on prevention will be necessary. Notably, the more severe the pest, the greater will be the need for effective preventive procedures.

Closing the Gap Between Theory and Practice

Agricultural production faces many crucial issues today. Some of the most significant issues include food safety, ground water contamination, environmental quality, and agricultural sustainability. Because of these issues, the need to close the gap between IPM theory and practice has never been more urgent. Closing the gap will mean a greater dedication of resources and time to pest ecology, as well as a more thorough understanding of insect-plant relationships. But, closing the gap will especially mean that we will have to develop efficient methods for convincing farmers of the benefits of multiple-tactic programs. Perhaps we can be more convincing if our recommendations have a more easily understood and logical basis for integrating multiple tactics.

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IPM Today: Are We Fulfilling Expectations?[1]

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ABSTRACT Since its inception, Integrated Pest Management (IPM) has generated expectations that vary among different groups of people, including the general public, university researchers and extension specialists, and growers. Because growers ultimately implement IPM strategies and tactics, their expectations for IPM are paramount if IPM programs are to be adopted successfully. A series of regional workshops were conducted throughout the United States in 1993. These workshops enabled growers to express their opinions about constraints against adopting IPM and solutions for overcoming these constraints. Research and extension specialists at land-grant institutions should address growers' constraints and solutions by focusing research and extension programs primarily on nonchemical IPM tactics, by strengthening the links among research, extension, and implementation of IPM tactics, and by making a concerted effort to educate the general public about IPM.

KEY WORDS Integrated Pest Management, IPM, pesticide use, corn, soybeans.

To address the question posed in the title of this article, additional questions must be answered first. Who are "we," and whose expectations are "we" trying to fulfill? Within the context of this article, "we" refers to university specialists, specifically entomologists, who conduct research focused upon some aspect of Integrated Pest Management (IPM) and who work with and educate diverse clientele about the principles and implementation of IPM. Many university specialists have accepted a responsibility for seeing that at least some of the expectations for IPM are fulfilled. However, expectations for IPM vary widely among people, depending upon their comprehension of IPM, their experiences, and their level of involvement in implementing IPM practices. For example, a corn grower in central Illinois, an urban pest control specialist in Saint Louis, an apartment dweller in Chicago, and an environmental activist in Washington, D.C., likely have different expectations for IPM. These expectations may range from allowances for substantial use of pesticides to complete elimination of pesticide use. In fact, expectations for IPM among university specialists are also quite divergent. Consequently, the fulfillment of expectations for IPM requires an understanding of whose expectations "we" are trying to fulfill and reasonable evaluations of "our" accomplishments.

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What is IPM? Because IPM is the focus of this article, an explanation of IPM seems warranted. Unfortunately, definitions of IPM are almost as numerous as those individuals who attempt to define it. Several books are devoted to detailed definitions and explanations of IPM, so a thorough accounting of IPM is beyond the scope of this article. However, a definition of IPM may provide a backdrop against which the fulfillment of expectations of IPM can be assessed.

Rabb (1972) defined pest management as the intelligent selection and use of pest-control actions that will ensure favorable economic, ecological, and sociological consequences. More recently, Leslie and Cuperus (1993) stated that IPM combines a comprehensive analysis of the problem and a broad selection of management methods to produce the maximum cost-effective yield for the crop while minimizing adverse effects on human health and the environment. Although these and other definitions of IPM are much broader than mere explanations for the use of pesticides, the use of pesticides inspired the integrated control concept (Stern et al. 1959) and, therefore, virtually all definitions of IPM. Consequently, a change in the amount of pesticide use is usually the measurement of success or failure of IPM programs. Not surprisingly, the use of pesticides is usually the focus of expectations for IPM.

Within this article, although expectations for IPM among different groups of people are stated as opinion, the expectations of growers of agricultural crops will be explored in more detail. Because of the experiences of the author, emphasis is placed upon the expectations for IPM among growers of corn and soybeans in the north central states. However, these expectations are not intended to preclude expectations among other individuals or groups. Expectations for the future conclude the article.

Expectations for IPM

What are the expectations for IPM among the general public? A simple, specific answer to this question is difficult to formulate because, as stated previously, peoples' comprehension of and expectations for IPM vary radically. However, an attitude that the use of pesticides must be curtailed is prevalent among the general public because of the continuing concern and frequent reports in the media about the effects of pesticides on human health and the environment. Consequently, the general public's probable expectation for IPM is a reduction in the amount of pesticides used. Some special interest groups may not be satisfied with IPM until the use of pesticides is eliminated. This latter expectation is difficult for many IPM practitioners to address because virtually all definitions of IPM allow for the judicious use of some pesticides.

What are the expectations for IPM among university entomologists? As is true for the general public, university researchers, teachers, and extension specialists are a diverse group of individuals, so their expectations for IPM also vary. In general, most university entomologists want to advance the philosophy of IPM and encourage implementation of IPM practices allowing for judicious use of pesticides. Although IPM research and educational programs have evolved since their inception and numerous IPM "success" stories have been documented, some entomologists would argue that IPM has reached stasis and

needs to evolve further. These entomologists cite the continued misuse of pesticides as evidence that IPM has not fulfilled its expectations. Other entomologists would argue that the documented reduction in the number of insecticide applications and the amounts of insecticides applied to some agricultural and horticultural crops have fulfilled at least some of their expectations for IPM.

What are the expectations for IPM among individuals who must ultimately implement IPM practices, including growers of agricultural crops and urban pest control operators? Many of these individuals have adopted IPM practices and have altered the manner in which they manage pests. However, continued criticism and scrutiny of pesticide use, even when pesticides are used in a judicious manner, induces a common response from some IPM practitioners: "We are adopting IPM practices. What more do you want?" Is this response appropriate? In some respects, this response to criticism about using pesticides is fitting because there is evidence that growers have reduced their use of insecticides. The number of hectares of corn in Illinois treated with soil insecticides has decreased from 65% in 1978 to 33% in 1990 (Pike et al. 1990). This reduction in insecticide use on corn has occurred primarily because growers have learned to trust crop rotation to manage some of their insect problems, specifically corn rootworms, *Diabrotica* spp. (Coleoptera: Chyrsomelidae), and have reduced their use of soil insecticides on corn planted after soybeans. For decades, many corn growers have applied soil insecticides annually to corn as "insurance" against attack by several soil-inhabiting insects. However, rootworm adults do not oviposit in soybeans and rootworm larvae cannot survive on soybean roots. Therefore, annual rotation of corn and soybeans eliminates the need for insecticides to prevent injury caused by rootworm larvae. As corn growers have learned about this aspect of corn rootworm biology and cultural control, the use of soil insecticides on corn rotated annually with soybeans has declined throughout the north central United States. In Iowa, 56% fewer hectares of corn after soybeans were treated in 1985 than in 1979 (Wintersteen and Higley 1993).

On the other hand, many acres of corn planted after corn are still treated prophylactically with soil insecticides to prevent injury to the root systems by corn rootworm larvae. In 1990, growers in Illinois treated 88% of the hectares of corn-after-corn (Pike et al. 1991). However, results from on-farm research conducted in Illinois in 1990 and 1991 revealed that 30 of 56 trials (55%) did not have rootworm larval injury at or above the commonly accepted economic rootworm injury index (Gray et al. 1993). These data suggest that growers in Illinois continue to apply soil insecticides to prevent rootworm injury in many fields where rootworm densities are insufficient to cause economic losses.

From another perspective, people who campaign against the use of pesticides have referred to the number of hectares of soybeans in the north central United States that were treated in 1988 to control twospotted spider mites, *Tetranychus urticae* Koch (Acari: Tetranychidae). During that severe drought year, 1.4 million ha (3.5 million acres) of soybeans in Illinois alone were treated with miticides (Pike et al. 1990). Unfortunately, the number of hectares of soybeans treated with insecticides or miticides in 1988 is frequently taken out of context. During more typical years in Illinois, less than 1% of approximately

4.05 million ha (10 million acres) of soybeans are treated with insecticides (Pike 1985, Pike et al. 1991).

Soybeans were treated for control of twospotted spider mite in 1988 in response to real infestations detected by monitoring the fields. Adoption of field scouting has been heralded as a measure of success for the implementation of IPM. In fact, one perception among many people is that if more hectares of crops were scouted for pests, fewer hectares would be treated with pesticides. Wallace (1993) stated that a major benefit of IPM has been the increase of private agricultural consultants in the United States. Unarguably, scouting is a principal strategy in IPM programs. However, scouting may be a two-edged sword. Growers in Illinois do not treat many hectares of corn that have infestations of European corn borers, *Ostrinia nubilalis* Hübner (Lepidoptera: Pyralidae), that would economically justify control activities (Briggs and Guse 1986). An increase in scouting activity would disclose economic infestations of corn borers, possibly resulting in more hectares of corn being treated with insecticides.

Understanding Expectations of Growers for IPM

Both agricultural and urban pest managers have expectations for IPM. However, this article focuses on agricultural pest management to illustrate these expectations and how researchers and extension specialists can help pest managers fulfill expectations.

University researchers and educators can help growers implement economically viable pest management strategies and tactics that are socially acceptable to the general public by first understanding the expectations of growers for IPM. Additionally, growers need to understand and accept the benefits of IPM before they will be willing to implement its strategies and tactics. Some recent surveys of growers and their levels of understanding and practice of IPM may shed some light on growers' expectations for IPM.

Several surveys of growers of different crops demonstrated that most growers use some IPM tactics on their farms (Sorenson 1993a). However, many growers are unaware that the tactics are or can be linked under the auspices of an IPM program. In other words, growers do not necessarily associate practices with an IPM program. Sorenson (1993a) also concluded that the definition of an "IPM-grower" is not standard. Some self-proclaimed IPM-growers utilize two or more IPM-tactics on their farm, while others implement a fully integrated program (refer to Sorenson (1993a) for a more detailed explanation of types of growers and criteria for IPM programs).

The rate of adoption of IPM among growers also may be interpreted differently, depending upon the definition of IPM used. Most growers adopt tactics that best fit their current management systems, gradually incorporating more tactics as long as profit and confidence are maintained. This type of piecemeal adoption of IPM eventually leads to crop production systems in which pest management tactics are integrated with other crop management decisions. Growers who indicated on the survey that they use IPM stated they are not unique and that implementation of IPM is mostly common sense. They indicated that growers who do not practice IPM can and will do the same when

they are equally convinced that IPM can save them money and time (Sorenson 1993a).

In 1993, university scientists and Environmental Protection Agency (EPA) representatives throughout the United States listened to growers express their opinions about IPM. Five regional workshops, entitled *Constraints to the Adoption of Integrated Pest Management*, were held at Monterey and Fresno, California; Bloomington, Illinois; Gettysburg, Pennsylvania; and Lubbock, Texas. Each workshop focused on a different set of commodities, fruits and vegetables in California, corn and soybeans in Illinois, apples in Pennsylvania, and cotton in Texas. At each of these workshops, EPA representatives and scientists listened to growers identify constraints to the adoption of IPM and propose solutions to overcome those constraints to initiate implementation of IPM practices.

The constraints against the adoption of IPM identified by the growers were numerous and could not be listed within this article. Fortunately, all of the constraints and solutions are listed and discussed in some detail in a summary of outcomes of the workshops (Sorenson 1993b). However, despite the geographical differences and the diversity of commodities focused upon at the workshops, several constraints identified by growers were virtually identical among at least three of the workshops. The top five constraints against growers adopting IPM were a lack of incentives (economic benefits of IPM did not justify increased demands), differing agendas and conflicting messages from governmental agencies, loss of funding for applied research, lack of adequate funding for IPM education and research, and government-sponsored commodity programs that discourage crop rotations. A lack of effective marketing and promotion of IPM, slowness of EPA pesticide registration, lack of availability of pesticides thereby limiting flexibility, and problems with the Delaney Clause restrictions that limit pesticide availability were also listed as common constraints among geographical regions and growers of different crops.

At the workshop in Illinois, some unique constraints and solutions were identified. Several of the constraints identified by growers had the same solutions, most of which involved improved education about IPM. Growers attending the Illinois workshop indicated that low profit margins in corn and soybeans and the inability of growers to pass along costs to others provide little incentive to adopt IPM. They suggested that this constraint could be overcome, at least partially, if university researchers and extension specialists demonstrated IPM practices that include economic benefits. Other constraints associated with the low profit margins for corn and soybeans were that economics sometimes favor prophylactic application of pesticides and that farm managers and landlords have unreasonable expectations, so the pressure to treat fields with pesticides hinders the adoption of alternatives. The growers attending the workshop suggested that both they and farm managers needed to change their attitudes about inputs as suitable replacement for better management. The growers also identified a need for more scouts, better training of scouts, and less labor intensive methods of scouting. Their suggested solution for this constraint was improved technology and tactics that make IPM more efficient. Finally, growers indicated that fertilizer and chemical dealers have an insufficient level of education about IPM. Their

suggested solutions were to improve the education of pesticide dealers, make advertising of pesticides more accurate and honest, and improve the education of farmers and farm managers.

Randy Dickhut, a grower from Camp Point, Illinois, offered another list of constraints against the adoption of IPM and solutions to overcome the constraints, gleaned from the growers who attended the National IPM Forum in Washington, D.C., in June, 1992. He indicated that growers want to be more involved in IPM research and educational programs, a practice that would foster better communication. Growers also want more proven and cost effective pest control tactics, supported by more research and educational programs. Farm visits by government officials and regulators would help inform their discussions and decisions related to IPM on the farm. Growers also indicated that they need to change their attitudes and adopt a willingness to try new things. Growers also want to be given sufficient time to change their practices.

The Future for Implementation of IPM

After university researchers and extension specialists have listened to the opinions of growers about constraints against adopting IPM practices and solutions for overcoming those constraints, they should ponder the future of their own programs. Entomologists in land-grant institutions should emphasize biological control, host resistance, and cultural management as primary pest management tactics. The use of pesticides should be suggested only after all nonchemical alternatives have been explored. Recommendations of pesticides to use should be made within the context of environmental and user safety.

University entomologists also need to make a concerted effort to educate the general public about IPM. Although most individuals involved with agriculture understand the principles and concept of IPM, most of the nonagricultural public does not understand IPM. However, they can relate to pests that attack structures in which they live and the landscapes that surround them. Wallace (1993) has suggested that we should focus on urban-IPM programs, possibly by establishing a national initiative in urban-IPM. The understanding of the general public and their participation in urban-IPM programs would enhance efforts to educate them about IPM in general. An understanding of IPM in urban areas should foster greater acceptance of IPM practices in rural areas.

Links among researchers, extension specialists, and growers need to be strengthened (Steffey and Gray 1992). Better cooperation among these groups would foster equitable involvement in all phases of problem identification and resolution. Many growers, particularly those involved in sustainable agriculture movements, believe that they are not adequately involved in the research and implementation process. Scientists at land-grant institutions need to re-examine their traditional roles and move toward a more appropriate partnership among research, extension, and implementation. Delivery of information must be an equal priority with development of IPM programs.

Have "we" fulfilled expectations for IPM? Depending upon the perspective of whoever answers this question, the answer could be either yes or no. If the expectation for IPM is the elimination of pesticide use, the answer is no.

However, if the expectation for IPM is for more judicious use of pesticides, some optimism is warranted. Some evidence suggests that IPM is delivering on its promise to reduce the unnecessary use of agricultural chemicals. However, growers of agricultural crops continue to rely upon pesticides as a primary pest control strategy. The adoption of more nonchemical pest management tactics and strategies by growers and their endorsement of the IPM concept will require more time. IPM will be adopted by today's well trained and concerned growers if IPM programs are focused upon the practical needs to run a profitable business. Growers are the key to successful implementation of IPM programs. They must overcome their natural conservatism and skepticism (Sorenson 1993a) before they implement IPM tactics and strategies that are effective, economical, and will satisfy the general public.

"We" have fulfilled some of the expectations for IPM through research and educational programs that address both economical and environmental concerns. Growers have fulfilled some of the expectations for IPM by reducing the amount of pesticides they apply to some crops. However, even greater expectations for IPM are apparent. Only through continued research, educational programs, and cooperation with those who implement IPM tacitcs will "we" ever achieve our expectations for IPM, whatever those expectations may be. Our dedication to this process may convince most of the general public that IPM will fulfill their expectations.

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Components of the Economic Injury Level[1]

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ABSTRACT Results from the Grasshopper Integrated Pest Management (GHIPM) project are used to demonstrate the agreement between agricultural economists and entomologists on the economic injury level (EIL) concept. Further, including non-chemical control management options in evaluations of the EIL in Integrated Pest Management (IPM) approaches is discussed. Measures of costs of economic externalities are made and methods to incorporate such costs into an environmental EIL are shown. The EIL is shown to be dependent on a number of economic, biological, and physical factors.

KEY WORDS Integrated Pest Management, IPM, economic injury level, benefit/cost ratio, economic externalities, environment costs

Entomologists have long applied the concept of an economic injury level (EIL) with respect to pest populations (Stern et al. 1959). Since response may not be instantaneous to pest populations that reach the EIL, the economic threshold (ET) is defined as the level of pest population necessary to initiate control actions. Depending on the pest, the time necessary to obtain pest population information, its population dynamics, and the predictability of the pests' behavior, the ET may be variably different from the EIL, depending on the insect species. For rangeland grasshoppers, the pest control problem of concern in this paper, the difference between the ET and EIL is only a few days.

More recently, economists involved with integrated pest management programs have contributed to the economics of pest control (Headley 1972a,b). Applying marginal economic analysis, Headley (1972a) redefines the ET to be the pest population that produces incremental damage which is just equal to the incremental cost of preventing that damage. Headley's (1972a,b) definition of the ET is identical to what entomologists define as the EIL. Economic damage may be occurring at pest populations less than the ET, but the damage is less than the cost of control. Similarly, at pest populations exceeding Headley's (1972a) ET, the incremental economic damage exceeds the incremental cost of control and economic losses result if control does not occur. The end result of applying marginal economic analysis is that there is an optimum level (density) at which to treat a pest population. This density is the population which defines the ET.

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Pedigo and Higley (1992) summarize the primary variables to define the EIL as, EIL = C/V*I*D*K, where C = cost of the management tactic per production unit, V = market value per production unit, I = injury units per pest, D = damage per injury unit, and K = proportional reduction in pest attack. This definition recognizes that the EIL is not a discrete pest density, but is variable depending on control costs, the value of the production protected, production losses per pest, and the efficacy of the control. Pedigo and Higley's (1992) reference to unit measurements for the parameters defining the EIL indicates that by equating the incremental costs of control with the incremental benefits gained from control, as argued by economists, the concepts of economic entomology and economic analysis have come together. Pedigo and Higley (1992) distinguished between pest density and the damage caused by pests. It should be noted that estimate of damage caused by pests rather than pest density is especially important for grasshoppers. Variation in food preferences occurs among species of grasshoppers and within species because grasshoppers vary in size and the heartiness of their appetites. Therefore, damage to forage resources are only indexed to grasshopper densities.

With the increasing attention given to environmental protection, food safety, and human health, Integrated Pest Management (IPM) concepts must be included in the determination of the EIL. Integrated Pest Management poses some added considerations to the estimation of the EIL. Under most definitions, IPM involves substitution of information for pesticide applications, recognizes costs of pest control beyond the direct chemical and application costs, and requires consideration of management options to reduce the necessity for chemical treatment. In many cases, IPM increases the EIL density of pests necessary to apply treatments. Analyses taken from the Grasshopper Integrated Pest Management (GHIPM) project are used to demonstrate applications of economics to pest management.

This paper demonstrates the applications of marginal economic analysis to the calculation of benefit/cost (B/C) ratios for control of rangeland grasshoppers, demonstrates the definition of the EIL advanced by Pedigo and Higley (1992) to estimate the B/C ratios, including consideration of some non-treatment options available to the producer, and presents an application of the procedure discussed by Higley and Wintersteen (1992) to measure some of the environmental costs associated with pest treatment.

Benefit/Cost Ratios and the EIL

The EIL is defined when incremental benefits (B) are equal to the incremental costs of control (C) or when B/C = 1. Benefits are measured as the reductions in income avoided (damages abated) by application of the treatment to control the pest population. The costs are the unit cost of treatment.

Although the analytical demonstrations are drawn from the GHIPM project and publicly assisted programs to control grasshoppers on public lands, the approach has potential for broader pest management applications. If issues of the incidence of benefits and costs (who pays and who benefits)

are considered, pest management on public lands can add some complications to the analysis. However, if it is sufficient to establish the EIL on measured benefits and costs regardless of who benefits and who pays the cost, the approach is directly applicable to other pest management cases.

The GHIPM project facilitated the development of a decision support system, termed Hopper, to provide information to rangeland grasshopper control program and public land managers regarding the economic justification for implementing control treatments (Davis et al. 1992). The economic justification is based on the economists' concept of an ET, as defined by Headley (1972a,b). Hopper includes three components. The first component, RangeMod, simulates range forage production (Berry and Hanson 1991). Given a soil and range type, RangeMod considers climatic variables to simulate the amount of grazable forage available to all potential users of range forage. The second component, HopMod, is a grasshopper population dynamics model which determines the effects of grasshopper infestations on range forage availability (Berry et al. 1995). It is based on the observed response of grasshoppers in rangeland and laboratory environments. It considers the amount of forage eaten or destroyed by grasshoppers by species, life-stage, and temperature (Kemp and Onsager 1986, Hewitt 1978, Hewitt and Onsager 1982, Parker 1930). HopMod also estimates natural mortality of grasshoppers according to their population density (Onsager 1983).

As one of five approved treatments are applied, HopMod includes the established efficacy of each treatment corresponding to canopy cover, grasshopper species, and the timing of application. HopMod and RangeMod interact to determine the treatment appropriate for the conditions encountered and determines the amount of grazable forage available with and without each treatment.

The third component of Hopper is RanchMod, an economic decision model for a typical ranch. Typical ranches have been defined within each important range type which reflect the modal type of ranching situation. A typical ranch is characterized by modal practices with respect to livestock species, livestock management system, forage use, ranch size, and technology applied. These typical ranches serve as barometers of the impacts of grasshoppers and their control on the majority of ranches in the area. RanchMod models the management decisions on the typical ranch in response to changes in the availability of grazable rangeland forage. For example, an infestation of grasshoppers which reduces the availability of range forage will require adjustments in the ranch's operations. Each of these adjustments may occur at some cost or reduction in net returns to the rancher. However, if treatments are applied and grasshopper populations suppressed, damages to rangeland forage and, hence, reductions in ranch net returns will be prevented. Differences in ranch net returns with and without pests are the estimated benefits of controlling grasshoppers. The damages or prevented reductions in ranch net returns which are abated is estimated as, $DA_{t,d,c} = NR_{t,d,c} - NR_{o,d,c}$, where DA = damages abated (net income loss prevented) on a typical ranch and NR = ranch net returns for t = treatment, d = grasshopper density, c = climatic condition, and o = no treatment.

The costs (C) to apply the alternative approved treatments are taken from the recent experience of those implementing control programs. Commercial applicators bid on a per hectare basis. Bids take account of ingredient costs, application costs and size of the area to be treated. Bids may also be dependent on the terrain and the other demands for the applicator's services.

For rangeland grasshopper control programs, marginal costs tend to be constant at the per hectare bid price. The benefits, measured as damages abated on a typical ranch and expressed on a per hectare basis, tend to increase with grasshopper densities. The shape and position of any particular B/C ratio curve depends upon rangeland productivity, adjustment options available to the rancher and their costs, the amount of forage eaten or destroyed by the grasshopper species mix present, and the efficacy of the treatment.

Linking RangeMod, HopMod, and RanchMod through Hopper provides a decision support system which captures the critical elements in the range forage-grasshopper-ranch system. By varying the density (number of grasshoppers counted per square meter, GH/m^2) of grasshoppers of a given species mix, damages to range forage are estimated and used in a B/C ratio for each grasshopper population density and each of the treatment alternatives. Using the Headley (1972a) criteria of equating marginal benefits to marginal costs, the economic threshold is calculated for the optimal density at which grasshopper control should occur, which is when the B/C = 1 (Fig.1). The marginal benefits of the treatment are determined to be less than the marginal costs if the B/C < 1 for any treatment. The marginal benefits exceed the marginal costs of treatment if B/C > 1 which indicates that the economic losses will occur which are in excess of control costs.

Management adjustments. Hopper includes each of the important variables discussed by Pedigo and Higley (1992) plus some IPM options available to the producer. Consistent with the IPM concept, RanchMod, the economic decision component of Hopper, considers non-treatment management adjustments to cope with a pest invasion as alternatives to treatments. For example, while calculating the B/C ratio for a particular grasshopper density and treatment option, RanchMod considers ranch management options to adjust to reduced forage availability. Ranchers may lease other lands for grazing their livestock, they may sell their annual produce (calves, yearlings, culls) at an earlier date, they may cull their herd to smaller numbers, and/or they may develop harvested forage (hay) supplies to supplement variable supplies of grazed forage. While each of these options may be more costly or produce a smaller net return than the management plan employed, they may be less costly than options to implement grasshopper control programs. The livestock and forage management adjustments mentioned above may be available to a rancher. In the context of annual cropping, non-control program options may include use of pest resistant crop varieties that may have reduced yield potential, altering planting date to minimize exposure to a pest, and/or implementing other cultural practices, such as rotations, which are found to limit the incidence of pests reaching their EIL.

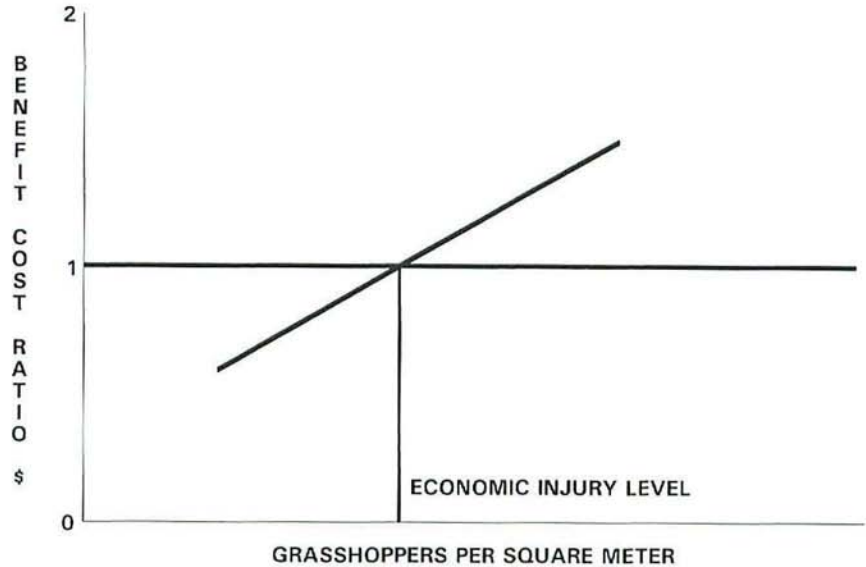

Fig. 1. Benefits and costs in relation to pest population and resulting B/C ratio.

Environmental costs. Applying IPM strategies requires that environmental costs applied as an environmental EIL (Pedigo and Higley 1992) be an explicit part of B/C calculations. Higley and Wintersteen (1992) suggest a procedure by which environmental costs or environmental risk assessments can be evaluated. The GHIPM project has applied this procedure. Given the potential damage to non-target species, the ecosystem may be adversely affected by treatments to reduce grasshopper populations. Throughout the GHIPM project, environmental monitoring has been conducted to identify any adverse effects of treatments applied on rangeland breeding bird populations (George at al. 1995, McEwen et al. 1991). In addition, economic evaluations have been made of the environmental costs associated with the potential damage to non-target species from grasshopper control programs (Kitts 1992). Kitts (1992) developed a procedure to estimate the economic effects of grasshoppers and grasshopper control programs on the amount of consumptive and non-consumptive wildlife-associated recreation of effected rangelands.

The contingent valuation method applied by economists is suggested by Higley and Wintersteen (1992) as a method to evaluate environmental costs. Contingent valuation involves determining the willingness to pay by an appropriate subpopulation for some environmental amenity. The technique

is becoming widely accepted among economists. Contingent valuation estimates for a population, which desires a particular environmental amenity, the willingness to pay for that amenity by that population. It is primarily used for estimating economic value of benefits for which no market values exist. Care must be taken to define the geographic and socioeconomic characteristics of the population to query about their willingness to pay for environmental amenities. Further, the survey of willingness to pay must place the willingness to pay for environmental amenities in the context of other relevant expenditures from a limited budget.

The effects of grasshoppers on wildlife and wildlife associated recreation is only one of many potential effects of grasshoppers on the environment. Severe grasshopper infestations may result in loss of rangeland productivity, increase soil erosion, and threaten water quality. An economic value or cost is placed on these losses if the environmental monitoring component observes a decline in population of wildlife species. The valuation process applied contingent values estimates to wildlife associated recreation. Both consumptive (hunting and fishing) and nonconsumptive (hiking, bird watching, and photography) wildlife associated recreation are considered. Consumption and nonconsumption forms of wildlife associated recreation have no market values. The contingent valuation technique determined the willingness to pay for the opportunity to participate in wildlife-associated recreation by individuals participating in those activities.

The recreation values applied were estimated by Hay (1988a,b, U. S. Department of Interior Fish and Wildlife Service 1988). Hay's (1988a,b) estimate of the willingness to pay is expressed as a net economic value; a net economic value is defined for each category of wildlife-associated recreation.

Given the net economic values, the next step is to estimate the probability and extent of participation in wildlife-associated recreation in response to changes in the wildlife resource base. Using data from the 1985 Survey of Fishing, Hunting, and Wildlife-Associated Recreation, Kitts (1992) derived equations to predict the probability of participation in wildlife-associated recreation in relation to the extent of the wildlife resource base and a number of social and economic variables. Those probabilities were derived for a region involving eight states in the northwestern U.S., the region to which Hopper has been applied. Fewer people will participate in that recreation and those who do participate may recreate less if a rangeland grasshopper control program results in degradation of the wildlife resource base which is used for recreation.

The economic loss from less wildlife-associated recreation is found by multiplying the reduction in days of participation by the net economic value per day of participation. Reductions in total net economic value is a measure of the potential environmental costs of a grasshopper treatment program.

Environmental monitoring under the GHIPM project has not identified a significant effect of grasshopper treatments on breeding bird populations (George et al. 1995). Thus, there is no empirically justified basis to say that wildlife populations important to recreation will be diminished by grasshopper treatments. Even though the procedure to estimate wildlife recreation values is developed, the environmental costs have not been

incorporated into Hopper since the link between grasshopper treatment and the wildlife base has not been observed.

If linkages between pest control and wildlife damage were present, the potential non-treatment adjustments available to managers responding to pest outbreaks could be recognized in the evaluation of benefits. Instead of applying the chemical or biological treatments necessary to reduce the pest population, it may be less costly and more friendly to the environment to take advantage of pest resistant varieties, cultural practices, or management systems that offset the impacts of the pest. Furthermore, environmental values can and should be explicitly included in the B/C ratio calculations (Higley and Wintersteeen 1992). Net economic benefits as derived by the contingent value method can be used to quantify some of the environmental costs.

Results and Discussion

Including producer-initiated, non-chemical treatment management strategies in the pest control decision effects the ET for controls. Use of such strategies could be part of an IPM practice. The example is taken from analyses of a typical ranch in the northern Great Plains. Such a ranch utilizes public grazing lands for a portion of its rangeland forage. The typical ranch has about 200 cows; male calves and female calves, which are not kept for herd replacements, are sold annually along with the cull cows and bulls. About 68% of the grazed forage comes from pubic lands and the balance, 32%, is from privately owned lands.

Observe the B/C curve in Fig. 2 labeled "Base." The Base curve considers use of only those livestock and forage use practices applied in a normal year. The ranch relies only on grazed forage from the land base that is immediately available. The EIL for the most cost-effective control option, malathion spray, is found at a density of about 14 GH/m^2. The choice of approved treatment options is determined by the physical and biological conditions prevailing as well as economic considerations. For example, malathion is not as effective with a dense canopy of vegetation nor if the air temperature is cool. Some grasshopper species feed only on grass, hence, bait treatments are not effective. For other treatment options (not shown), densities necessary to make the B/C = 1 are greater due to higher per acre treatment costs and/or lower or more delayed grasshopper mortality rates.

The IPM management options available to the typical ranch are based on interviews of ranchers in the area. Since each year's offspring are sold as calves, there are no forage saving herd management options available such as shifting from cow-yearling to a cow-calf livestock management system. Ranchers can and do produce hay and lease other grazing land if supplies of grazable forage on the ranch are not sufficient. Hay produced on the ranch is primarily used as a supplemental feed during the winter months. In addition, ranchers have the option of purchasing hay. Another strategy is for ranchers to expand their hay production beyond their anticipated winter needs and hold it as a forage reserve for unexpected short-falls in grazable forage. Each of these forage replacement options are evaluated with Hopper.

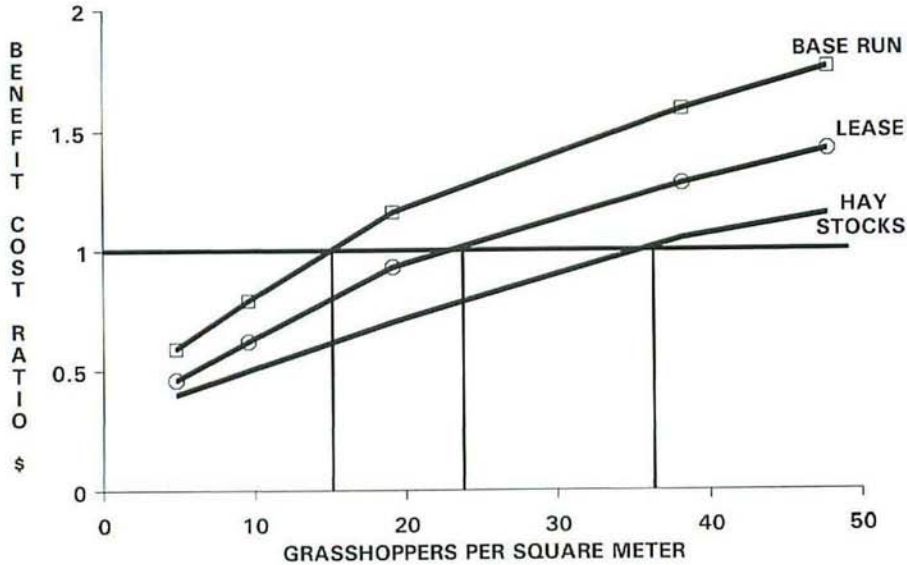

Fig. 2. Effect of non-treatment management adjustments on the EIL for a northern plains ranch for base, land leasing, and maintaining hay stocks cases.

In Fig. 2, the curve labeled "Lease" shows what happens to the B/C ratio for the malathion treatment if other rangelands are leased to offset the forage reduction from grasshoppers. The B/C = 1 at 23 GH/m^2 when the IPM option of leasing other grazing land is considered. It is less costly for the rancher to lease other grazing land than it is to initiate malathion treatment programs at 14 GH/m^2. Only when grasshopper densities exceed 23 GH/m^2 is the EIL for malathion reached.

Another option available is for the rancher to produce more hay to maintain hay stocks for feeding in case grasshoppers reduce grazable forage. For example, suppose hay production by is increased by 20 percent and hay stocks are maintained on the typical ranch. Use of this IPM forage management option, shown as "Hay Stocks" in Fig. 2 increases the EIL to 33 GH/m^2.

The EIL varies depending on the options available to the livestock producers. It is important to remember that what may be an option to one or a few ranchers may not be an option during an extensive outbreak of grasshoppers. For example, the option to lease grazing lands may not be available in a major infestation of rangeland grasshoppers because grazing lands over a wide area would be affected.

The EIL also varies with the climatic conditions. Precipitation and temperature can vary greatly from year to year and are primary determinants of range forage production. In a year which has less than normal precipitation, forage is more scarce and hence, more valuable. In our example, the EIL was 23 GH/m^2 when the alternative of leasing alternative grazing lands was considered. The EIL decreases to 19 GH/m^2 (not shown) if the grasshopper infestation occurs in a year which is about 20% dryer than normal.

Environmental externalities can be quantified and included in the EIL measure. Kitts (1992) found both hunting and nonconsumptive wildlife associated recreation participation to be responsive to changes in the wildlife resource base. The analysis would be improved by direct measurement of the effect of the control programs on wildlife populations. Consistent wildlife population data across states are not available. Consequently, the area of wildlife habitat subject to control programs is used as a proxy for wildlife populations. However, since wildlife populations were not found to be affected by grasshopper control programs, more careful measurement of wildlife populations would not influence the results. The probability of participation in these wildlife derived recreation activities varies with changes in the extent of the wildlife resource within an eight-state region of the northwestern U.S. For hunting, a 1% reduction in range habitat for wildlife results in a 3.2% reduction in participation in hunting. Similarly, a 1% reduction in the range habitat of wildlife results in a 2.9% reduction in participation in nonconsumptive forms of wildlife associated recreation. Kitts (1992) did not find participation in fishing to vary with changes in the fishing resource base.

Applying Hay's (1988a,b) net economic values to estimates of changes in participation, Table 1 shows how participation, expenditures, participation days, and net economic value varies with that in the wildlife resource base. Estimates are shown for both hunting and nonconsumptive wildlife-associated recreation activities.

Rangeland grasshoppers are potentially a two-edged sword for wildlife recreation. Serious infestations of grasshoppers could destroy cover for ground-nesting birds, ground dwelling mammals, and large game animals. Wildlife populations could be reduced by uncontrolled grasshopper outbreaks. Alternatively, grasshopper treatments are toxic to non-target insect species which may be critical components of the food chain of birds and mammals. Further, the chemicals applied may be toxic to the wildlife species which are contacted by chemicals. The GHIPM environmental monitoring has found no deleterious effects on wildlife from grasshopper treatments. Consequently, only the potential exists for linkage between grasshopper control and wildlife populations. If the linkage between resource depletion and/or grasshopper treatments and wildlife is established, the net economic value estimates in Table 1 can be expressed in per hectare terms as are other benefits and costs of grasshopper control programs and incorporated into the EIL calculations.

Table 1. Influence of variation in hunting and nonconsumptive wildlife associated recreation on number of participants, expenditures, participation days, and net economic value for eight northwestern states.

Wildlife Resource Level and Activity	Number of Participants (1,000)	Trip-Related Expenditures (million $)	Participation Days (1,000)	Net Economic Value (million $)
Hunting				
Base level	790	$191.2	11,847	$355.4
1% decline	-25	-6.1	-371	-11.1
Nonconsumptive				
Base level	1,501	$253.7	15,009	$330.2
1% decline	-43	-7.3	-429	-9.4

Conclusions

While it has not always been so, economists and entomologists have the same working definitions for economic injury levels for pests. Further, both disciplines are struggling together to find ways to account more completely for the costs and benefits of pest management strategies. A particular goal is to reduce chemical pesticide use and evaluate the often external environmental costs associated with pesticide use. The operating EIL concepts for the two disciplines are shown to be the same. Further, it has been shown within the context of IPM how non-treatment options, which may be available to the producers, can affect the EIL. Finally, a method to evaluate some of the environmental costs of pests and their control was demonstrated.

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Integrated Pest Management Systems: Back to Basics to Overcome Adoption Obstacles[1]

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ABSTRACT Adoption of Integrated Pest Management (IPM) practices into agricultural programs and the constraints affecting adoption are topics that have been addressed since the mid-1970s when the implementation of agricultural IPM programs began. Adoption has never occurred at the levels hoped for and the constraints slowing this process have been well reviewed by many authors. The purpose of this work is to highlight the primary obstacles to IPM adoption and discuss solutions that could bring about positive change. As the title implies, these solutions are not new, but basic to implementation of any innovative system or change. With a new focus on these basic solutions, it is hoped that those involved with IPM may be reminded of their importance and reemphasize them in the planning, development, and implementation phases of programs.

KEY WORDS Integrated Pest Management, IPM, adoption, constraints, solutions

The Problem

The rate and degree of adoption of Integrated Pest Management (IPM) systems by intended users continues to be a frustration for those associated with the development and implementation processes. Slow or poor adoption rates are eroding further with many farmers backsliding and reverting to previous non-IPM practices, a process of gradual decay besetting many innovative programs that Whalon and Croft (1984) termed "implementation entropy." Evidence for slow adoption can be found throughout the U.S. and affects many commodities, e.g., apples in New York (Whalon and Croft 1984), cotton in Texas (Stoner et al. 1986), peanuts in Georgia (Musser et al. 1986). The purpose of this paper is to highlight the primary obstacles to IPM adoption and discuss solutions that could bring about positive change.

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The Obstacles

Technical, financial, social-marketing, educational. Many constraints hamper or prevent adoption of IPM practices. Wearing (1988) surveyed more than 150 research and extension specialists in four countries. He used this survey to classify constraints into four general categories, technical, financial, social-marketing, and educational. Wearing (1988) found the most important technical constraints to be lack of simple pest monitoring devices and methods, lack of applicable economic thresholds, lack of selective or IPM-compatible pesticides, and the existence of cosmetic quality standards which result in downgrading the value of the crop produced for small amounts of pest damage.

Major financial constraints listed were lack of short-term profit for IPM users, increased labor costs, low cost of chemical control, and shortage (or lack) of extension-funds for sustaining implementation processes (Wearing 1988). Constraints in the social-marketing category included the general resistance to change, lack of grower confidence in IPM alternatives, and grower satisfaction with existing chemical control. Wearing (1988) further explained that satisfaction with chemical control was enhanced by the high ratio and accessibility of chemical sales personnel in relation to extension personnel, the advanced marketing skills of chemical companies, and growers' experience, confidence, and satisfaction with chemical pesticides.

Educational constraints, also referred to as organizational constraints (McNamara et al. 1991), have been found in all phases of IPM programming, from development through adoption. They include lack of interdisciplinary collaboration within agricultural-related disciplines during the development phase, lack of planning for the implementation phase, a shortage of scouting services-personnel, and a shortage of trained on-site extension personnel for implementation and maintenance phases (Wearing 1988).

Complexity. Complexity also has been presented by several IPM specialists as a major constraint to adoption of IPM (Lambur et al. 1985, Stoner et al. 1986, Wearing 1988, McNamara et al. 1991). McNamara et al. (1991) stated the following in their definition of IPM, "IPM is a systematic approach to crop protection using increased information to make better pest management decisions." Their discussion implies that the complexity inherrant in this information-based system may be both the most important strength as well as weakness of the IPM paradigm. Although integration of complex information allows development of holistic and more sustainable pest management programs, the difficulty of integrating this information impedes progress at several levels. The development process of IPM is slow, however ambitious the scientists involved, because of the complexity of agroecosystems and the almost unlimited number of possible interactions (Lambur et al. 1985).

In addition to biological complexity, successful IPM programs also must encompass a comprehensive view of the entire production system, including the technological, commercial, social, political, and economic aspects (Stoner et al. 1986). Complexity also impacts adoption because the end user is often required to process large amounts of information. Although many computer

programs have been developed to aid in this decision-making process (e.g., Herbert et al. 1987), programs often incorporate such large quantities of complex and diverse information that their operation can be difficult and time-consuming for the user.

Perceived risk and lack of trust. Perceived risk and lack of trust also are cited as major constraints to IPM adoption. A shift to IPM represents adoption of new technology whose association with risk is a natural response. In summarizing literature concerning adoption of IPM technology, Musser et al. (1986) and McNamara et al. (1991) conclude that growers perceive information that is different from original beliefs as having risk. For example, Wearing (1988) states that risk associated with implementing the IPM scout-treat-as-needed alternative, rather than using conventional treatments and spray schedules, constituted a major obstacle to IPM in all regions surveyed. Many growers view pesticide treatments as "insurance" against the risk of loss (Stoner et al. 1986). Changing attitudes of growers has proven difficult even when pesticide treatments have not resulted in economic gains.

Lack of convincing information. Another constraint to IPM adoption is the lack of convincing information that IPM works (Musser et al. 1986, Wearing 1988, McNamara et al. 1991). Growers' doubt and perceived risk associated with changing to a new technology must be overcome by providing access to information through a number of media that presents clear, accurate, and convincing data demonstrating advantages over the standard practice. McNamara et al. (1991) concluded that this lack of convincing information constituted a major constraint, especially regarding the information required to integrate IPM into current management practices.

Lack of incentives. Finally, lack of incentives to use IPM has been identified as an important constraint to IPM adoption. Poor or poorly defined incentives affect both development and implementation of IPM practices. Incentives for development of IPM programs by industry have been hampered. To ensure adequate investment return, the product or practice must be patentable, marketable, and registrable, i.e., with the United States Environmental Protection Agency. These conditions do not fit most multifaceted IPM approaches to pest management. Incentives for adoption of IPM also are lacking and difficult to develop, for they must compete with the entrenched experience with pesticides that are easy to use, provide highly visible results, and achieve high and predictable levels of pest control.

New "Old" Strategies to Improve Adoption of IPM

Fit, collaboration, funding and "good old-fashioned extension." Many authors have put forth suggestions for improving or maintaining current levels of IPM adoption. Wearing (1988) specifies four key principles of successful adoption of IPM, fit, collaboration, funding, and "good old-fashioned extension." For adoption of innovative IPM practices to proceed, they must fit the intended users. In addition, analysis and improvement of the user-fit must begin early in the research and development stages. Programs of IPM must first, and perhaps foremost, satisfy a need by offering

a clear advantage to the standard or old practice. Programs must fit the perceptions, resources, and constraints of intended users. Programs must be modified to satisfy a multitude of local conditions including growers' requirements, such as equipment, irrigation constraints, and /or rotation practices, as well as local climate, marketing strategies, financial and political climates, and labor constraints.

A high level of collaboration and cooperation among all groups affected by IPM programs is critical to successful implementation. The chances for success increase when cooperative teams are comprised of representatives from funding agencies, administration, research, extension, and the intended user group. It is especially important to encourage involvement with, and continual feedback from the intended users.

Funding, a key to any program, must be available for the development, implementation, and maintenance of IPM programs. Wearing (1988) specifies that distinct financing for implementation has been a severe shortcoming for IPM programs. Lack of funds for extension personnel and programs has been a traditional problem that continues to decline as states reduce funding for research and extension.

The importance of what was termed "good old-fashioned extension" was emphasized by Wearing (1988) as necessary for successful implementation of IPM. Increased availability of trained extension specialists was viewed as one of the most critical ways to improve IPM adoption. Although expensive, one-on-one verbal exchange with support from other methods is most influential in gaining and nurturing the confidence of users while providing the continued support necessary for promotion of new IPM programs. Maintaining this level of contact requires research and development to take place on the user's site. Knowledgeable support personnel should be continually accessible to users to whatever extent is feasible.

Emphasize incentives and improve communication of information. Another important attribute for successful promotion of IPM programs is the presentation of clear incentives. McNamara et al. (1991) stated that psychological learning theory espouses that beliefs underlie attitudes and attitudes motivate response. Correct information that is different from original beliefs must be provided in a way that stresses incentives for change. To adopt a new activity, an intended user must be sufficiently convinced of its value and the rate of adoption is increased by the perceived advantage over the old method (Musser et al. 1986). In the case of IPM programs, producers choose not to adopt because they lack access to and/or trust in IPM information. In general, IPM users hold more positive beliefs concerning IPM than non-users, but even they need continued reinforcement. Therefore, just as adoption and continuance of IPM are constrained by lack of accurate information, educational theory also holds that educational programs tailored to address IPM can have a positive effect on adoption.

Educational programs for IPM must emphasize incentives. McNamara et al. (1991) and Musser et al. (1986) suggest that concerns for health and the environmental impact of pesticide use had little importance in influencing the adopting process, but incentives associated with increased yield and ultimately profit did have a strong impact. More information must be

developed and presented through a number of media that clearly states the profit incentives associated with adoption of IPM. Additional information is needed for intended users on the cause-and-effect relationships of pest-related damage and suggested economic thresholds (Harper et al. 1990).

Characterize and target intended user groups. In addition to improving IPM information with an emphasis on incentives, educational programs should be tailored to target specific intended user groups, such as those involved in agricultural activities. Some studies suggest that growers, for example, may adopt IPM practices for one particular crop and not another, depending on many factors (McNamara et al. 1991). A general approach using materials containing information on IPM principles may not provide the impetus to change. Policies to expand educational programs to non-traditional audiences and those not reached by traditional extension programs must be developed. Non-traditional audiences, such as part-time farmers that may not normally attend extension functions, could benefit if reached. Educational programs targeting urban groups, homeowners, and other non-farming groups also could improve IPM adoption. Such programs would increase the awareness of the positive aspects of IPM, such as benefits to the environments and thereby help generate a more supportive social and economical environment.

If IPM adoption is to increase through restructuring of educational programs to reach a broader range of clientele, the first step will be to characterize different groups in terms of beliefs and attributes (Kovach and Tette 1988). For example, assessing beliefs concerning IPM is helpful in identifying the incorrect beliefs of non-users that may be changed with specific information. Characterization of the factors associated with adoption of IPM also is helpful. McNamara et al. (1991) grouped and ranked the attributes of peanut farmers as to their importance in influencing IPM adoption. They included the three general categories of producer characteristics, differences in management practices, and differences in farm structure. Producer characteristics included age, which has been positively correlated to adoption (Napit et al. 1988), level of education, which has been shown to have both a positive correlation (e.g., increased cognitive skills linked to increased adoption) and a negative correlation (e.g., more educated growers felt they could get a better return on their time doing other things, Harper et al. 1990), level of farm experience, and total family income.

Differences in management practices also influenced adoption. For example, farm operators who participate in other innovative activities, such as forward contracting (Napit et al. 1988), federal crop programs, and new varieties (e.g., rice farmers using new semidwarf varieties in Texas, Harper et al. 1990), are more likely to adopt IPM practices. Contacts with extension, attendance at field days, reading farm literature, and the practice of IPM on other crops also are positively correlated with adoption (Harper et al. 1990).

Several farm structure components, including total area farmed and the percent of total area in the crop in question, also are related to IPM adoption (McNamara et al. 1991). Time available for IPM, which implies willingness or ability to participate, is an important factor. For example, splitting effort with off-farm enterprises was negatively correlated with adoption. In

addition, number and extent of animal enterprises or other high management input crops also conflicted with adoption because increased demand for managerial time leaves less time for participation in IPM efforts. Crop value also influences adoption. Adoption of IPM occurs more readily on high value crops, or even in the same crop where yields are higher because of differences in soil type or rainfall patterns, such as rice farmers in Texas (Harper et al. 1990) and soybean farmers in Virginia (Herbert, unpublished data).

A general summary of IPM participant characteristics was provided by Napit et al. (1988). A typical IPM-user is white, male, with a least some college education, has frequent contact with extension agents, has higher than average gross farm income, and a higher than average percent of total income from farming.

Dispel the risk myth. As discussed above, perceived risk and lack of trust are major constraints to IPM adoption. Risk is associated with change, especially in the fiscally conservative farming socioeconomic environment. Tradition is strong in farming and the attitude prevails that what has worked in the past is good for the present. As discussed above, typical IPM-users generally have larger farms, higher gross incomes, a higher percentage of total income from farming, and are more likely to participate in other innovations. It also has been suggested (Napit et al. 1988, Szmedra et al. 1990) that these growers could view IPM as risky, but adopt practices anyway because their larger operations make them more resistant to, or capable of taking risk.

The risk associated with IPM is "perceived" rather than "real" for the most part, and in reality practicing IPM strategies can reduce risk. Napit et al. (1988) cite a significant correlation between risk reduction and use of IPM. Budgeting analyses indicated that IPM increased respondents revenues per hectare in most states. Long-term increase in profits reduced uncertainty about the potential for pest damage and, thus, reduced the need for pesticide applications as insurance against loss. In addition, IPM significantly decreased the variability of revenues per hectare, and in the final analysis, growers who used IPM practices had more profitable, less risk-prone farming operations. Logic follows that action based on determining and using economic thresholds will almost guarantee three results. No crop loss to the pest in question will occur because treatments will be applied if populations reach critical levels. No money will be spent unnecessarily because no pesticide applications will be made unless yield is threatened. Thus, net profit will be higher and less variable from field-to-field and from year-to-year.

Role of Extension. One of the most effective components in the IPM adoption process is the Cooperative Extension Service, and many authors have referred to the importance of extension in implementation (Stoner et al. 1987, Wearing 1988, Harper et al. 1991, McNamara et al. 1991). The positive influence that extension had on IPM adoption by Georgia peanut growers was elucidated by McNamara (1991). Educational extension programs that informed producers of the merits of IPM and how to incorporate IPM into current management practices increased adoption. The extension component

had one of the largest associated changes in probability of adoption, 0.184, compared with education, 0.092, or user age, 0.011 (McNamara et al. 1991). Mass media was effective in promoting knowledge and changing attitudes (Stoner et al. 1986), but the inter-personal contact (espoused as one-on-one verbal exchange, Wearing 1988) offered through extension programs was considered necessary for successful adoption of IPM practices. Attendance at extension field days with educational programs on the expected benefits of IPM also was ranked as important (Harper et al. 1990). The shortage of personnel and reduced funding that besets many state extension programs must be addressed if IPM is to continue benefiting from the positive influence of extension.

Maintaining funding. Just as funding has been identified as a constraint to IPM adoption, it is a component that can provide stability and growth. Because incentives (as discussed) are generally lacking for industry development and marketing of IPM programs, funding must fall to public and political interests. Interest in IPM must be maintained in the private sector and political arenas where funding decisions are made by presenting educational programs that stress socioeconomical and environmental benefits. Although funding has traditionally been more available for development of IPM programs, funds must be encumbered from the outset to finance not only implementation, but adoption and continued maintenance as well. Funds for existing programs that deliver results must be maintained along with funding for new programs as they evolve.

Summary

Adoption of IPM has never occurred at the levels hoped for, and the constraints that slow this process have been well reviewed. The purpose of this work was to highlight the primary obstacles to IPM adoption and discuss solutions that could bring about positive change. As the title implies, these solutions are not new, but basic to implementation of any innovative system or change.

Teams consisting of members from all levels and functions, users to administrators, should be organized and maintained from development through adoption. Programs must offer advantages to old methods and fit within identified constraints. Incentives for adoption of IPM should be well presented. Educational programs must be expanded to target non-traditional groups and the agencies responsible for funding. Funding for the entire process should be encumbered from the outset. The importance of personal contact between implementors and users, or potential users, must be realized and supported. Funding and training for adequate personnel must be maintained if implementation and personal contacts are to remain in the purview of extension. Whether responsibility for IPM programs falls to extension or the private sector, users must take an active role in the decision-making process. Without this involvement, users could lose touch with the problems and the outcome of recommended actions, and lose appreciation for the IPM technology.

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Free Enterprise: The Only Sustainable Solution to IPM Implementation[1]

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ABSTRACT To be successfully implemented, Integrated Pest Management (IPM) must be a sound financial enterprise represented through value-added services and products. Five principles for successful implementation are outlined, including the need to recognize that value is defined by the farmer, not by the scientific community. If IPM adds value, it will be exploited, with objective decisions on selection and use of specific tactics based on margin contribution. Regulatory emphasis should incorporate societal concerns leading to science-based use restrictions that mitigate true risks. In addition, the cost of registration as translated through the price of technology or service further incorporates societal concerns. Ultimately, IPM will succeed and be sustained if adopters are successful and laggards are not. The action agenda based on these principles must include a renewed focus on decision making criteria by using the economic injury level variables of injury and damage as a guide for planning research. In addition, organizational hindrances in the public and private sectors must be eliminated coincident with a renewed professional focus on leadership. The target audience must be IPM practitioners, with science and continuous learning integrated through professional certification. The implementation principles, combined with the proposed action agenda and professional expectations of leadership, teamwork, and accountability, can narrow the gap between IPM theory and practice.

KEY WORDS Integrated Pest Management, IPM, economic injury level, decision making

Integrated pest management (IPM) clearly has been one of the most influential concepts affecting the research, education, and practice of agriculture in the United States. Indeed, since Stern et al. (1959) first introduced "The Integrated Control Concept," a plethora of modifications, refinements, and corollary concepts to efficiently manage pests (i.e., maximize benefit-to-cost ratio) have been theorized and investigated with both small scale and area-wide research initiatives (Norton and Mullen 1994). This paper, however, will not debate the "validity" of IPM as a theory, but focus on assessing the hypothesis that IPM is removed from implementation at the farm level.

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The premise offered in this paper on IPM implementation is simple: to be successfully implemented at the farm level, IPM must be a sound financial enterprise represented through value-added services and products. Whether or not it is inherently obvious, the reality is that capitalism, tempered by the collective values of our society, form the rationale for cost-to-benefit decision making in the United States. The farmer is the customer for IPM, proprietors of pest management products and services are the suppliers, and society as a whole is the secondary benefactor (via lower food prices).

IPM Implementation Principles

Consistent with the premise that IPM must be a sound financial enterprise in order to be economically sustainable, five implementation principles are proposed and must be embraced by public and private interests alike. With each principle, a perspective is presented on the central issue, along with critical aspects of what must be recognized and ultimately overcome in order to develop a value-added paradigm for IPM.

Implementation principle 1. The first principle relates to assignment of accountability for defining value: value is the key concept of IPM, but can only be defined by the user. In a free-enterprise economy, the customer (i.e., farmer or his/her agent) determines value. Boehlje and Eidman (1984), in their farm management text identify a number of farmer goals that affect allocation of scarce resources within any given farming enterprise. These include, but are not limited to, maximize profit or revenue, increase net worth, control a larger business, avoid low returns or losses, reduce borrowing needs, increase family living, increase leisure time, have a neat and well-kept farmstead, and provide community service. In essence, therefore, the definition of value is circumstantial because each farmer has his/her own personal value system. It follows, then, that for IPM to be successfully implemented, it must have the flexibility to accommodate this diversity without being considered an implementation failure by the scientific community. Indeed, much of the crisis or perceived gap between theory and practice actually is a gap between a theory of "idealistic IPM" where societal values are assumed (e.g., reduce pesticides) and "realistic IPM" where farmers have clearly considered their goals and personal values and made their choices accordingly.

Because the customers of IPM are managing a complex business in which pests are only one consideration, the reality that farmers have the responsibility to use control tactics as they see appropriate, so long as treatments are within regulatory specifications, must be accepted. Knowing this, IPM techniques that recognize individual preferences regarding income risk must be developed and incorporated within a value-sensitive decision model. The farmer and his/her products and services retailer are the financial stakeholders with IPM decision-making. Academia, extension, and government are third parties that will influence decisions within the scope of their mission, but are not accountable (not liable) for attainment of individual farmer objectives.

Implementation principle 2. The second principle states: if true value is present, it will be exploited as a business enterprise. Today, finally, IPM is

beginning to be recognized as a business opportunity rather than an academic initiative. IPM will (and should) be developed as value-added services and products (per the first implementation principle) for farmers, but that trend should be positively influenced by scientists to ensure that the business of IPM is consistent with good science. In other words, the scientific community must embrace the notion that IPM is represented by value-added products and services, overcome the belief that IPM can be successfully implemented by public entities, and establish business support mechanisms along with focused research and continuing education processes.

Implementation principle 3. With the belief that objective cost-to-benefit decision analysis itself adds value, the third principle becomes elementary: IPM is input-independent; all control tactics should be considered based on their ability to add value to the pest management decision. As a theory and a practice, IPM should not, a priori, exclude any tactic or class of tactics. The successful business will, however, evaluate the potential of each alternative based solely upon the value it adds to the enterprise. If, for example, the personal goal of the farmer is to optimize the value of inputs, which seems like a reasonable goal for IPM decision making, then determinations of total physical product, average physical product, and marginal physical product per unit of input should be considered for each alternative (Boehlje and Eidman 1984). From an efficiency standpoint, the farmer would seek to invest with inputs until the marginal return approaches zero.

Numerous techniques exist for optimization of inputs; however, the key point is objectivity in cost-to-benefit input analysis. If a particular prejudice exists against any legal control tactic by the decision maker, whether it be chemical, cultural, or biological in nature, then a personal value decision has been made by the farmer which is consistent with principle 1. For all remaining alternatives, however, the final choice should use objective criteria for assessing value. In order to support the business of IPM as advocated in principle 2, the scientific community should advocate a robust set of alternatives for situation-specific consideration and not recommend one tactic over another, but provide objective evaluation criteria. Recommendation of one tactic over another is a clear violation of principles 1-3 and, therefore, a hindrance to IPM implementation.

Implementation principle 4. If farming is a business, driven by cost-to-benefit analysis and objective decisions, how does the non-farming sector of the United States (98% of the population) implement its own values regarding IPM? After all, the customer value paradigm also applies to farmers. There should be no mistaking that regulatory policy regarding the safe use of all IPM technology is a necessity. Society has the right, indeed the obligation, to affect these policies. Principle 4, however, insists that: regulatory emphasis should be on protecting the public from known risks associated with specific tactics (appropriate restrictions should be intrinsic to the decision). In other words, the regulation of control tactics should be the result of scientific determinations regarding risk, whether it be the risk of adverse environmental effects from a particular chemical tactic or adverse propagation of an introduced biological control agent. The Environmental Protection Agency (EPA) is expected to critically assess the environmental risk of any technology and correctly limit

usage (via labeling) to mitigate adverse effects. The degree to which a tactic is investigated by EPA and other public regulatory agencies is directly related to the societal concern about that particular tactic (or class of tactics). Hence, the cost of data generation and review by the EPA will be applied disproportionately to registrants of tactics that are viewed by society as "risky" (e.g., pesticides and genetically altered species). In turn, the cost of this process will be passed on to the farmer, along with all the required use restrictions, and, thus, also represents and incorporates the collective influence society has on farmer decision making. This influence is evident when using the economic injury level (EIL) model for IPM decision making (Pedigo et al. 1986) because the determination of "economic damage" is directly related to projected control costs.

So, with societal concerns addressed scientifically through regulatory critique and restriction of real risks, the scientific community must overcome any tendency to "double count" and associate IPM with the promotion of any single tactic (e.g., biological control) over another (e.g., pesticides). Promotion of any tactic over another by IPM would be overestimating adverse effects (or perceived adverse effects) and hinder the implementation of principle 3. The critical need here is for the scientific communities of academia, government, regulatory, and industry to assess each tactic with clearly understood and communicated criteria regarding risk to ensure that the potential for true adverse effects is mitigated. Finally, in a broader sense, administrators and political leaders should avoid the development of policies that inhibit the implementation of IPM through violation of principle 4.

Implementation principle 5. If competitiveness in business and cost-to-benefit concepts seem foreign, consider the fact that IPM itself was born from these concepts as a proposal for continuous improvement in pest control. Our system of economics is painfully simple; if IPM delivers real value, those who adopt it should realize a differential advantage. Stated another way, poor decision makers must fail and exit the business.

As research on pests, hosts, and host response to pests provides a better understanding of the biological variables required by the EIL model, the use of that information for decision-making should strengthen the farming enterprise. As new biological knowledge and pest control technology evolve, there must be a benefit for early adopters and a penalty for laggards. In effect, therefore, principle 5 recognizes that the biological and free enterprise principle of selection must apply to agriculture as it does within any other business venture.

The five implementation principles represent a framework from which to develop the infrastructure to close the gap between theory and practice with IPM. If these principles are substantially violated, IPM will remain a theoretical program to be debated among "third parties" and not fully utilized for value.

Building an IPM Action Agenda

Implementation is an action-oriented word. With principles in place, an action agenda can be constructed to narrow the gulf between theory and

practice of IPM. Three categorical areas of action are required: focus IPM research on decision making needs, eliminate organizational hindrances, and focus on key performance dimensions to accomplish results.

IPM decision-making research. Regardless of whether or not research is "basic" or "applied" in nature, it should be focused on some vision for an outcome. For IPM decision making, the variables of the EIL model represent a guide to assess the knowledge that is required to enable decisions by end users. For example, is the injury potential of the pest species understood? Does knowledge of host response, or a damage curve, for the key physiological processes affected through injury exist? If so, has the sensitivity of this relationship under varying environmental conditions been documented? Has an efficient sampling technique been developed that is conducive to assessing injury?

Answering these questions through biological research forms the scientific core for IPM decision making. Indeed, combining the results of this research with information on control costs and efficacy, as well as market value of the crop, enables objective decisions. The successful implementation of IPM, however, also requires the transfer of knowledge and pest control technology expertise to the farmer (or his/her agent). Five suggested research needs are required to support IPM implementation. The first need is to develop consensus on key physiological processes of hosts that are affected by pests. Pedigo et al. (1986) and Hutchins et al. (1988) propose a core set of physiological processes that form the dependent variables for damage curves, but wider validation of these is necessary. This activity is primarily the responsibility of public research institutions. The second research requisite is to design and implement experimentation that characterizes host productivity as a function of the key physiological processes. In addition to a mean or median response, sensitivity analysis for the primary abiotic factors (e.g., water stress) affecting growth must be mapped as a measure for uncertainty. This research activity also is a primary responsibility of public institutions, with a critical emphasis on maintaining a practical perspective on data gathering. The third research need involves the development of transfer systems and decision models for use at the field level. Here, information must be effectively summarized as knowledge and put in a usable context for decision making to meet the needs at the field level. Static thresholds that do not account for changing economic or biological variable values do not represent continuous improvement in decision making. Public and private entities must work closely and cooperatively to meet these needs. It is the sole responsibility of the private sector, however, to develop and position individual control technologies (i.e., products) with IPM services in mind. This responsibility of the private sector represents the fourth critical research need. Product characterization must elucidate the value added to the farmer as a means to provide objective criteria for decision making. Finally, the fifth need is for IPM implementation to be driven through the continuous discovery, development, and use of value-added products as well as services that determine how they fit in prescriptive management.

The five research needs identified as supporting IPM implementation are consistent with the implementation principles and represent a planned technology transfer. The relative effectiveness and efficiency by which these

steps are undertaken through a public-private partnership clearly will affect the rate of implementation.

Eliminate organizational hindrances. If the first action item has identified the critical needs, the second must focus on what needs to change. Because IPM has become a "buzzword" to extremists on both sides of the pesticide issue, focus on developing initiatives to address decision making has diminished. There is little or no concerted focus nationally on the research issues forming the foundation of IPM, and most IPM-sponsored research is not currently directed toward improving decision-making by the end user. It is time for federal and state administrators to direct their research resources toward the objective of characterizing injury and damage so the EIL model can be used as a decision tool.

The private sector also must change its paradigm of insecticide development and explore all value-added tactics for insect management. The realism of having to create value for shareholders, however, must be recognized and will set staggering hurdle rates for "non-conventional" technology. Still, the railroad industry in the U.S. essentially vanished because of a failure by management to recognize that they really were in the transportation business in the broader sense. Similarly, insecticide manufacturers should never lose sight of the fact that their business, while dominated today by chemical insecticides, is really a pest management business in the broader sense.

In addition to a redirection of resources and emphasis on developing the knowledge for IPM decision making, the profession of entomology and other agricultural professions must come together and provide leadership. Today, there are conceptual rifts of various degrees between public and private entomologists, as well as basic and applied entomologists. While often referred to as an asset, one cannot help but wonder if the extreme diversity of interests and micro-agendas characteristic of these professions has not hindered progress on IPM, especially through a potentially influential organization such as the Entomological Society of America (ESA).

A fourth organizational hindrance, one that drastically limits the influence of science on decision making, is the failure to establish a working certification program for practitioners of IPM. The ESA Certification Board (formerly ARPE) has made impressive progress and still offers much hope, but the reality is that demand for professional certification of IPM decision-making knowledge has not been established. The scientific community must support certification of practitioners as the only sustainable means to translate new knowledge into new capabilities for managing pests.

Key Performance Dimensions. In addition to "what" must occur in support of IPM implementation, focus on "how" to behave is also important. For IPM implementation to succeed on the scale that has been proposed, three performance dimensions are critical: leadership, teamwork, and accountability. Leadership is a broad expectation, but for IPM-based research it can simply mean plan, plan, plan and focus, focus, focus. Indeed, it will take great leadership by all entities to focus substantial resources on the central issues of IPM implementation in a fashion that eliminates waste and enables decision making. Because the suggested action items for research include sponsors from both the public and private sectors, teamwork will be critical to ensure that the

knowledge supply chain is functional and intact. A prerequisite to teamwork, however, is trust. All "factions" involved with IPM implementation must seek to understand the unique perspectives of their cohorts and take the time to build trust and trustworthiness. With leadership providing the planning focus, and teamwork enabling synergy among the participants, the level of accountability for each aspect of IPM implementation must be elevated. The integrated control concepts originally proposed by Stern et al. (1959) are now 35 years old. Implementation has stalled because of many reasons, but primarily because theoretical consensus has not translated into professional accountability within the entomology community.

There clearly is a gap between theory and practice insofar as IPM is concerned. Still, the foundation for IPM implementation exists using the EIL model as the basis for objective decision making. This tool, combined with the principles of IPM implementation and the initiation of focused research programs through the elimination of organizational hindrances, will enable IPM to narrow the theoretical and practical differences that exist today. Our role as a scientific community is to actively participate toward change as outlined, with special attention to excellence in leadership, teamwork, and accountability.

Acknowledgment

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Implementing IPM Through New Technologies and the Non-Agricultural Community[1]

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ABSTRACT Implementation of Integrated Pest Management (IPM) practices by growers has been less than expected by the developers of IPM. The key may be the difficulty growers face in obtaining the information they need to make IPM decisions and the difficulty growers have in integrating and interpreting the information when it is obtained. New technologies such as expert systems and simulated weather information can make IPM decision making easier for growers. In addition, agriculture and IPM is affected by the non-agriculture community. Only when the non-agricultural community is involved in IPM and understands its importance to them, will they support the use of IPM through legislation and at the market place. For IPM to be truly successful, it must be accepted and understood by both producers and consumers.

KEY WORDS Expert systems, Integrated Pest Management, weather, pest management, disease management, pesticide

The Key to the Future Success of Agriculture is Information

Agricultural production has evolved into a complex business. It requires the accumulation and integration of knowledge and information from many diverse sources (Fig. 1) including marketing, horticulture, pest (insect, mite, disease, and weed) management, accounting, and tax laws. Emerging sustainable practices require even more information (to substitute for purchased inputs such as pesticides) for implementation. Growers seldom have at their disposal all information available in a usable form when major management decisions must be made. Increasingly, modern growers must become experts in the acquisition of information for decision making in order to remain competitive. However, they use the expertise of agricultural specialists (consultants, university extension personnel, etc.) because integrating and interpreting information from many sources may be beyond the means of individual growers.

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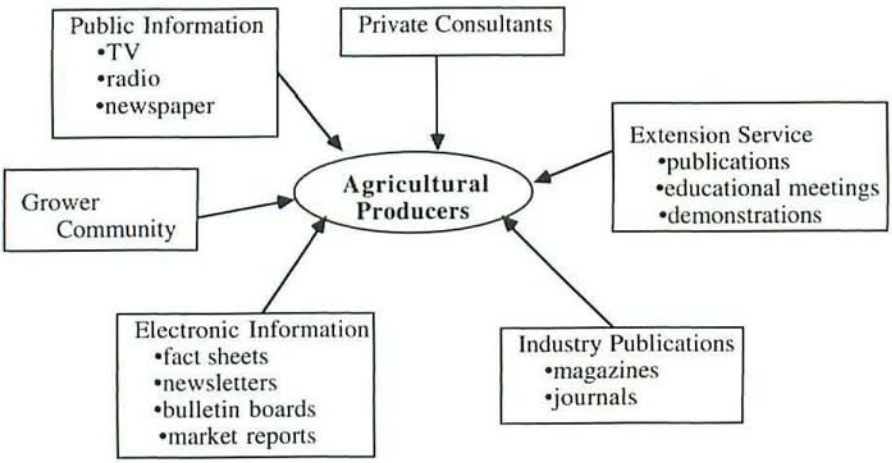

Fig. 1. Information sources for agricultural producers.

Unfortunately, assistance from specialists is becoming relative scarce as the complexity of agriculture is increasing. As growers struggle with the new "rules" of agricultural production, they are faced with a still greater problem. The public wants reduced pesticide residues, but high quality fruit. The rapid change in pest control is further complicated by new labor, marketing, and social concerns that threaten to exceed the capacity of what growers can manager.

Integration of Pest Management Strategies

Historically, growers and consultants have effectively controlled apple diseases and insects by protective pesticides applied at regular application intervals. There was very little day-to-day decision making and pest damage in orchards. However, circumstances surrounding pest management have changed during the last two decades. Growers find many previously effective pesticides no longer available because they have been removed by the company for marketing reasons, they are available for restricted use only due to new regulations, or the most effective materials they once used are no longer effective due to pest resistance. Integrated Pest Management (IPM) practices have replaced complete dependence on pesticides. These practices utilize all possible control strategies available to the producer with the goal of reducing purchased inputs while maintaining crop yield, quality, and profit. The practice of IPM advocates the integration of pest control technologies. Biological control uses beneficial organisms to manage pest organisms. Plant

resistance removes the plants susceptibility to a given pest or disease. Cultural control maximizes the effect of crop rotations, cultivation, sanitation, and other farm practices that reduce pest problems. Chemicals are limited to the minimum usage necessary for control. All control strategies are utilized within state and federal regulations.

Integration and Interpretation of IPM Information

The practice of IPM also involves the collection of information used in decision making. Careful monitoring of the environment and pest populations in the field are combined with mathematical models and precise weather information to predict the occurrence of insect populations and plant disease epidemics. To manage a crop using IPM practices and strategies a grower must understand how the crop grows and matures, how pest populations develop, what management options are available, the impact on the environment and health, and the return on the investment for the control option. The practice of IPM requires a very knowledgeable grower and the collection, integration, and interpretation of crop, pest, and environmental information.

The IPM Information Challenge

Agricultural educators who promote IPM have a diverse audience. They range from commercial agricultural producers who are concerned with profitability within a complex production system, through part-time and hobbyist producers who require assistance in pest and crop management and instruction in the safe use of pesticides, to the consumer who wishes to make informed decisions on purchasing quality and safe fruit products. Not all individuals in this audience contribute directly to agricultural production, but all have an impact on agricultural production in the United States.

The non-agricultural public is becoming increasingly important because their opinions influence regulations and markets. The non-agricultural public is increasingly "setting the agenda" in agriculture. Agricultural educators must communicate the issues of agricultural production to the non-agricultural public to earn their support of reasonable regulations on agriculture. The non-agricultural sector must feel that it has a stake in and can participate in the decision making and planning of agricultural programs. Information transfer must be increased to the non-agricultural community. The historical trend in agriculture is to react with educational programs when a problem arises. Agricultural educators must develop and implement active programs of education for the non-agricultural community. Agricultural scientists, producers, and processors have not done this very well. Agricultural educators must begin to tell the public of the problems, such as labor issues, the success stories with biological predators or disease resistant varieties, and their goals to reduce pesticide use. Only when the public is educated can they be expected to make wise decisions at the grocery story and the voting both.

Legislative groups must also receive information from the agricultural community. It is the responsibility of lawmakers to blend the needs of the agricultural and non-agricultural sectors to make mutually beneficial laws.

Participatory Development of IPM Programs

Agriculture programs, such as IPM, will require participatory development in the future to be successful. Parallel to the Total Quality Management practices used in industry, agricultural practitioners must learn to integrate the greater community into the decisions used to develop and implement their programs. This integration may include both agricultural and non-agricultural segments of the community and the private sector. This integration will result in several advantages. Programs using IPM will better fit the needs of the entire community. Organized communication and understanding will be established between the agricultural and non-agricultural sectors. The non-agricultural public will have "ownership" of agriculture programs. Environmental and health issues can be addressed before a crisis occurs.

The Pennsylvania Department of Agriculture and The Pennsylvania State University are cooperatively developing an education and certification program for agricultural consultants. Diverse clientele groups are being consulted about their thoughts on the program as it is developed. Meetings are taking place with environmental groups, such as the Chesapeake Bay Foundation, and representatives from the private sector, such as the Pennsylvania Agricultural Production Association. By including many levels of the community in discussions of program development and planning, all the parties involved will be satisfied that they had a part in the decision making process and will be more likely to support the resulting certification program.

Utilizing Private Sector Information Transfer

Information transfer in the private sector will be an increasingly important part of the delivery system. There is growth of the private sector businesses providing consultation to growers. Private companies are establishing new units which will specialize in information transfer. DowElanco recently established a new unit of technology transfer which will concentrate its efforts on computer based decision support programs. The challenge to agricultural educators is to determine how best to multiply their impact to all our clientele through this new group transferring information and technology. Agricultural educators must determine how to deliver information through this group, and how it should be packaged for maximum effectiveness.

Educators of IPM must be aware of the latest IPM strategies and be able to train growers in these strategies to keep them competitive. These educators must also be able to relate the issues of production to consumers and involve the community in agricultural programs. The challenge of transferring information to such a diverse audience is difficult, but must be successful if IPM is going to benefit growers so they remain nationally and internationally competitive.

Traditional Sources and Methods of IPM Information Transfer

Agricultural producers have traditionally received information through production meetings, extension educational meetings, extension publications (production guides and newsletters), and research demonstrations on grower farms. These educational methods have proven to be very effective. They will continue to be the primary method of educating growers in the future. These methods, as useful as they are, have limitations. University extension and research personnel are concerned that traditional methods of information delivery seem inadequate for the delivery of the complex, dynamic information used in IPM. For example, recommendations are made on a state wide basis through the Pennsylvania Tree Fruit Production Guide (The Pennsylvania State University, University Park, PA), which has been the traditional means of getting published production information to growers since the mid 1940's. Ranges for pesticide application rates and timing are given in this publication, but these rates and timings for specific locations depend on local circumstances. This form of information delivery inhibits implementation of new, site-specific IPM strategies by growers. Changes in new pesticide labels and other new information occur weekly or monthly, but the production guide can be updated only annually.

For agricultural producers to be competitive, they must have integrated, interpreted information that is timely and site-specific to their farm. They must also have access to national and international production and marketing information that affects their decision making.

IPM Adoption Through New Technologies

Traditional methods of information delivery can be combined with new technologies, such as electronic decision support aids, to assist agricultural producers in decision making. Electronic decision support technologies, such as expert systems, have the capability of incorporating constant change into complex management strategies to provide interpretive, integrated, timely, and site-specific decision support (Fig. 2).

Implementation of IPM Through Expert Systems

An expert system is a computer program designed to simulate problem-solving mechanisms that imitate those used by experts in a narrow domain or discipline. An expert system is normally composed of a knowledge base and the end user interface which accepts inputs and generates outputs.

Expert systems can deliver quantitative information, much of which has been developed through research and includes, economic thresholds for pests, crop development models, and pest population models. Heuristics, which are rules-of-thumb, are used to interpret qualitative values which may be used in lieu of quantitative information. Expert systems can address imprecise and incomplete data through the assignment of confidence values to inputs and conclusions. A powerful attribute of expert systems is the ability to explain reasoning. Since the system remembers its logical chain of

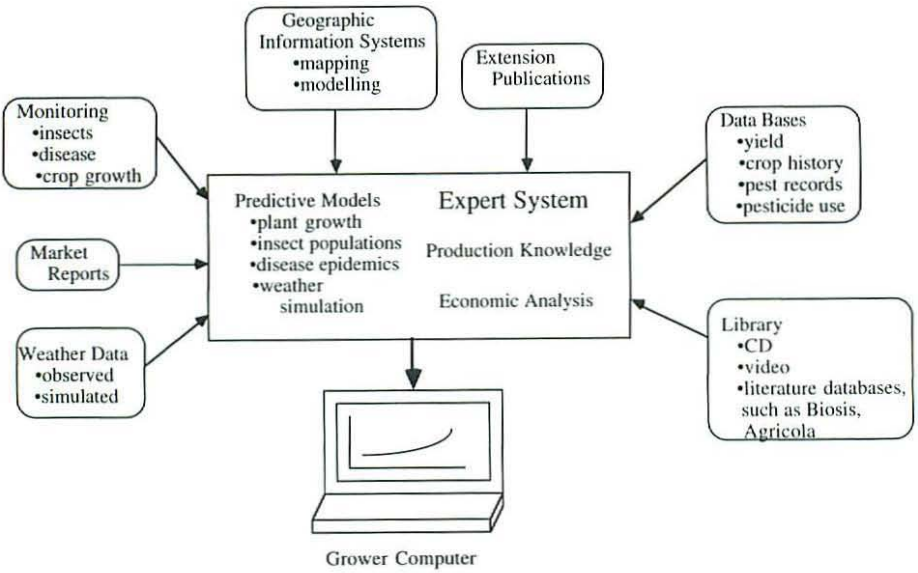

Fig. 2. Electronic decision support for grower decision making.

reasoning, a user may ask for an explanation of a recommendation. The ability of the system to display the factors it considered for a particular recommendation enhances user confidence in the recommendation and acceptance of the expert system.

Development of an electronic decision-support system requires combined efforts of specialist from many fields of agriculture and cooperation of the growers who use them. Specialists tend to be trained in narrow domains and are best at solving problems within that domain. However, the complex problems faced by growers go beyond the abilities of individual specialists. Interdisciplinary teams of specialists working in unison can be effective when agriculture is viewed as a system of interacting parts where the perturbation of one part affects many others. In agriculture, expert systems are capable of integrating the perspectives of individual disciplines, such as plant pathology, entomology, horticulture, and agricultural meteorology, into a framework that best addresses the type of integrated decision-making required of modern growers. Expert systems can be one of the most useful tools for providing growers with the day-to-day, integrated support needed for crop production.

The Penn State Apple Orchard Consultant

The Penn State Apple Orchard Consultant (PSAOC) (Travis et al. 1990) was developed on a Macintosh® computer and employs a frame-based expert system tool called Pennshell©, which was written in the C programming language. However, it can be used on both Macintosh and DOS (IBM) based computers. Different components or modules of the expert system are accessed through a menu interface. The menu items for the IPM portion of PSAOC include orchard profile, scouting, weather, diseases, insects, and IPM. Horticultural modules for analysis of leaf nutrients, tree spacing, irrigation scheduling, and weed control are also available for grower consultation. The user can choose one insect or disease, all diseases, all insects, or receive an integrated insect and disease control recommendation by selecting IPM. Some information used by PSAOC during an interactive session may originate from sources other than the user. A profile of permanent (e.g., cultivar, expected harvest date, etc.). and temporary information (e.g., plant stage of development, last spray date, etc.) can be created (Travis and Latin 1991, Travis et al. 1992).

The PSAOC covers the range of problems encountered by a fruit grower, but was built as a series of modules such as pest management, leaf analysis, tree spacing, etc. Each module may be subdivided several more times to arrive at a point of simplification where the information is manageable. For example, the pest management module of PSAOC includes lower level modules encompassing potentials for apple scab, powdery mildew, cedar apple rust potentials, insect thresholds, insecticide rate, and spray intervals. Modules below these lower level modules predict infection periods, chemical residue levels, etc. These module levels, which were built separately, interact to derive an integrated disease and insect recommendation. The pest management portion of PSAOC is composed of three parts, the orchard profile comprised of the variables (such as cultivar, tree spacing, pest history etc.) that describe the orchard, the pest rating modules that determine the pests (a subset of the 5 apple diseases and 17 insect pests in the system), level of severity, and beneficial organisms, and the management modules which determine the appropriate control strategies (no action needed, further scouting required in the near future, preventative or eradicant pesticide required) for each circumstance.

Improved IPM Through Simulated Weather Information

Weather influences nearly all of man's surface activities. In agriculture, weather is primarily responsible for crop development, disease, insect outbreaks, and often plays a major role in the success or failure of management strategies. Because of its importance to agriculture, increasing the accuracy and precision of weather information will improve decision making. However, the collection of accurate weather information is one of the most difficult tasks that face a grower who desires to make informed production decisions. Traditional and automated weather stations are expensive and difficult to operate and maintain. The stations often have failures just when critical weather data is required for decision making.

Growers could obtain their weather information from several public and private sources of weather information, but the user faces the problem of "scale." Short of personally collecting all the necessary weather data right at the point where a decision must be made, a user must rely on observations distant from his or her operations. This distance can be across a farm or a county away. In general, the farther a weather station is from the point of decision the more uncertainty is associated with the collected data. The challenge to a grower is to either somehow locally "adjust" their current source of weather information or to secure a new source that overcomes this scale problem.

There are some innovations on the horizon that may provide users with weather data that has not be recorded on the farm, but is indicative of the local conditions and satisfactory for operational decision making. Current satellite and radar images can be frequently updated and rapidly distributed to users. In addition, weather data can be simulated.

Simulated weather data refers to interpretive models that improve upon current weather station observations or numerical forecasts. Through the use of statistical techniques and mathematical algorithms, meteorologists can give the user the simulated local weather even though the original source of information is miles away. Simulated weather data has many advantages over traditional sources. Growers do not have to maintain weather stations. They do not have to read and summarize weather data. The cost of simulated weather data is equal to the cost of traditional weather station maintenance and data handling. The simulated weather data is automatically and regularly transmitted electronically to the grower. Since simulated weather is computer-derived, it can be automatically distributed to users in very short turn-around times. Simulated weather data are available for past, present, and future weather events. This information allows users to include both trends and extremes in their decision making. Simulated weather data can be easily interfaced with other computer-based decision support programs such as expert systems or geographic information systems.

Truxall and Travis (1994) have found that simulated weather information results in the same apple scab management recommendations given by PSAOC as when weather information was derived from on-site weather monitoring units. Simulated weather information allows growers to effectively use accurate, timely, site specific weather information in their day-to-day decision making without the cost and time required to operate their own on-farm weather monitors. Site-specific, simulated weather information summarized and interpreted within expert systems, such as PSAOC, will result in a greater reliance on weather information by growers in making IPM decisions, and therefore, greater acceptance of IPM.

Summary

In summary, the following activities will contribute to solving the IPM crisis. New technologies that are available for IPM information delivery and effective IPM decision making must be utilized more fully. The IPM audience

must be expanded to include both the agricultural and non-agricultural communities. Agricultural and non-agricultural segments of the community must be included in the planning and implementation of agricultural programs like IPM. Information on the impact of IPM must be conveyed to all clientele through private information and technology programs.

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Computer Models in Integrated Pest Management: A Case Study of the Grasshopper Integrated Pest Management Project[1]

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ABSTRACT The Grasshopper Integrated Pest Management Project (GHIPM) was a $15 million project that lasted from 1986 to 1994 to identify, develop, and implement rangeland grasshopper management tactics within the framework of Integrated Pest Management (IPM) in the western United States. Computer simulation has been used to fulfill many original objectives for GHIPM and help bridge the gap between theory and practice. One group of computer simulation studies was developed to probe basic mechanisms of rangeland grasshopper ecology. For example, an object-oriented simulation is being developed that can represent any number of unique grasshopper cohorts for specific species, life stages, and disease status. Soil temperature and moisture are also being simulated to support a grasshopper egg hatch model. These research models were designed for basic science with a focus on improving management of rangeland grasshoppers. Another group of models has been developed and/or used to simulate grasshopper population dynamics, forage growth and destruction, and ranch economics for essentially all rangeland areas in the western United States. These models are used in a computer decision support system called Hopper to structure and provide knowledge to land managers who make decisions about grasshopper control. Hopper provides objective analyses of management options including innovative IPM strategies that could not be effectively evaluated in the past. The development of Hopper and supporting models has caused a paradigm shift from the goal of maximizing control mortality to the IPM goal of optimizing economic, environmental, and social values. Hopper was adopted in 1994 and is used to evaluate all federal programs for rangeland grasshopper management. Now the scope of grasshopper management includes techniques that may or may not cause grasshopper mortality. For example, modifying cattle herd size and grazing management strategies may allow the IPM goal to be reached better than control options. Also, reduced control and the associated reduction in cost from a reduction in pesticide used for control can sometimes provide the best economic return in addition to other longer term benefits. Computer simulation within Hopper has provided the flexibility to apply IPM to a complex of grasshopper species over a geographically very large and ecologically diverse area.

KEY WORDS Computer simulation, IPM, economic threshold, population dynamics, Orthoptera

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Grasshoppers are the major invertebrate pests of rangelands in the western United States (Hewitt 1977). For example, Hewitt and Onsager (1983) have estimated losses to grasshoppers to be about $393 million/year on western rangeland. Grasshopper infestations often occur over large areas of land owned or managed by many private individuals and land management agencies. Therefore, coordinated management efforts are required when dealing with large infestations. The United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA-APHIS-PPQ) has been authorized to administer these cooperative management programs since 1937 under the Incipient and Emergency Control of Pests [Act] (1937), the Organic Act of the Department of Agriculture (1944), the Cooperation With State Agencies in the Administration and Enforcement of Certain Federal Laws Act (1962), and the Food Security Act of 1985 (see USDA-APHIS 1987).

In 1986, APHIS initiated a 5 yr, $15 million Grasshopper Integrated Pest Management Project (GHIPM) to identify, develop, and implement grasshopper management tactics in the framework of Integrated Pest Management (IPM). The project received a 3 yr extension that ended September 1994 to facilitate IPM technology implementation. A programmatic Environmental Impact Statement (EIS) of rangeland grasshopper management identified IPM as the preferred strategy for rangeland grasshopper management (USDA-APHIS 1987). In the 1987 EIS, IPM was defined as " . . . the selection, integration, and implementation of pest control tactics in a systems approach based on anticipated economic, ecological, and sociological consequences." IPM can also be thought of as a decision-making process that relies on information at each step. Some information, such as pest density, can be found directly by sampling the pest population in the field whereas other information is very difficult to obtain. For example, projected yield loss and future damage potential cannot be determined directly and may depend on many factors, such as weather, grasshopper species and age structure, and plant species composition (Berry et al. 1992, Davis et al. 1992).

The rangeland ecosystem is less productive per unit area and is, thus, less intensively managed than most crop systems. Also rangeland is more complex than monocultures. For example, there are more than 400 species of grasshoppers that inhabit the 17 western states (Pfadt 1988). Also, rangeland occurs from hot desert to lush mountain valleys. Within the rangeland ecosystem, weather can greatly affect a management decision (Davis et al. 1992) and can vary from year to year and site to site. Therefore, rangeland grasshoppers cannot be managed with simple decision rules such as a static economic injury level. In addition, the per unit area value of forage is low, about $2.50 to $7.50/ha (Hewitt and Onsager 1983). Consequently, decisions must be accurate and precise to efficiently deal with control measures that cost from $5.00 to $11.50/ha. The 1987 EIS (USDA-APHIS 1987) set forth seven objectives for GHIPM to account for this complexity and an essentially unlimited number of management situations. Five of these objectives related to computer simulation as follows (noted by the *).

(1)* "To refine an existing [grasshopper] phenology model to maximize the efficiency of management activities."

(2) "Demonstrate that early sampling can detect and classify incipient infestations that are amenable to management with alternative registered tactics."

(3)* "To develop economic thresholds and prescribe selective or nonselective treatments to reduce infestations to noneconomic levels with minimum effects on nontarget species."

(4)* "To quantify current-season and long-term responses of infestations following each available control tactic to support a model of population dynamics in response to treatments."

(5) "Develop new selective methods for management of grasshoppers, including grasshopper virus and fungal pathogens."

(6)* To provide for coordinated research on economics, range management, and ecology of nontarget species as components of a systems approach to grasshopper management."

(7)* "To integrate all pertinent data into one expert system that can be turned over to APHIS [university and extension service personnel] and private enterprise upon completion of the project."

The overall goal of GHIPM was to refine rangeland grasshopper management so that economic and environmental values could be optimized. To realize that goal, some new research was required to produce needed information and develop technologies. However, there was also a need to incorporate existing information and technologies into effective management tools. Consequently, some modeling effort in GHIPM was directed toward knowledge discovery and research. These models provide a framework to test hypotheses and explore innovative management options. Another substantial modeling effort was directly focused on building and implementing management tools. In a management setting, computer models can provide information that is otherwise impossible or very expensive to acquire. In this paper, the computer models used in GHIPM are briefly presented and their role in IPM for rangeland grasshopper management is discussed. See Berry (1995) for a more detailed review of some of these models.

Research Models

Technologies can be developed using data and knowledge from basic research. Therefore, GHIPM has supported computer simulation studies that probe basic mechanisms of rangeland grasshoppers. This research is basic science with a focus on improving management of rangeland grasshoppers.

Landscape level grasshopper simulation. GHIPM had the resources to bring together a substantial amount of expertise and effort for studying rangeland grasshoppers. Consequently, several entomologists involved with GHIPM saw that a rare opportunity existed to collaborate on formalizing knowledge about rangeland grasshopper ecology. Some of this knowledge was published, but some existed only in the minds of experienced entomologists. Therefore, Berry et al. (1993) began developing a detailed simulation of rangeland grasshopper population dynamics. Object-oriented programming was used to model individual grasshopper cohorts, habitats, parasites, and predators in substantial detail, and then aggregate them at the landscape level. Such a spatio-temporal model may provide insight into new grasshopper management strategies, prediction of outbreaks, epidemiology, and responses of populations to selective management tactics. See Logan (1994) for a discussion of the usefulness and importance of large detailed models.

In the object-oriented paradigm, generalized objects may serve as templates to build specific instances of that type of object. For example, a generic grasshopper object can be defined. This object can contain the general attributes (size, age, location, etc.) and functions (movement, feeding, starvation, oviposition, etc.) of a grasshopper. Then these attributes and functions can be inherited and slightly modified to simulate any species.

Once each object is defined, any number of copies (with different ages, body sizes, etc.) can be created in a simulation. For example, new instances of grasshoppers would be created each day during spring egg hatch. Each object in the model functions automonously. The general attributes are given specific values to represent the state of that object (e.g., sex = male, mass = 2 g, etc.) In the same way, grasshopper habitats and predators or parasites can be abstracted and modeled. Because each entity is autonomous, the model is very flexible and can handle numerous and different types of habitats, predators, and grasshoppers. The object-oriented model is essentially a collection of autonomous submodels (grasshoppers, habitats, etc.) that dynamically respond to conditions in the simulated environment, including other effects from other submodels.

Model development with the modeling team led to some very interesting discussions about grasshopper ecology. Often, data gaps have been discovered and experiments conceived. There has probably never been such a formalization of grasshopper ecology. In a sense, the model provides an uncompromising framework to formalize and assimilate current theory about grasshopper biology and population dynamics.

Object-oriented modeling has allowed this model to contain much more detail about grasshopper species differences and spatial dynamics. The ability to easily model many species in a heterogeneous environment (many different patches) may help to unravel the mysteries of rangeland grasshopper outbreaks, and to evaluate selective management strategies such as baits, range management, and biological control in an IPM framework.

Soil temperature model. Most economic species of rangeland grasshoppers spend much of their lives as eggs located just below the soil

surface. These eggs are the overwintering stage. They may experience mortality due to predators, parasites, pathogens, and environmental conditions. In addition, timing and synchronization of spring time egg hatch can greatly influence management activities. Egg hatch is determined primarily by environmental conditions in the top 5 to 10 cm of the soil. Any accurate prediction of egg hatch and mortality depends on good estimates of soil temperature and moisture. Therefore, GHIPM included a soil hydrology team (Pierson and Flerchinger 1993, Pierson et al. 1992) to collect detailed soil environmental data and develop models to estimate soil variables related to grasshopper egg biology. This team cooperated with GHIPM entomologists to collect data and run simulations at sites with ongoing grasshopper research. The detailed research model could be used to extrapolate soil environmental variables to other grasshopper research sites where detailed soil measurements are not feasible. Also, the effect of plant canopy on soil environmental variables was evaluated with the model.

Egg hatch model. Fisher (1993) collected data to determine the date of the end of grasshopper egg diapause in the autumn and subsequent temperature-dependent development rate for a common rangeland grasshopper species. Diapause is a state of arrested development that requires a certain amount of chilling before development can proceed. This attribute may prevent some grasshoppers from hatching during a warm autumn only to die in freezing winter temperatures. The development rate data and soil temperature data were submitted to a generalized insect modeling system called Population Model Design System (PMDS), developed by Logan (1988). PMDS produced the parameters and computer code to simulate egg hatch.

The egg hatch model combined with the soil temperature data collection and modeling activities in the last section may provide new understanding into the population dynamics of various mixtures of grasshopper species. Ultimately, simplified hatch models may be used in a management setting to allow more precise timing of management options, such as survey and control.

Management Models

The main vehicle currently used to deliver computer simulation to management decision makers is a computer-based, decision support system called Hopper (Kemp et al. 1988, Berry et al. 1991, Berry et al. 1992). Hopper runs on MS-DOS microcomputers and was developed within GHIPM to provide information for real-time tactical decisions for grasshopper management at a local scale. The program is used to help a land manager determine if other ranch management alternatives are preferable to grasshopper control. Hopper can evaluate the economic return for each control option when control is justifiable. Field use for Hopper also includes preseason grasshopper problem assessment and planning by APHIS-PPQ. In severe outbreak years, this planning is critical because personnel, equipment, and time are severely strained during control operations in the summer. Hopper has also been used to analyze alternative control strategies

(Larsen and Foster 1996), economic consequences of grasshopper control (Davis et al. 1992), and benefits versus costs for introducing to the United States exotic biological control organisms that attack grasshoppers (J. Berry, unpublished data).

As with many of today's agricultural problems (Stone 1989), grasshopper management cannot be solved with expert systems or simulation models alone. Therefore, Hopper was designed to integrate an expert system with two simulation models and a linear programming model. The expert system considers current weather conditions, grasshopper life stage, and environmental concerns to qualitatively select appropriate control options. The control options selected by the expert system are then evaluated quantitatively for economic efficacy.

Expert system technology is not well suited for the economic analysis component in Hopper because economic analysis is inherently procedural and quantitative. For example, the economic analysis depends on forage yield for a given scenario that includes the effects of many variables such as weather, soil type, and grasshopper population. These effects are time-dependent and must be integrated sequentially over a growing season. Simulation models can be effectively used to represent these time-varying systems. In addition to forage yield, the simulation models can provide information to the expert system during a consultation. The simulation models also can use site-specific data (weather, site productivity, vegetation type, etc.) to simulate many of the diverse rangeland ecosystems across the western United States. This flexibility greatly expands the geographic scope of Hopper. Some information provided by simulation (such as percent of grasshopper egg laying completed) would not be feasible for the user to acquire otherwise. Six computer models that are used in Hopper to provide important information for management (i.e., a grasshopper population and forage destruction model, a forage growth simulation model, a weather simulator, a generalized grasshopper simulation model, a ranch economics model, and a grasshopper hazard prediction system) are described below.

Grasshopper population simulation model. Some of the most important information needed for grasshopper management is related to the grasshoppers themselves. For example, damage potential of a grasshopper population with and without control is needed to estimate economic benefit of a control operation. Damage potential depends on habitat, grasshopper species composition, average life stage, and density. Average life stage, species composition, and density change as the growing season progresses. In addition, species composition and density can vary between sites and years. A rangeland grasshopper model called HopMod was developed to incorporate phenological development, forage destruction, natural mortality, and control option efficacy (of the current registered treatments) for a complex of rangeland grasshopper species (Berry et al. 1995). These factors must be considered to make economically-based management decisions for rangeland grasshoppers. HopMod also provides information to Hopper's expert system, such as percentage of egg laying completed and average life stage at the time a control option should be implemented.

Forage production simulation model. On rangeland, the crop (forage) is harvested indirectly by using cattle or wildlife. Therefore, although forage destruction by grasshoppers can be estimated by HopMod (Berry et al. 1995), total forage available for cattle is more important in a management setting. For example, during years of above average precipitation there may be enough forage available so that even high densities of grasshoppers do not compete with most other herbivores. During dry years, the same amount of forage destruction by grasshoppers may cause a severe shortage for other herbivores. Consequently, the effect of grasshoppers on rangeland depends both on the amount of forage destroyed by grasshoppers and the amount of forage produced at a site. In addition, grasshopper consumption often occurs while the forage is actively growing. There is potential for forage regrowth both while grasshoppers are present and after grasshoppers are removed through control activities. Traditional field experiments used to determine the economic injury level can only control or account for a few variables at a time. Especially for ecologically diverse rangeland ecosystems, a limited number of field experiments in a handful of locations could not provide the data required to extrapolate to the vast number of potential situations across western rangelands in the United States. Therefore, computer simulation is necessary for Hopper to account for an unlimited number of potential scenarios and locations that may occur. Consequently, a forage model called RangeMod was developed to simulate daily forage production for any given temperature and precipitation scenario at any rangeland site in the western United States (Berry and Hanson 1991). The model can simulate forage growth for the major rangeland ecosystems simply by using different parameters and weather. Users can modify the parameters, however, ecosystem-specific parameters are supplied along with each economic model. HopMod and RangeMod dynamically interact to provide yield estimates that include daily grasshopper feeding and forage growth.

Weather generator. Temperature primarily determines grasshopper and range plant phenology in both HopMod and RangeMod whereas precipitation is used by RangeMod for timing of growth. Site specific temperature and precipitation data allow both models to be used in any rangeland location in the western United States. Early in GHIPM these data were compiled from national weather records for the sites in areas of interest. As GHIPM progressed, the geographic extent of areas in the project increased. This increase required much more weather to be compiled and sent with Hopper to end users. Instead of sending weather data, a daily weather simulator developed by Hanson et al. (1993) was used to estimate daily precipitation, maximum and minimum temperatures, and solar radiation. Included with the simulator are parameters, summarized from 30 years of weather data from long-term weather stations. The weather model will use these parameters to generate a typical weather scenario for the site. Hopper has a spreadsheet-like editor so users can modify the generated temperatures and precipitation events to fit current conditions. Also, users can increase or decrease temperatures or precipitation for the entire year at once (e.g., increase all the daily maximum temperatures by 5 degrees). Using this feature, a generally hotter-colder or dryer-wetter season could be quickly set up and evaluated with Hopper.

Ranch economics linear programming model. RanchMod (Davis et al. 1992) is a linear programming model of a typical ranch in a proposed grasshopper control area. The results from the grasshopper and forage models in Hopper are used by RanchMod for economic analyses. RanchMod calculates the net return for the typical ranch using each control option submitted by Hopper. The benefit for any control option is calculated by Hopper as the difference between the net return for the control option less the net return for a no control scenario. Costs are calculated by Hopper as the control cost per unit area times the area. A benefit-cost ratio is calculated and displayed to the user along with the expected total forage production obtained when each control option is used. RanchMod is linked in Hopper to the grasshopper simulation model and the forage production model. Therefore, the economic analysis is based on a very multidisciplinary effort and is very dynamic. Consequently, Davis et al. (1992) could evaluate the effects of important factors not explicitly included in RanchMod, but were included in the other two models. For example, they showed that rangeland productivity per unit area can have a substantial effect on a management decision. This model linkage in Hopper allows the economic consequences of biological, environmental, and economic factors to be evaluated in a seamless operation for an essentially unlimited number of situations. Hopper users can evaluate the economic effects of factors such as grasshopper species composition, site productivity, grasshopper density, treatment timing, cost and amount of alternative forage, herd size, cost of treatment, etc. Therefore, computer simulation has eliminated the need for static economic thresholds for rangeland grasshoppers and allows non-control options to be evaluated.

General grasshopper simulation. Hopper users expressed a need for a general grasshopper model that could be used to evaluate timing of control options relative to grasshopper phenology. Therefore, a simulation model called SimHop was developed and included as a module in Hopper to simulate the general pattern of grasshopper development, forage consumption, and control-option mortality. This information from SimHop is useful for teaching or explaining why it may be too late or too early in the year to use a control option. Furthermore, effects of longlasting (long-residual) treatments and timing of control options can be demonstrated using text and graphics to display the results. Users can modify all of the life history parameters and treatment mortality. Entomologists have used SimHop to evaluate the effects of sustained low mortality on total egg production and forage consumption. This type of mortality might be caused by different cattle grazing management strategies or introduction of a biological control agent.

Grasshopper hazard prediction. An adult grasshopper survey is done each year during mid to late summer by APHIS-PPQ. The data are used to produce maps of grasshopper density throughout the western United States. These maps show potential grasshopper densities for the following year and provide opportunities for advance planning of grasshopper management activities. The grasshopper density contours on the maps have traditionally been drawn by hand and represent only current conditions, not a true forecast. Kemp (1993) developed methods to produce maps that represent true forecasts. First, geostatistics are used to spatially interpolate field data (2400

sites) at a scale of 5 km by 5 km grids throughout the area surveyed (Kemp et al. 1989). Second, a statistically-based projection to account for historical patterns of grasshopper population dynamics in a given region is applied to the interpolated data (Kemp and Dennis 1993). The result is a map of predicted grasshopper densities. These techniques have only been applied to the state of Montana, but could be applied to other states where the historical data are available. Hopper users can display on-screen any of the available maps.

Discussion

Research models are part of the knowledge and technology discovery process. Some things learned while developing detailed and large research models can be incorporated into management guidelines or software systems (Logan 1994). For example, the object-oriented modeling techniques developed for the landscape level grasshopper simulation have already been used to change Hopper's rule-based expert system to an object-oriented style. This change provides more flexibility in the user interface requested by field practitioners. In addition, there are plans to redesign Hopper's grasshopper models into objects to allow simulation of individual grasshopper species. This redesign is important because species have different forage consumption rates, intrinsic rates of increase, and susceptibility to management options (e.g., range management, baits, and biological control agents).

Computer simulation also plays a direct role in rangeland grasshopper management. For example, the Hopper software was adopted by APHIS-PPQ in 1994 as part of its decision-making process for rangeland grasshoppers management. In fact, APHIS-PPQ no longer uses static economic thresholds, but uses dynamic evaluations from Hopper to help evaluate the need for control (USDA-APHIS 1994). This use of Hopper shows that the technology exists to shift from simplistic static thresholds to more realistic dynamic thresholds as part of an IPM Program.

The development and implementation of Hopper have facilitated a paradigm shift in rangeland grasshopper management. The goal in many IPM systems is to kill or control a pest below some fixed density. Higley (1993) calls this the "body bag" mentality of pest management. In this paradigm, a tactic (pest control) has been confused with the objective (profit, increased yield, predictable yield, etc.). Under the new paradigm the ultimate objective becomes the focus rather than the tactics. A better definition for IPM (modified from the January 1994 newsletter of the National Coalition on Integrated Pest Management) would be: a sustainable approach to managing agroecosystems and associated pests by combining biological, cultural, physical, and chemical tools in a way that optimizes economic, health, social, and environmental values. With this definition the focus is on managing the entire system to optimize the ultimate objectives. The tactics can be used to control a pest directly or to modify the agroecosystem without directly controlling the pest. For example, in a rangeland system, ranchers may prefer to reduce herd size rather than control grasshoppers. Hopper allows this type of option to be evaluated and compared to control. APHIS-PPQ is embracing

this new paradigm by considering management options that produce less than maximum control of grasshoppers. Hopper has also been used to show the feasibility of these innovate grasshopper management schemes that involve reduced pesticide use with a corresponding reduction in treatment cost and grasshopper control (Larsen and Foster 1996). A key for success of Hopper in GHIPM is the blending of qualitative reasoning, simulation, and a robust and intuitive user interface. Also, development and implementation were guided by the Hopper Implementation Team that consisted of scientists and field practitioners from several federal and state agencies. By including these people, Hopper developed into a product that was actually usable in management settings. In addition, Hopper's models contain or use vast amounts of scientific knowledge (from many sources) and data. Without the automation and speed of computers, most of this information could not be used in a management setting and would not be used effectively for research purposes.

Another important aspect of these models is that they provide a focal point of interaction for a development team that consists of both scientists and practitioners. This focal point occurs because models are tangible products that can hold the attention of administrators and a development team. People enjoy seeing their knowledge synergistically used and integrated with others' knowledge into a form that is greater than the sum of its parts.

An unusual feature of IPM in rangeland is rangeland's extensiveness and low productivity per unit area. The value of rangeland resource in the western United States is enormous. However, its value on a local scale (rancher or community) is not great enough to provide funding for a project like GHIPM and the resulting Hopper software. Yet, the low productivity of rangeland makes correct management even more important than for a high value crop. For a high value crop, one extra treatment may mean less profit but for rangeland it may mean no profit, the difference between success and failure. Hopper and its directly associated models (not including the research models) probably cost over $500,000 to produce. This cost seems like a high price but a typical 30,000 acre treatment of rangeland for grasshoppers could cost more than $100,000. In addition, Hopper can be applied to essentially all rangeland areas in the United States and Canada west of Iowa.

The goal of GHIPM was to refine rangeland grasshopper management across the entire rangeland areas of the western United States. The Hopper software, through the use of computer simulation, provides the flexibility that would have been very difficult and expensive to achieve through site-specific field work that is typically associated with the development of static economic thresholds.

A major challenge faces the modeling efforts I have described. Most of these modeling projects have been funded or, at least, administratively focused by GHIPM. However, GHIPM officially ended September 1994. Without an administrative sponsor or funding source, many of the modeling efforts will probably not continue. Therefore, APHIS-PPQ plans to support maintenance of the Hopper software and has created a position to do so. This support is critical because Hopper and its associated models will need to be updated to account for new management options and fix any program errors

encountered. Often research grants will pay for model development but sources of funding for maintenance are difficult to locate. The commitment by APHIS-PPQ will provide some funding and an important focal point for research and development. However, the success of these modeling projects was the result of an individual programming effort and the cooperation and scientific development among a diverse team of individuals, including field ecologists, computer programmers, modelers, land managers, and economists. In addition, field practitioners added critical knowledge needed to apply the scientific knowledge to management problems. This project successfully applies interdisciplinary research and modeling to help bridge the gap between rangeland grasshopper IPM theory and practice.

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END OF SYMPOSIUM

Effectiveness of Four Blends of European Corn Borer (Lepidoptera: Pyralidae) Sex Pheromone Isomers at Three Locations in South Carolina[1, 2]

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ABSTRACT A field study was conducted at Florence, Newberry, and Clemson, South Carolina, to determine the relative attractiveness of four isomeric blends of 11-tetradecenyl acetate to male moths of the European corn borer (ECB), *Ostrinia nubilalis* (Hübner). The *E* and *Z* isomers were formulated in *E*:*Z* ratios of 99:1, 97:3, 65:35, and 3:97. Trap capture data indicated that the *E* pheromone strain of the ECB was predominant at Florence and the *Z* strain was predominant at Clemson. Both strains appeared to occur sympatrically at Newberry. Pheromone analysis of 46 ECB female moths at Florence indicated that 43 were the *E* strain and 3 were hybrids. The 99*E*:1*Z* pheromone blend captured over four times as many male moths as the 97*E*:3*Z* blend at Florence. The 65*E*:35*Z* blend captured 5%, 11%, and 12% of the moths at Florence, Newberry, and Clemson, respectively, indicating the possible presence of hybrid moths. The superior performance of the 99*E*:1*Z* blend of 11-tetradecenyl acetate should enhance the development of a more effective lure for the *E* strain of the ECB.

KEY WORDS European corn borer, *Ostrinia nubilalis,* Lepidoptera, Pyralidae, pheromones, pheromone trapping, (*E*)-11-tetradecenyl acetate, (*Z*)-11-tetradecenyl acetate.

The identification of (*Z*)-11-tetradecenyl acetate as a sex stimulant of the European corn borer (ECB), *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae), by Klun and Brindley (1970) led to the use of pheromone traps for monitoring this important pest of corn, cotton, sorghum, and vegetable crops in the eastern United States. Male moths in Iowa responded to this pheromone but were inhibited by the

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E isomer (Klun and Robinson 1971). Klun et al. (1973) reported that optimum attractiveness occurred in Iowa when 4% *E* isomer was added to the *Z* isomer, and that geometrically pure preparations of the *Z* isomer were relatively unattractive. Kochansky et al. (1975) observed that maximal attractiveness occurred in New York when 2% of the *Z* isomer was added to the *E* isomer. Roelofs et al. (1985) analyzed pheromone blends from glands of female ECB and reported the existence of three distinct populations of ECB in New York based on sex pheromones and voltinism. These populations were a bivoltine biotype utilizing the *Z* isomer as the primary pheromone component, a univoltine *Z* biotype, and a biovoltine *E* biotype. Ratios of *E:Z* were not constant among biotypes, with the percentage of *E* isomer ranging from approximately 0-27 at a location where the *Z* strain predominated and the percentage of *Z* isomer ranging from approximately 0-24 at a location where the *E* strain predominated. Several moths which produced approximately 59-78% *E* isomer were presumed to be hybrids. Glover et al. (1987) analyzed behavioral responses of male ECB from New York to 11-tetradecenyl acetate and found that univoltine and bivoltine *Z* biotypes exhibited the greatest response to the 3% *E* isomer compared with the 0, 0.5, and 1% *E* isomers, whereas the bivoltine *E* strain produced and responded better to the 1% *Z* isomer compared with the 0, 0.5 and 3% *Z* isomers. Differences among responses for each bivoltine biotype were nonsignificant for the 0.5, 1, and 3% isomers, but were significantly greater than for the 0% isomers. For the univoltine *Z* biotype, response to the 1 and 3% *E* isomers was significantly greater than for the 0 and 0.5% *E* isomers.

Studies conducted in the southeastern United States document the sympatric occurrence of *E* and *Z* strains. Kennedy and Anderson (1980) reported that *E* and *Z* strains occurred sympatrically in North Carolina. They captured significantly more moths in the 4*E*:96*Z* traps than in the 96*E*:4*Z* traps, and stated that the occurrence of significant catches with 50*E*:50*Z* and 65*E*:35*Z* blends may indicate the existence of F_1 hybrids. DuRant et al. (1986) and DuRant and Manley (1987) reported the sympatric occurrence of both the *E* and *Z* strains of ECB in South Carolina, with the *E* strain predominating in eastern South Carolina and the *Z* strain predominating in western South Carolina. DuRant and Manley (1987) compared Trece New York (*E*) lures with Trece Iowa (*Z*) lures in several locations in South Carolina. The *E* lures captured 91.8%, 10.9%, and 1.1% of the ECB moths at Florence in northeastern South Carolina, Newberry in central South Carolina, and Clemson in northwestern South Carolina, respectively. Although both lures captured significant numbers of ECB males in central South Carolina, captures for the *Z* blend at Florence and for the *E* blend at Clemson did not differ significantly from captures for the unbaited traps.

In order to successfully monitor populations of ECB, both traps and lures must be efficient. Kennedy and Anderson (1980) concluded that sticky traps were inadequate for timing insecticide treatments in North Carolina, but Fletcher-Howell et al. (1983) reported that pheromone traps provided reliable monitoring of ECB. They attributed low second-flight catches to improper trap placement. Webster et al. (1986) and DuRant et al. (1986)

reported that *Heliothis* Scentry cone traps captured approximately seven times as many male ECB as Pherocon 1C wing traps. DuRant et al. (1986) compared commercial lures (Albany, Zoecon [Trece]) with lures formulated by R. T. Cardé (Department of Entomology, University of Massachusetts, Amherst). The Zoecon *E* lure, but not the Albany *E* lure, captured significantly more male ECB than the Cardé *E* lure (97*E*:3*Z*) in eastern South Carolina. A preliminary study which we conducted in eastern South Carolina during 1992 indicated that lures containing 99*E*:1*Z* were significantly more efficient than 95*E*:5*Z* lures and Trece *E* lures. Lures containing 99*E*:1*Z* captured approximately 10 times as many male ECB as either of the latter two lures.

The primary objective of the present study was to evaluate the relative attractiveness of four blends of (*E*)- and (*Z*)-11-tetradecenyl acetate to male ECB in three locations in South Carolina that appear to differ in predominance of the pheromone strains of the ECB. An additional objective of this study and studies conducted during 1991 and 1992 (J.A.D., unpublished data) was to determine if the relative abundance of the pheromone strains had changed since 1986 (DuRant and Manley 1987).

Materials and Methods

Pheromone gland analysis. Diapausing ECB larvae were collected from sorghum plants at Florence from 28 January - 3 February, 1993, and shipped to C.E.M. at the University of Delaware for sex pheromone gland analysis. Each larva was held in a 28 ml plastic food service cup containing a cotton dental wick saturated with water to provide a source of moisture. Larvae were maintained in a reverse photoperiod (dark cycle initiated at 1000 hours) under nondiapausing conditions at 25 ± 2°C, 16:8 (L:D) photoperiod, and a relative humidity of 50-80%. Pupae were monitored daily until adult eclosion and pheromone gland removal.

Following methods similar to Roelofs et al. (1985), pheromone glands from adult females were excised just anterior of the ring gland. Glands were excised at the sixth hour of scotophase on the second day after eclosion (moths 24-48 h old). Glands were placed with a dissecting needle into 6 µl of heptane containing 1.8 ng cis-7-tetradecenyl acetate as an internal standard in a point-tipped autosampler vial for at least 30 min and injected in a Varian 3500 gas chromatograph (Varian Associates, Sunnyvale, California) after being evaporated to approximately 3 µl. Injections of 3 µl were made using a sandwich technique where a 0.5 µl air gap was placed between the solvent plug and sample plug in a 10 µl syringe, thus preventing contact and sample contamination by the solvent plug. The gas chromatograph was equipped with a Varian 1077 split/splitless injector fitted with a 4 mm ID open-top glass uniliner (Restek Corporation, Bellefonte, Pennsylvania) containing glass wool, a fused silica capillary column 60 m by 0.25 mm with 0.25 µl Stabilwax® film thickness (Restek Corporation), a 5 m by 0.25 mm fused silica guard column, and a flame ionization detector. The gas chromatograph was programmed as follows: injector at 200°C, splitless for 2.5 min, then set to split for the remainder of the run (split ratio 50:1 set at

60°C); detector at 250°C, attenuation set at 32^{-11}; column oven programmed at 60°C, hold 1.0 min, heat from 60-240°C at 8°C/min, hold at 240°C to end of the run; and total run time was 32 min. Nitrogen was used as carrier gas at a flow rate of 19 cm/sec and as makeup gas. Under these conditions, the internal standard and two pheromone isomers eluted at approximately 28 min with each of the three peaks being separated by 0.2-0.4 min which allowed for distinct separation and detection of these compounds.

Female moths for which pheromone glands were excised and analyzed by gas chromatography were categorized by pheromone strain based on the percentage ratio of the two pheromone isomers. The percentages were determined by comparison of peak heights of the isomers at the appropriate retention times on the chromatogram. Samples with the peak height consisting of 85% or more of the *E* isomer compared with the *Z* isomer were classified as *E* strain, those with 35-80% *E* isomer were classified as hybrids, and those with 15% or less were classified as *Z* strain. Samples were not classified if there was insufficient quantity of pheromone as indicated by the lack of gas chromatography peaks at the appropriate retention times.

Preparation of lures. (*E*)- and (*Z*)-11-tetradecenyl acetate were purchased from Sigma Chemical Company, St. Louis, Missouri. Stock solutions of each isomer were prepared by adding 0.4 ml of pheromone to 3.6 ml of heptane for lures used during April and May, and by adding 0.1 ml of pheromone to 9.9 ml of heptane for lures used during the remainder of the season. Four pheromone blends, 99*E*:1*Z*, 97*E*:3*Z*, 65*E*:35*Z*, and 3*E*:97*Z*, were prepared by combining the appropriate proportions of the stock solutions with additional heptane to obtain a concentration of 100 µg pure pheromone per 12.5 µl total solution. Lures were prepared by pipetting 12.5 µl of the appropriate blend onto a silicon rubber septum (rubber stopper, red, sleeve type, 5 by 9 mm, Arthur H. Thomas Company, Swedesboro, New Jersey). Septa were placed under a fume hood for at least 1 h to evaporate the excess heptane and subsequently held in sealed glass jars in a freezer until needed.

Analysis of pheromone blends. Samples of the stock solutions of the four pheromone blends were shipped to C.E.M. at the University of Delaware and H.W.F. at Clemson University for determination of the percentage composition of each isomer.

At the University of Delaware, each stock solution was serially diluted (1:1,000) with heptane to obtain a solution containing approximately 10 ng/µl of the combined weight of the two isomers. Injection of 3 µl of this solution was made in the gas chromatograph using the same procedure as for the pheromone gland analysis except that a 30 m by 0.25 mm fused silica capillary column with 0.5 µm Stabilwax® film thickness was used and the total time for the run was reduced to 26 min. Under these conditions, the internal standard and two pheromone isomers eluted at approximately 24 min with each of the three peaks being separated by 0.2-0.3 min. Two runs were made of each of the blends tested. Detector response was recorded with a computer using a GC Star Workstation program (Varian Associates) which computed the areas of the peaks. Area for the (*E*)- and (*Z*)-11-tetradecenyl acetate peaks on the chromatogram was used to determine the percentage of each isomer in the blends.

At Clemson University, each stock solution was diluted 1:40 with heptane. These dilutions were injected (3 µl) without splitting into a gas chromatograph (Varian 3400 equipped with a Varian 8100 autosampler; Varian Associates). A 60 m by 0.25 mm fused silica capillary DB-wax column with 0.25 µm film thickness (J & W Scientific, Folsom, California) was used with the following conditions to improve separation, injector at 250°C, detector at 300°C, oven programmed for a 0.45 min hold at 90°C followed by an increase at 25°C/min to 220°C where temperature was held for 23 min. The head pressure of the columns was 703 g/cm^2. Peaks were detected using flame ionization. A Varian DS601 data system (Varian Associates) was used to integrate peak areas as a percentage of the area in the peaks for the two isomers. Dilutions containing 100% of either isomer were 99.9% pure with no cross-contamination between the isomers.

Field study. Lures were positioned in the center of the entrance (lower opening) of Albany *Heliothis* Scentry traps (United Agri Products, Fresno, California) using a taut wire. Traps were attached to metal conduit pipes so that the entrance was 1 m above the soil surface, and were arranged in a linear, randomized complete block design with three replications of each treatment (pheromone blend) adjacent to field boundries. The unbaited traps contained lures impregnated with 12.5 µl pure heptane. A fifth treatment, the Trece *E* (NY) lure (rubber stoppers, red, sleeve type, 5 by 9 mm, Pest Management Supply, Inc., Amherst, Massachusetts), was evaluated at Florence beginning on 10 June. Traps and replications were at least 30 m apart. All traps within each replication were monitored and rerandomized weekly (6-8 d intervals), at which time lures were replaced. ECB males were removed weekly and identification was confirmed when necessary by examination of genitalia (Mutuura and Munroe 1970).

Locations (dates in 1993) monitored were Florence (1 April - 2 September), Newberry (30 March - 1 September), and Clemson (25 March - 2 September). At Florence, all traps initially were located in the edge of a wheat field. Fields in this vicinity had contained corn and cotton the previous season (1992). On 3 June all traps were moved into the edge of a corn field which was adjacent to the wheat. Although the corn field was irrigated by a center pivot system, all trap locations were not within the irrigated area. Three, four, and four of six traps in replicates one, two, and three, respectively, were located outside the irrigated area. At Newberry, all traps initially were located in the edge of a wheat field which had contained corn the previous season. On 3 June, all traps were moved into the edge of an irrigated corn field which had contained corn and soybeans the previous season. At Clemson, all traps were located in grassy areas adjacent to fallow fields. Corn was planted adjacent to the traps during late May. Trap captures were summed for the season and transformed to log (x + 1) for analyses, which were performed using the ANOVA-2 and RANGE programs of MSTAT-C. Means were separated using protected least significant difference (LSD) at the 5% level of probability (MSTAT Development Team 1988).

Results and Discussion

Analyses of pheromone blends indicated that the actual ratios of *E:Z* were near the desired ratios (Table 1). Results of the analyses conducted at Clemson University differed from those of the analyses conducted at the University of Delaware, with the percentage of *E* isomer being greater for the Clemson analyses than for the Delaware analyses for the 99*E*, 97*E*, and 65*E* blends and less for the 3*E* blend. These variations between the actual and desired ratios probably had little impact on the trap captures. Roelofs et al. (1985, 1987) found that ratios of *E:Z* produced by ECB females varied widely for both the *E* and *Z* strains for mixed field populations, but exhibited very little variation in pure strains in laboratory cultures. Glover et al. (1987) reported that for bivoltine *E* and *Z* strains, differences in male responses were nonsignificant for pheromone blends containing from 0.5-3% of the minor isomer. The greatest variations from the desired ratios were observed for the Clemson University analyses of the pheromone blends used before 10 June. Since moth activity peaked after this date, any aberrations in trap capture data would have affected only a small percentage of the total number of moths captured.

Pheromone blend significantly influenced trap captures at all locations (Table 2). Moth captures at Florence ranged from 2.7-281.0 males/trap for the unbaited lure and 99*E*:1*Z*, respectively. The 99*E*:1*Z* blend was significantly superior to the remaining blends. The 97E:3Z blend was significantly superior to the 65*E*:35*Z* blend, which was significantly superior to the 3*E*:97*Z* blend and the unbaited lure. This trend was relatively consistent throughout the season, with the 99*E*:1*Z* blend producing the greatest trap captures for 15 of the 18 weeks during which moths were captured at Florence (Fig 1). Moth captures for the 97*E*:3*Z* lure and the Trece *E* lure were nearly identical, with the 97*E*:3*Z* and Trece *E* lures capturing 144 and 158 moths/traps, respectively (Fig. 2). Weekly variations in apparent relative efficacies between these two lures may have been influenced by trap location within each replication, since several trap locations for each replication were beyond the range of the irrigation system. Drought conditions during July and August 1993 severely affected the corn and other vegetation at these locations and the preference of the ECB moths for traps located within irrigated areas was obvious. However, these differences were minimized over the entire trapping period by the weekly rerandomization of the treatments.

Analysis of pheromone blends produced by ECB female moths reared from the larvae which had been collected from sorghum at Florence confirmed the presence of the *E* strain. Of 56 pheromone glands analyzed by gas chromatography, 46 had sufficient peaks for the two pheromone isomers to be determined. The percentages of *E* isomer for 43 classified as *E* pheromone strain had a mean of 96.75%, standard deviation of 2.66%, and a range of 87.8-99.1%. The percentage of *E* isomer for the three classified as hybrid had a mean of 69.4%, standard deviation of 5.82%, and a range of 65.0-76.0%. None were classified as *Z* pheromone strain.

Table 1. Results of European corn borer pheromone blend analyses at Clemson University and the University of Delaware.

Desired ratio (*E*:*Z*)	Clemson			Delaware		
	No. Samples	% *E* isomer		No. Samples	% *E* isomer	
		Mean %	Range		Mean %	Range
Lures used until 10 June (Florence, Newberry), 13 June (Clemson)						
99:1	5	99.9	NV[a]	2	99.2	99.1 - 99.4
97:3	6	98.8	97.7 - 99.4	2	97.1	97.1 - 97.2
65:35	6	64.4	63.4 - 65.7	2	60.3	60.0 - 60.6
3:97	3	1.2	0.6 - 2.3	3	3.1	3.0 - 3.2
Lures used after 10 June (Florence, Newberry), 13 June (Clemson)						
99:1	3	99.2	NV[a]	2	98.7	98.6 - 98.8
97:3	3	97.1	NV[a]	2	96.8	96.7 - 96.9
65:35	4	67.0	66.2 - 68.5	2	66.3	66.2 - 66.4
3:97	1	3.0	–	2	3.9	NV[a]

[a] NV means no variation among samples.

The absence of the *Z* phenotype in the gland analysis and the very low number of males in the 3*E*:97*Z* traps indicate that the *Z* strain is not maintaining a reproducing population in the Florence area. The presence of the 6.5% hybrids in the gland analysis and the 4.9% males caught by the 65*E*:35*Z* traps suggest that immigration of *Z* strain adults is occurring occassionally in this population.

Moth captures at Newberry ranged from 0.3-36.3 males/trap for the unbaited lure and 3*E*:97*Z*, respectively (Table 2). The 3*E*:97*Z* blend was significantly superior to all remaining blends except 99*E*:1*Z*, and all blends significantly increased moth captures compared with the unbaited lure. This trend was relatively consistent throughout the season except for June, when the remaining three blends produced the greatest moth captures (Fig 3). The 65*E*:35*Z* traps captured 11.2% of the total males collected in baited traps suggesting that natural crossing of the two strains is occurring.

Moth captures at Clemson ranged from 0.7-84.0 males/trap for the unbaited lure and 3*E*:97*Z*, respectively (Table 2). The 3*E*:97*Z* blend was significantly superior to 65*E*:35*Z* which was significantly superior to the remaining blends. This trend was consistent throughout the season (Fig. 4). The 12.1% of total males captured in the baited traps for the 65*E*:35*Z* blend

Table 2. European corn borer male moth captures in traps baited with four blends of (*E*) - and (*Z*)-11-tetradecenyl acetate at three locations in South Carolina during 1 April - 3 September, 1993.

Blend (E:Z)	Mean number of males/trap (percentage of total)[a,b]		
	Florence	Newberry	Clemson
99.1	281.0a (77.0)	21.3 ab (27.4)	2.3 c (2.3)
97:3	62.0b (17.0)	11.3 b (14.6)	3.0 c (2.9)
65:35	17.7c (4.9)	8.7 b (11.2)	12.3 b (12.1)
3:97	4.0d (1.1)	36.3 a (46.8)	84.0 a (82.7)
Unbaited	2.7d	0.3 c	0.7 d

[a] Means within a column followed by the same letter do not differ significantly ($P < 0.05$ by protected LSD) (MSTAT Development Team 1988). Data were transformed to log (x + 1) for analysis but original means are presented.
[b] Unbaited trap catches were excluded from percentage calculations.

appears high considering the relatively low percentage caught in the 99*E*:1*Z* and 97*E*:3*Z* traps combined and the 11.1% captured by the 65*E*:35*Z* traps at Newberry where relatively high proportions of both the *E* and *Z* strains were captured. This may be partially due to the response of the males of the *E* strain and the hybrids to a range of pheromone blends as discussed by Glover et al. (1991). Hybrid males tend to respond to intermediate blends (65, 50, and 35% *E*) and 3*E*:97*Z*, but not to 99*E*:1*Z*. The *E* strain males will also respond to intermediate blends in addition to the 99*E*:1*Z* blend. Perhaps another factor is that the low proportion of the *E* strain in the population may lead to most of its F_1 progeny being hybrid. Also, there may be immigration of some *E* strain and hybrid individuals. Collectively, these factors might explain the relatively high percentage of males captured in the 65*E*:35*Z* traps at Clemson compared with Newberry. Pheromone gland analysis of females sampled simultaneously from the populations at the three locations used in this study is needed to provide additional information on the proportion of pheromone phenotypes and the degree of natural hybridization in South Carolina.

Comparison of the relative proportions of *E* and *Z* strains of the ECB for 1993 versus 1986 is impeded because only two lures, Trece *E* and Trece *Z*, were compared at each location during 1986 whereas in 1993 three *E* lures (99*E*:1*Z*, 97*E*:3*Z*, and Trece) were evaluated at Florence and two *E* lures (99E:1*Z* and 97*E*:3*Z*) were evaluated at Newberry and Clemson. Competition among these similar blends may have resulted in reduced capture of moths by each lure compared with the 3*E*:97*Z* lure. However, during 1991 and 1992 only Trece *E* and Trece *Z* lures were compared at all three locations (J. A. D.,

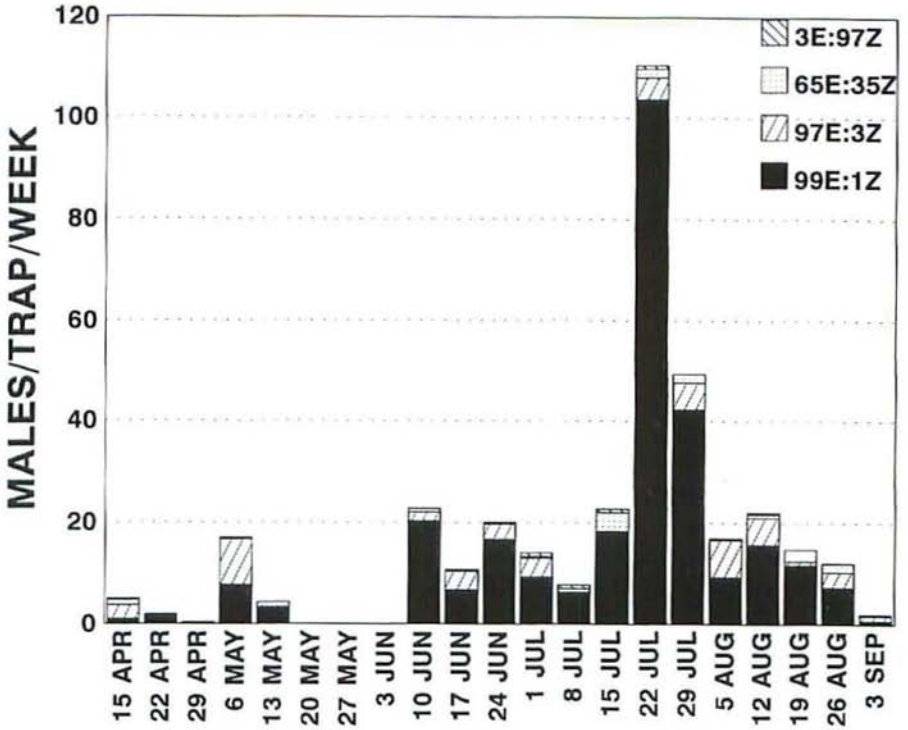

Fig. 1. Weekly mean numbers of European corn borer moths captured by traps baited with four blends of (*E*)- and (*Z*)-11-tetradecenyl acetate at Florence, South Carolina during 1993.

unpublished data). At Florence, the Trece *E* lure captured 91.8%, 95.9%, 92.9%, and 93.9% of the ECB moths during 1987, 1991, 1992, and 1993, respectively, indicating that no substantial change has occurred in the relative proportions of *E* and *Z* strains. At Newberry, the Trece *E* (97*E*:3*Z* in 1993) lure captured 10.9%, 22.6%, 23.0%, and 23.7% of the moths during these four years, indicating that the proportion of the *E* strain increased between 1986 and 1991, but since then has remained relatively stable. At Clemson, the Trece *E* (97*E*:3*Z* in 1993) lure captured 1.1%, 18.7%, 14.0% and 3.4% of the moths during 1987, 1991, 1992, and 1993, respectively, indicating that the proportion of the *E* strain increased between 1986 and 1991, followed by a gradual decline during the past two years.

The relatively low proportion of moths captured by the 65*E*:35*Z* lures at Newberry and the apparent relative stability of the ratios of the two pheromone strains at each location since 1986 indicate that genetic shift of sex pheromone blends has not occurred to any great extent. Glover et al.

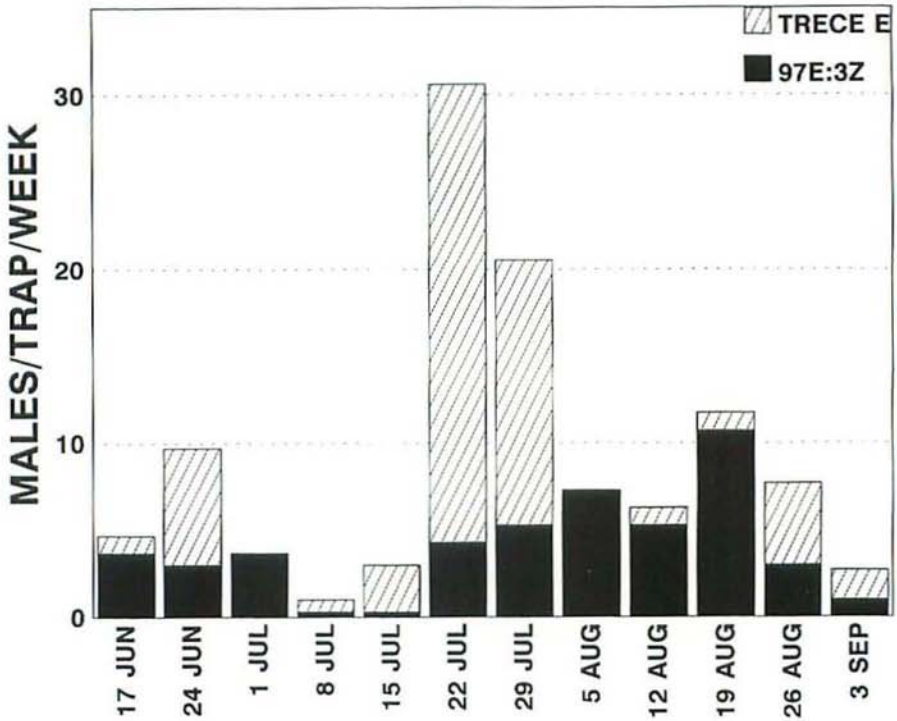

Fig. 2. Weekly mean numbers of European corn borer moths captured by traps baited with a known blend of (*E*)- and (*Z*)-11-tetradecenyl acetate and a commercial lure at Florence, South Carolina during 1993.

(1991) reported that *Z* races of the ECB predominate over most of the ECB range in Europe and North America, whereas the *E* race is restricted to select locations in Switzerland, Italy, and eastern North America. They cited the unidirectional gene flow from the *E* populations into the univoltine *Z* populations in New York and the resulting apparent genetic isolation of the *E* race as a possible reason for the limited geographical range of the *E* strain.

The *E* pheromone strain of the ECB was predominant at Florence in northeastern South Carolina and the *Z* strain was predominant at Clemson in the northwestern portion of the state. Results for 1993 were consistent with earlier results (DuRant and Manley 1987) in that trap captures of the *Z* strain at Florence were not significantly greater than captures for the unbaited traps. Although analysis of pheromone glands of ECB females from Florence confirmed the presence of the *E* strain, but not the *Z* strain, at this location, the presence of the *Z* strain cannot be ruled out. A relatively low population of *Z* strain moths could have been missed due to the small number (46) of females analyzed. Both studies indicate that both strains occur sympatrically at Newberry, in central South Carolina. Possible hybrids

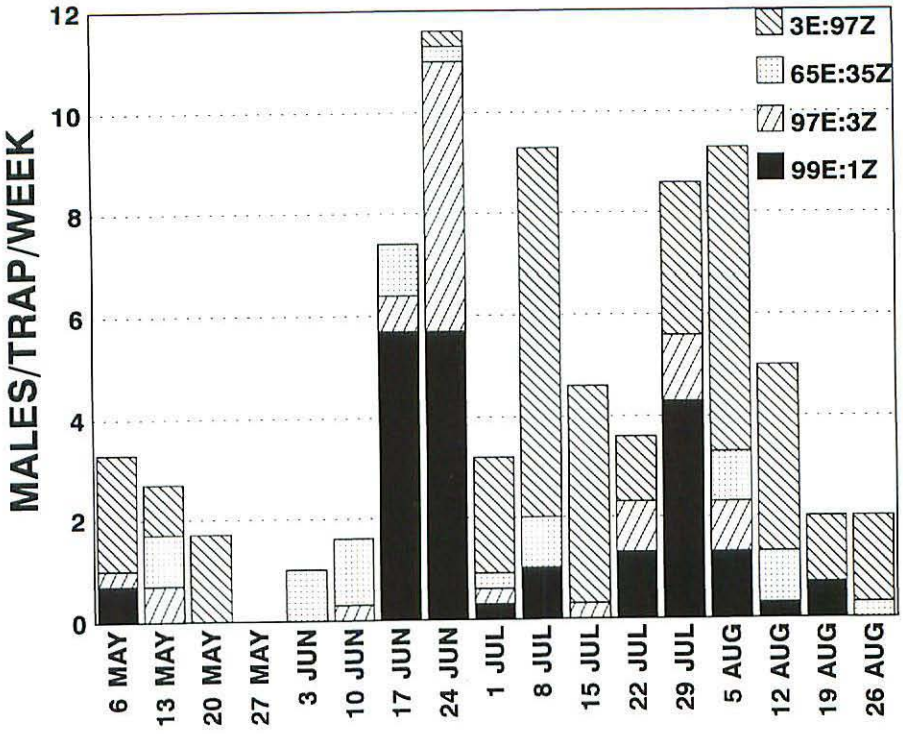

Fig. 3. Weekly mean numbers of European corn borer moths captured by traps baited with four blends of (*E*)- and (*Z*)-11-tetradecenyl acetate at Newberry, South Carolina during 1993.

were detected at all three locations, indicating that both strains may occur at Florence and Clemson, possibly as a result of occasional immigration. This study confirmed the superior effectiveness of the 99*E*:1*Z* pheromone blend at Florence compared with the 97*E*:1*Z* blend and the Trece *E* lure. These results should enhance development of a more effective lure for the *E* strain of the ECB in South Carolina and at other locations where this strain occurs.

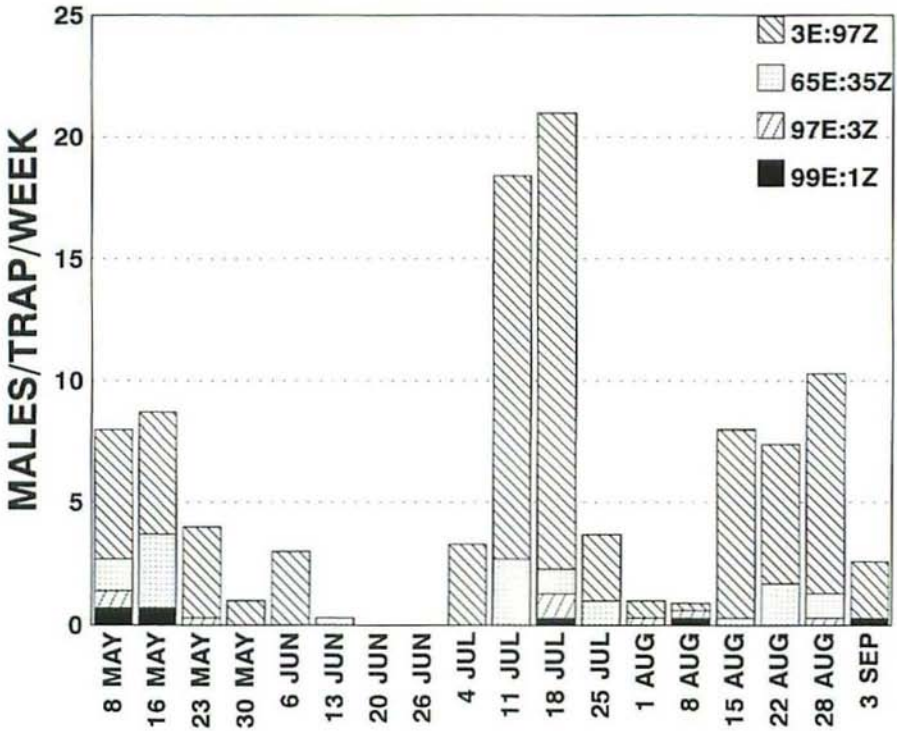

Fig. 4. Weekly mean numbers of European corn borer moths captured by traps baited with four blends of (*E*)- and (*Z*)-11-tetradecenyl acetate at Clemson, South Carolina during 1993.

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Effects of Malathion Bait Sprays on Nontarget Insects Associated with Corn in Western Kauai, Hawaii[1]

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ABSTRACT Malathion bait sprays were applied to border rows of sweet corn (*Zea maize* L.) planted adjacent to papaya and cucurbit fields in Kauai, Hawaii. The sprays were used to control the tephritid fruit flies, *Bactrocera dorsalis* (Hendel) and *B. cucurbitae* (Coquillett), that oviposit into papaya and cucurbits but spend much of their time roosting on adjacent border vegetation. Sweep-net samples in both treated and untreated corn plantings showed that significant reductions in overall species richness and species diversity occurred in malathion-bait treated corn. Numbers of beneficial insects (predators and parasitoids) were also reduced in treated corn, although this reduction may have resulted from prey depletion as well as direct mortality. Endemic insects were not well represented in the samples, and do not appear to be at risk from corn border spraying in western Kauai.

KEY WORDS Fruit flies, nontarget insects, malathion, bait sprays, corn

Four species of alien tephritid fruit flies are major pests of agriculture in Hawaii. Of these, the most damaging to vegetable crops is the melon fly, *Bactrocera cucurbitae* (Coquillett) (Diptera: Tephritidae). This species is known to spend a large amount of time on vegetation surrounding crop fields, and minimal time on the crop itself (Nishida and Bess 1950). Thus, treatment of border vegetation with malathion baits is a widely used method to control melon fly on many small truck farms in Hawaii. The effectiveness of this technique has been documented in tomatoes (*Lycopersicon esculentum* Mill.), cucumbers (*Cucumis sativus* L.), and watermelons (*Citrullus lanatus* (Thunb.) (Nishida and Bess 1957). It is also sometimes used by growers of tropical tree fruits to control the Oriental fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae).

A pilot project by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) in Hawaii was implemented to test the feasibility of creating a 9 km^2 fruit fly-free zone in the Moloa'a agricultural area on the island of Kauai (see USDA-ARS 1989 report for complete description of the Moloa'a site and project goals). One of the protocols of this project involved planting 2 m wide borders of corn,

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Zea maize L., as a trap crop around all vegetable and papaya, *Carica papaya* L., fields. The trap corn was treated weekly with applications of malathion bait sprays to control both melon fly and Oriental fruit fly (USDA-ARS 1989). Success with this technique could lead to its incorporation into large-scale eradication programs throughout Hawaii in the future.

The potential application of malathion bait sprays throughout large areas of agricultural production land on Kauai has been controversial. An environmental assessment prepared for the project (USDA-ARS 1989) stated that there would be no nontarget impacts as a result of the sprays. Some entomologists stated that bait sprays would only affect tephritid fruit flies attracted to, and feeding on, the protein bait. However, a number of studies in California have documented significant impacts of malathion bait sprays on non-target species, including both beneficial predators and parasitoids (e.g., Ehler and Endicott 1984, Daane et al. 1990) and endemic or indigenous herbivores (e.g., Ehler et al. 1984, Troetschler 1983). Thus, possible effects of malathion and other fruit fly control measures on the Hawaiian insect fauna have raised serious concerns (Consortium for International Crop Protection 1985). Therefore, we initiated a study to gather baseline data concerning the effect of malathion bait sprays on insects associated with corn in western Kauai. Although border treatments are presently used by farmers throughout the state, no studies have examined the impact of these bait sprays on nontarget species associated with corn in Hawaii.

Materials and Methods

Bait spray treatments were replicated at four farm sites in western Kauai in 1991 where rows of corn were planted adjacent to crops supporting fruit fly populations. We chose actual farm sites rather than using experimental plots to reflect the more realistic interplanting and cropping practices used in Kauai, although this resulted in less uniformity and experimental control. Two of the sites, Moloa'a A and B, were at the Moloa'a agricultural area on the northeast coast of Kauai. The other two sites, Wailua A and B, were near the Kauai Agricultural Research Center which is approximately 8 km east of Kapa'a.

The Moloa'a A site consisted of approximately 0.1 ha of Hawaii Super Sweet #10A corn planted in nine rows 2 m apart adjacent to a 0.4 ha field of Sunrise papayas. The Moloa'a B site contained 0.4 ha of alternating double rows of corn and young papaya that were spaced 2 m apart. At both of these sites, the southern half of every corn-row was sprayed weekly with malathion-bait while the northern half of each row was left untreated.

The Wailua A site had between three and six rows of Super Sweet #9 corn completely surrounding a 0.2 ha field of cucumbers. The Wailua B site had between four and ten rows of corn surrounding a 0.1 ha field of mixed varieties of bittermelon, *Momordica charantia* L. An additional six rows of corn approximately 80 m in length were planted midway between the two sites. All border rows surrounding both cucurbit fields were treated with malathion baits. The northern and southern halves of the six-row corn plantings between the cucurbit fields served as untreated controls for A and B, respectively. Summer tradewinds on Kauai blow predominantly from the

B, respectively. Summer tradewinds on Kauai blow predominantly from the east-northeast, perpendicular to the untreated corn-rows.

Malathion bait treatments were applied beginning when corn seedlings were approximately 15 cm tall. The spray mixture consisted of 0.3 liters of malathion 5 EC (Drexel Co., Memphis, Tennessee), 1 liter of Nu-lure® protein bait (Miller Chemical Co., Hanover, Pennsylvania), plus sufficient water to make 12 liters. The mixture was applied to the point of runoff with a backpack sprayer fitted with a #6 nozzle tip to create uniform droplet sizes. Each field was treated weekly (as specified in the USDA pilot project) until the corn was harvested.

Insects were sampled from both treated and untreated corn plots at all sites two or three times prior to spraying, and once a week after treatment until harvest. A total of 100 sweeps with a sweep net (38 cm diameter) were made vertically (along the stalks) and horizontally (across the tops) of randomly chosen rows of corn plants in each treatment and control plot 2 d after each application. All insects collected were transferred to 70% alcohol in the field and taken to the laboratory for identification and counting. In addition, two whole corn plants from each treatment and control plot were covered with plastic bags, pulled out by the roots, and taken to the laboratory where they were placed in a freezer for 24 hr. These plants were examined and the adults and nymphs of the most abundant herbivore, the corn delphacid, *Peregrinus maidis* (Ashmead) (Homoptera: Delphacidae), were counted.

A clear vinyl floor runner (15 m long by 68 cm wide by 1 mm thick) was rolled onto the ground between the rows of corn before treatment. Two hours after treatment, the corn stalks were shaken vigorously to dislodge any dead insects onto the runners where they were collected and taken to the laboratory for identification. In control plots, vinyl runners could not be set out simultaneously with those on treated plots because of the labor requirements on any given day. However, a total of 18 samples were taken at irregular intervals during the season in which the unsprayed corn rows were shaken over identical vinyl runners.

Voucher specimens of all species collected were deposited in the insect collection at the University of Hawaii, Kauai Agricultural Research Center. Spiders were excluded from the study because of their infrequent occurrence in sweep-net samples and the difficulty of identifying the Hawaiian fauna.

Because the four corn sites were not planted simultaneously, sampling dates and the number of samples before and after applications differed slightly among fields. Therefore, data on species richness, species diversity, and total numbers of insects in particular taxa were not analyzed by Julian date. Instead, they were pooled into three phenological periods reflecting the time interval since planting. This grouping was justified because the weather stayed relatively uniform over the entire experimental period. The three periods were categorized as an early season, pre-treatment sample; a mid-season sample taken during the first 3 wk following treatment; and a late season sample taken during the period later than 3 wk after treatment until harvest.

Species diversity for each sample period was calculated using the formula

$$H' = \sum_{i=1}^{s} [P_i \bullet \ln P_i]$$

where H' = index of diversity, P_i = proportional abundance of each species, and s = total number of species in community (Magurran 1988). Species richness equals the cumulative number of species represented in each sample. Species diversity, richness, and population density of predators and parasitoids were determined from sweep-net samples. The density of *P. maidis* was determined from frozen whole corn samples. Relationships between plant phenology and species richness, species diversity, and predator-parasitoid density were examined using analysis of variance of untransformed data. Means of treatment versus control plots within each sample period were compared using Student's t-test.

Results

In the untreated corn, species richness was significantly higher during the late season than the early- and mid-season samples ($F = 3.949$, $P = 0.0290$). In three of the four untreated sites the number of species more than doubled from the initial to the final sample, and overall the mean increased from 10.8 to 17.7 species/sample. Species richness in bait-treated plots, however, did not increase during the study ($F = 0.322$, $P = 0.7267$), with only 11.4 species /sample at the end of the season compared with 9.7 at the beginning. There were no differences in numbers of species between treated and untreated plots during early and mid-season samples, but there were significantly fewer species in treated plots in late-season samples ($t = 5.41$, $P < 0.001$) (Table 1).

Species diversity (H') in untreated plots increased significantly from early-season to late-season ($F = 3.890$, $P = 0.0304$), but did not increase correspondingly in treated plots ($F = 2.324$, $P = 0.1137$). At the Moloa'a B site, H' was significantly lower in the treated than the untreated plot for all sample dates following the initial insecticide application (Fig. 1). In the three other field sites, species diversity in treated plots was lower than in untreated plots only during the last 2-3 wk of the season.

Two-hundred and fourteen dead insects from 65 species were collected beneath treated corn plants immediately following malathion bait applications, presumably killed by the spray or consumption of poisoned prey (Table 2). In contrast, only 23 insects from 11 species were collected beneath untreated corn, including a single unidentified micro-lepidopteran, a single unidentified carabid, and two specimens each of *Nezara* (Heteroptera: Pentatomidae) and *Micromeriella* (Hymenoptera: Scoliidae). There was a mean of 7.9 insects/sample in treated plots versus only 1.3 insects/sample for control plots, where a sample includes all insects collected from a vinyl runner on a given date. Although a strict statistical comparison cannot be made because control samples were not taken simultaneously with treated samples, the large differences in the number of insects per sample and the number of

Table 1. Effects of malathion-bait sprays on nontarget insects in corn.[a]

Season[b]	No. of Species		No. of Herbivores		No. of Delphacids		No. of Natural Enemies[c]	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
Early	10.8 ± 2.4	9.7 ± 2.8	7.7 ± 2.0	8.0 ± 2.6	5.2 ± 3.6	2.7 ± 1.8	4.4 ± 1.8	4.3 ± 2.0
Mid	11.7 ± 1.7	9.8 ± 1.3	25.9 ± 10.6	17.0 ± 5.2	20.8 ± 7.3	1.3 ± 0.5[d]	8.8 ± 2.4	2.8 ± 0.5[d]
Late	17.7 ± 1.7	11.4 ± 1.1[d]	21.2 ± 2.6	9.8 ± 2.7[d]	121.1 ± 44.8	8.9 ± 3.5[d]	9.4 ± 1.4	3.8 ± 0.8[d]

[a] Data expressed as mean ± SE/100 sweeps with sweep net or, for delphacids, mean ± SE/whole corn plant.
[b] Early season is the sampling period prior to treatment, mid-season is the sampling period during the first 3 wks following treatment, and late season is the sampling period later than 3 wks after treatment.
[c] Includes all species known to be predaceous or parasitic in at least one life stage.
[d] Treated and untreated in a sampling period were significantly different using a paired t-test ($P < 0.05$).

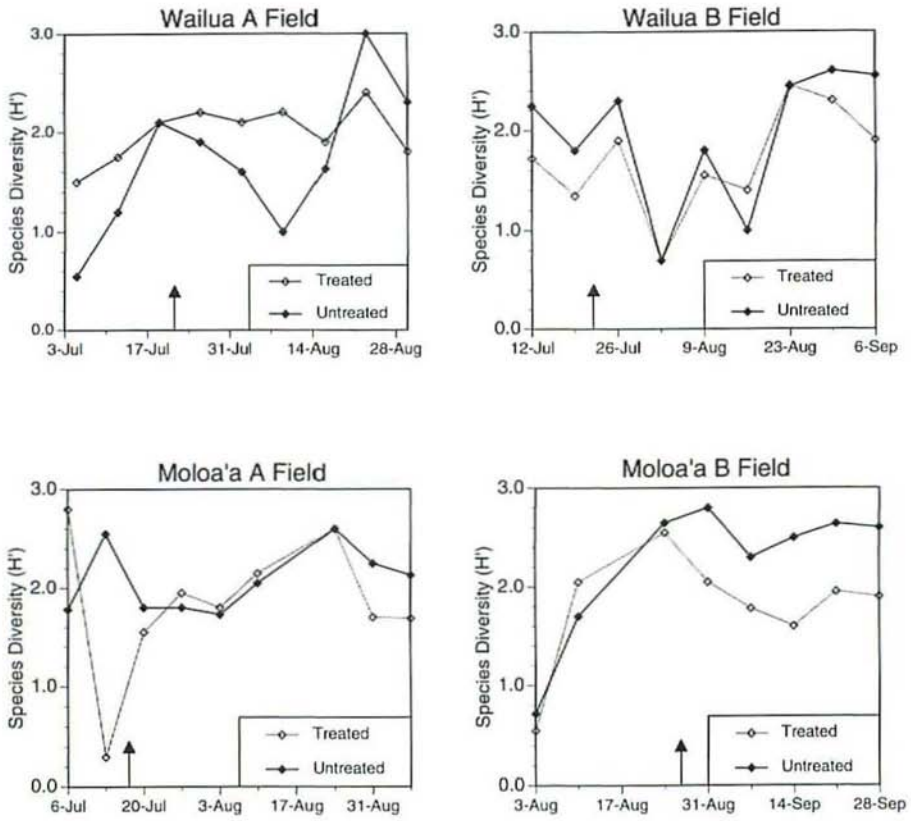

Fig. 1. Species diversity (H') in malathion-bait treated and untreated corn borders in western Kauai, Hawaii, 1991 (arrows indicate first malathion-bait spray in each field).

differences in the number of insects per sample and the number of species represented are consistent with an interpretation of malathion-induced mortality.

Insects from six species of parasitic Hymenoptera and 15 predaceous or partly predaceous species were among those found beneath sprayed plants and presumed killed by the application of the insecticide. Two of these, *Orius insidious* (Say) (Hemiptera: Anthocoridae) and *Cyrtorhinus lividipennis* Reuter (Hemiptera: Miridae), are known to be important biological control agents of preimaginal Lepidoptera and the corn delphacid, respectively (Dicke and Jarvis 1962, Liquido and Nishida 1985, Napompeth 1973). The number of living predators and parasitoids collected in sweep-net samples increased significantly in

Table 2. Dead insects collected beneath malathion-bait sprayed corn[a]

Feeding Behavior	Order	Family	Genus and/or Species
Parasitoids	Hymenoptera	Braconidae	*Chelonus blackburni* Cameron
	Hymenoptera	Chalcididae	*Antrocephalus* sp.
	Hymenoptera	Ichneumonidae	*Trathala flavoorbitalis* (Cameron)
	Hymenoptera	Ichneumonidae	*Xanthopimpila punctata* (F.)
	Hymenoptera	Pteromalidae	pteromalid sp. A
	Hymenoptera	Pteromalideae	pteromalid sp. B
Predators	Coleoptera	Coccinellidae	*Coelophora inaequalis* (F.)
	Coleoptera	Staphylinidae	*Philonthus discoideus* (Gravenhorst)
	Diptera	Dolichopodidae	*Chrysosoma globiferum* Wiedemann
	Diptera	Syrphidae	*Allograpta obliqua* (Say)
	Diptera	Syrphidae	*Symosyrphus grandicornis* (Macquart)
	Heteroptera	Anthocoridae	*Orius insidious* (Say)
	Heteroptera	Miridae	*Cyrtorhinus lividipennis* Reuter
	Heteroptera	Miridae	*Tythus mundulus* (Breddin)
	Heteroptera	Reduviidae	*Zelus renardii* Kolenati
	Hymenoptera	Formicidae	*Pheidole megacephala* (F.)
	Hymenoptera	Scoliidae	*Campsomeris marginella* Klug
	Hymenoptera	Sphecidae	**Liris* sp.
	Orthoptera	Gryllidae	*Cycloptilum bimaculatum* (Shiraki)
	Orthoptera	Gryllidae	*Gryllus bimaculatus* DeGeer
	Orthoptera	Gryllidae	*Metioche vittaticolis* (Stal)
	Orthoptera	Tettigoniidae	*Concocephalus saltator* (Saussure)
	Orthoptera	Tettigoniidae	*Xiphidiopsis lita* Hebard
Herbivores or Scavengers	Coleoptera	Anthribidae	*Araecerus fasciculatus* (DeGeer)
	Coleoptera	Bruchidae	*Acanthoscelides obtectus* (Say)
	Coleoptera	Chrysomellidae	*Epitrix hirtipennis* (Melsheimer)
	Coleoptera	Elateridae	*Conoderus exsul* (Sharp)
	Coleoptera	Elateridae	*Simodactylus cinnamomeus* (Boisduval)
	Coleoptera	Mycetophagidae	*Litargus vestitus* Sharp
	Coleoptera	Nitidulidae	**Carpophilus dimidiatus* (F.)
	Coleoptera	Nitidulidae	*Carpophilus hemipterus* (L.)
	Coleoptera	Nitidulidae	*Urophorus humeralis* (F.)
	Coleoptera	Scarabaeidae	**Adoretus sinicus* Burmeister
	Coleoptera	Sylvanidae	*Cryptamorpha desjardionsi* (Guerin-Meneville)
	Dictyoptera	Blattellidae	**Blatella lituricollis* (Walker)
	Diptera	Calliphoridae	*Chrysomya megacephala* (F.)
	Diptera	Ceratopogonidae	*Forcipomyia hardyi* Wirth & Howarth
	Diptera	Chloropidae	*Gaurax bicoloripes* (Malloch)
	Diptera	Chloropidae	*Monochaetoscinella anonyma* (Williston)
	Diptera	Drosophilidae	*Drosophila* sp.
	Diptera	Lauxaniidae	*Homoneura hawaiiensis* (Grimshaw)
	Diptera	Lauxaniidae	*Homoneura unguiculata* (Kertesz)
	Diptera	Lonchaeidae	*Lamprolonchaea metatarsata* (Kertesz)
	Diptera	Milichiidae	*Desmometopa tarsalis* Loew

Table 2. Continued.

Feeding Behavior	Order	Family	Genus and/or Species
Herbivores or Scavengers	Diptera	Milichiidae	*Milichiella lacteipennis* (Loew)
	Diptera	Muscidae	*Muscid sp. A
	Diptera	Otitidae	*Acrostica apicalis* (Williston)
	Diptera	Otitidae	*Euxesta annonae* (F.)
	Diptera	Otitidae	*Notogramma cimiciforme* Loew
	Diptera	Sarcophagidae	Sarcophagid sp. A
	Diptera	Syrphidae	*Eumerus aurifrons* (Wiedemann)
	Diptera	Syrphidae	*Eumerus figurans* (Walker)
	Diptera	Tephritidae	*Bactrocera cucurbitae* (Coquillett)
	Diptera	Tephritidae	*Bactrocera dorsalis* (Hendel)
	Diptera	Tephritidae	*Dioxyna sororcula* (Wiedemann)
	Heteroptera	Cydnidae	**Rhytidoporus indentatus* Uhler
	Heteroptera	Lygaeidae	*Nysius* sp. nr. *vinitor*
	Heteroptera	Miridae	*Spanagonicus albofasciatus* (Reuter)
	Heteroptera	Miridae	*Taylorilygus pallidulus* (Blanchard)
	Heteroptera	Tingidae	*Leptodictya tabida* (Herrich-Schaeffer)
	Homoptera	Delphacidae	**Perigrinus maidis* (Ashmead)
	Homoptera	Delphacidae	*Sardia rostrata pluto* (Kirkaldy)
	Homoptera	Flatidae	*Melormenis basalis* (Walker)
	Homoptera	Gryllidae	*Metioche vittaticollis* (Stal)
	Hymenoptera	Aphidae	*Apis mellifera* L.

[a] Only those species marked with an asterisk were also found beneath untreated corn.

control plots from early to late in the season, while in treatment plots their numbers did not increase. Treated plots had significantly lower populations of natural enemies than control plots during mid- and late-season samples (Table 1). The number of herbivores in the sweep-net samples was significantly lower in treated than in control plots during the late-season sample only (Table 1).

Discussion

The application of malathion bait sprays to corn had a demonstrable effect on insects other than the tephritid fruit flies which were the target pests. Two indices of community development, species richness and species diversity, showed significant increases in untreated corn, but no increases in malathion-bait treated corn during the season. Thus, treated plots had lower richness and diversity than untreated plots in late-season samples. The decline of insect species richness and species diversity in pesticide-treated plots is, perhaps, not surprising. Nevertheless, these data provide the first documentation that bait sprays do affect nontarget insect populations in Hawaii. The incorporation of malathion into a proteinaceous bait and the use

of a large droplet size is meant to make the insecticide application selective, killing only tephritid flies which consume the bait. However, these data indicate that additional species are directly or indirectly impacted by this method of fruit fly control in Hawaii.

Several field studies documenting direct mortality of nontarget arthropods by malathion bait treatments corroborate our results and illustrate that a large number and wide variety of species can be affected. For example, Troetschler (1983) listed isopods, earwigs, tree crickets, and carabids as being directly killed by bait sprays. He also documented massive mortality in a population of the California oakworm, *Phryganidia californica* Packard (Lepidoptera: Dioptidae). Ichinohe et al. (1977) also listed 99 species of insects and 17 species of spiders killed by malathion bait sprays.

Many dead predators and parasitoids as well as herbivores were collected from beneath treated corn plants 2 h following bait applications (Table 2). However, firm conclusions regarding any individual species cannot be drawn because only low numbers of individuals of most species were collected. The fact that numerous predators and parasitoids were represented in the vinyl runner samples is consistent with the reductions in predator-parasitoid density documented in the sweep-net samples (Table 1).

While it appeared likely that predators and parasitoids were killed directly by the treatments, starvation or emigration due to prey depletion may have also contributed to differences in natural enemy abundance between treated and untreated plots. The most abundant prey species at all sites was the delphacid, which increased 24 fold (from a mean of 5.2 - 121.1/plant) during the season in untreated plots, but only 3 fold (from a mean of 2.7 - 8.9/plant) in treated plots (Table 1). This reduction in delphacid population growth in treated plots (and noticeable concomitant reduction in honeydew on the corn plants) was a possible factor leading to the observed reductions of predators and parasitoids. However, overall reductions in delphacid abundance also suggest a possible secondary benefit of malathion bait applications applied for fruit fly control in corn. These treatments may reduce population growth of planthoppers (by direct contact toxicity) sufficiently to improve crop yield (although no yield data were taken in the present experiment).

In Hawaii, endemic arthropods receive critical attention in all evaluations of potential environmental impact because of the unique and fragile nature of the native fauna. However, lowland agricultural areas on Kauai are highly disturbed and inhabited overwhelmingly by exotic species (Asquith and Messing 1992). The only endemic Hawaiian insect which we found in any of the corn samples was *Forcipomyia hardyi* Wirth and Howarth (Diptera: Ceratopogonidae). It is common on all the Hawaiian islands at elevations up to 1200 m (Wirth and Howarth 1982) and breeds in a variety of aquatic habitats, including the base of cabbage plants and wet leaves and trash on the forest floor (Williams 1944, Hardy 1960). In a survey of the lowland arthropod fauna on Kauai, Asquith and Messing (1992) found *F. hardyi* to be the most common endemic species recovered. It was abundant even in samples from crop fields. Since this species can utilize intensively managed areas which have sustained large scale

monocultures and heavy pesticide use in the past, it is not likely to be adversely effected by corn border treatments.

Applying malathion bait sprays to border rows of sweet corn in lowland agricultural areas of western Kauai appears to be an innocuous fruit fly control method in terms of impacts on endemic Hawaiian arthropods. The practice may also contribute incidentally to the control of phytophagous pests such as the corn delphacid. Clearly, malathion bait sprays affect other insect populations besides the target fruit flies even though the toxicant is mixed with a proteinaceous bait and applied in large droplets. Treatments have either direct or indirect impacts on populations of some insect predators and parasitoids, but a reduction in biological control in corn or surrounding crops has not be demonstrated. Other workers have documented the susceptibility of natural enemies to malathion baits. They have pointed out that resultant predator and parasitoid mortality may lead to disruption of biological control (Daane et al. 1990, Cohen et al. 1988, Ehler and Endicott 1984, Ehler et al. 1984).

More than 40 ha of papaya are dispersed among 250 ha of agricultural production land at the Moloa'a area on Kauai. The original USDA-ARS protocol for establishment of a fruit fly free zone called for 2 m wide corn borders around all papaya fields to be treated with malathion baits (USDA-ARS 1989). The possibility of even more extensive malathion-bait applications in the future (e.g., in the 2,000 ha of coffee infested with Mediterranean fruit fly, *Ceratitus capitata* (Wiedemann) (Diptera: Tephritidae), in southern Kauai) has also been raised. The effect of such area-wide bait sprays on all nontarget species cannot be predicted, but the data presented here show that populations of insects other than tephritid fruit flies may be affected. More detailed studies under Hawaiian conditions are needed to assess potential side effects of widespread malathion-bait spray programs before appropriate cost-benefit analyses can be conducted.

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Susceptibility of Field Populations of the European Corn Borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae), to *Bacillus thuringiensis* (Berliner)[1]

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ABSTRACT Susceptibility to the CryIA(b) protein from *Bacillus thuringiensis* (Berliner) was determined for five field-collected populations and one laboratory colony of the European corn borer, *Ostrinia nubilalis* (Hübner). Field-collected larvae were reared for two generations in the laboratory, and susceptibility of neonate larvae was determined with feeding bioassays where increasing concentrations of the CryIA(b) toxin were applied to the surface of artificial diet. In general, the response to *B. thuringiensis* among the populations was similar based on the slopes of the dose mortality curves. However, significant differences in susceptibility (greater than 5 fold) based on LC_{50} values were observed. Repeated and prolonged exposure to *B. thuringiensis* is not known to have occurred in the populations tested indicating that the observed tolerance was due simply to natural variability among geographically distinct populations and unrelated to selective pressures associated with insecticide exposure.

KEY WORDS *Ostrinia nubilalis*, Lepidoptera, Pyralidae, *Bacillus thuringiensis*, bioassays

Microbial insecticides based on the bacterium, *Bacillus thuringiensis* (Berliner), are currently used for control of the European corn borer (ECB) *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae), in cultivated corn. In addition, corn plants which have been genetically altered to express the delta-endotoxin gene from *B. thuringiensis* are being developed, field tested, and may soon be marketed for use throughout the corn belt (Koziel et al. 1993). The advantages of genetically engineered plants include more efficient delivery of active ingredient to the target pest, less input in terms of the costs of pesticide application, and reduced

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environmental impact from pesticide use. Although genetically altered plants producing their own protective insecticides provide an exciting new approach to insect control, a large scale introduction of these crops could rapidly lead to the development of resistance to *B. thuringiensis* within pest populations (Tabashnik 1993). The combined impact of transgenic corn and increased use of formulated *B. thuringiensis* for ECB management increases the likelihood of resistance development which would negate the economic and environmental benefits of this important management option.

Bacillus thuringiensis resistance has been documented in the laboratory for several pest insects exposed to high doses of the toxin (reviewed by Tabashnik 1993) and in field populations of the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) (Tabashnik et al. 1990), where formulated *B. thuringiensis* was used repeatedly. Resistance to formulated *B. thuringiensis* in ECB has not been observed despite almost 20 years of field applications. However, current use of *B. thuringiensis* formulations is generally limited and occurs in conjunction with other control strategies such that reduced selection pressures may prevent resistance development. With genetically altered plants, however, every ECB larva that feeds on corn would be exposed to the toxin, and, therefore, the selection pressures may be greatly magnified.

One of the most important research needs currently in *B. thuringiensis* resistance management programs is the development of baseline susceptibility studies of key insect pests in all ecosystems where *B. thuringiensis* will be used (Whalon 1992). This study reports results from experiments designed to establish bioassay procedures and to determine if differences exist in susceptibility to CryIA (b) toxin among ECB field populations collected from Nebraska.

Materials and Methods

Insects. Late-instar ECB larvae were collected from five locations within Nebraska (Fig. 1) during June 1993. Each site was separated from the others by at least 100 km. Larvae were excised from infested corn stalks and immediately placed on ECB diet (Lewis and Lynch 1969) in individual containers to minimize disease transmission. Approximately 150 larvae were collected from each of the five sites and reared to the adult stage at 27°C in 24 h light and 80% relative humidity (Guthrie et al. 1965). Survival to the adult stage from the five collection sites averaged 20% so that colonies were initiated from approximately 30 individuals. Mortality was similar across collection sites. In addition to the five field collections, a lab culture was obtained from French Ag Research (Lamberton, Minnesota). This culture was originally field collected but had been maintained in culture for approximately 15 generations. Adults obtained from the field-collected larvae were allowed to mate, and eggs collected from the adults were used to establish a second generation. At least 200 adults were obtained from the first generation which were then mated to produce offspring for bioassays.

Bioassay. Feeding bioassays were performed to determine ECB susceptibility to *B. thuringiensis*. Snap-cap petri dishes (50 by 9 mm,

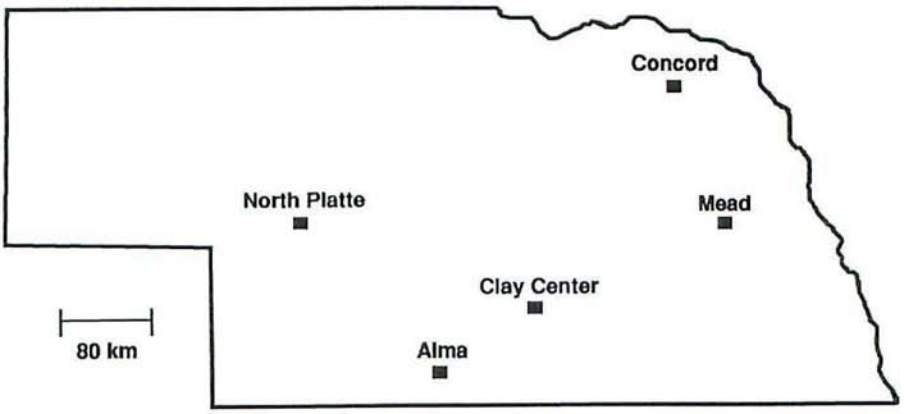

Fig. 1. European corn borer collection sites in Nebraska.

Gelman Sciences, Inc., Ann Arbor, Michigan) were used for holding diet and larvae. Molten ECB diet was poured into the dishes and allowed to solidify. Dilutions of *B. thuringiensis* toxin (200 µl) were applied to the diet surface in distilled water containing 0.1% Triton X-100 to aid in spreading. The *B. thuringiensis* CryIA(b) toxin used for bioassays was obtained from a fermentation run of *B. thuringiensis* subsp. *kurstaki* (HD1-9 strain) that produces only CryIA(b) protein (Carolton and Gonzales 1985). The concentration of protein toxin in the fermentation product was calculated to be 3% by weight based on enzyme-linked immunosorbant assays (Clark et al. 1986). Control treatments received 200 µl of a 0.1% Triton-X 100 solution. After allowing the treated diet to air dry for at least 2 h, 10 neonate larvae less than 48 h after hatching were transferred to bioassay containers with a camel hair brush. The dishes were sealed, and survival was determined 1, 2, 3, and 4 days after placing larvae on the diet. Because dead larvae were often consumed by other larvae in the dish, only living larvae were counted. Larvae were considered to be alive if they responded to prodding with a dissecting pin.

Analysis. The entire bioassay was repeated for each population at least three times, and each dose was replicated two or three times for each bioassay. Bioassays consisted of at least four concentrations of *B. thuringiensis* that produced mortality of > 0% but < 100%. Data were analyzed by probit analysis (Finney 1971) as adapted for PC use (POLO, Berkeley, California). The significance of differences among slopes for the five populations was determined by the likelihood ratio test for parallelism, and significance of differences among LC_{50} values was determined by the likelihood ratio test for equality with pairwise comparisons determined by non-overlapping confidence intervals (Savin et al. 1977).

Results and Discussion

The results of bioassays with the CryIA(b) *B. thuringiensis* protein against neonate ECB at 2, 3, and 4 d after initial exposure are presented in Table 1. These results demonstrate the suitability of the bioassay techniques and the variability in *B. thuringiensis* susceptibility among geographically distinct populations. In general, the 4 d readings provided the most consistent data because survival ranged from 0 - 100% for the concentrations tested. Therefore, both LC_{50} and LC_{90} values could be calculated. Significant regressions also were calculated for both 2 and 3 d readings, but not for 1 d readings because mortality did not differ from control at any of the concentrations tested. Control mortality was less than 20% for all bioassays.

In general, the 4 d susceptibility of ECB indicated that most populations were similar in their response to the *B. thuringiensis* toxin. However, the Mead population (LC_{50} = 4.2 ng/cm^2) exhibited significantly higher tolerance than three of the five other populations. The difference in susceptibility between the Mead population and the most susceptible population was almost 6 fold at the LC_{50} and greater than 9 fold for the LC_{90}. This Mead population was collected from an area not known to have received prior exposure to *B. thuringiensis,* and probably does not represent a resistant population. Surveys of susceptibility to *B. thuringiensis* in other pest species have shown that considerable interpopulation variation exists (reviewed by Tabashnik 1993). Although there has not been an extensive sampling of target pests, variation has been reported in other Lepidoptera including the diamondback moth (Tabashnik et al. 1990), Indianmeal moth, *Plodia interpunctella* (Hübner) (Pyralidae) (Kingsinger and McGaughey 1979), cotton bollworm, *Heliothis virescens* (F.) (Noctuidae), corn earworm, *Helicoverpa zea* (Boddie) (Noctuidae) (Stone and Sims 1993), and gypsy moth, *Lymantria dispar* L. (Lymantriidae) (Rossiter et al. 1990). Such differences are probably the result of natural variation among the populations (Robertson et al. 1995) and unrelated to prior exposure to the insecticide.

Our results indicate that similar natural variability exists among ECB populations, and may be responsible for small differences in susceptibility unrelated to prior exposure to *B. thuringiensis* toxin. It must be noted that the populations used in this study represent a relatively small sample, both in terms of the number of insects used to establish the populations and in the number of populations sampled. However, all the populations exhibited similar slopes for the dose versus mortality curves indicating that heterogeneity of *B. thuringiensis* susceptibility was not biased by the small sample size. The shallow slopes displayed by all of the populations tested reflect the genetic heterogeneity of the populations and are typical of the response of most insects to microbial insecticides (Stone and Sims 1993, Burges 1971). Steeper slopes and differences in slope among the populations would have been expected if the response had been biased because of a small sample size.

The results obtained from a limited number of ECB populations sampled suggest that variability in tolerance to *B. thuringiensis* may exist among geographically distinct populations. However, large unexplained variations

Table 1. Susceptibility of European corn borer to *B. thuringiensis* after 2, 3, and 4 d of exposure.

Location	Time (d)	N	Slope ± SE[ab]	LC_{50} (95%F.L.)[acd]	LC_{90} (95%F.L.)[acd]
Concord	2	1660	0.84 ± 0.07 c	5.76 (2.97 - 9.58) a	> 100
Mead	2	818	0.60 ± 0.09 b	22.8 (1.22 - 75.3) ab	> 100
Alma	2	1600	0.60 ± 0.07 b	23.2 (8.85 - 68.2) ab	> 100
North Platte	2	1330	0.54 ± 0.06 ab	33.7 (19.4 - 63.4) b	> 100
Clay Center	2	900	0.83 ± 0.11 bc	39.0 (13.8 - 136) b	> 100
Laboratory	2	1020	0.42 ± 0.07 a	> 100	> 100
Concord	3	1660	0.78 ± 0.06 a	0.87 (0.47 - 1.43) a	37.9 (23.1 - 71.8) a
Mead	3	818	0.64 ± 0.08 a	4.70 (1.95 - 9.16) b	> 100
Alma	3	1600	0.80 ± 0.06 a	2.74 (1.53 - 4.39) b	> 100
North Platte	3	1330	0.69 ± 0.05 a	2.20 (0.71 - 5.08) ab	> 100
Clay Center	3	900	0.94 ± 0.09 a	2.99 (0.12 - 9.50) ab	68.3 (11.4 - 122) a
Laboratory	3	1020	0.76 ± 0.08 a	3.10 (1.33 - 5.73) a	> 100
Concord	4	1660	0.98 ± 0.08 a	0.73 (0.45 - 1.08) a	14.8 (10.5 - 22.3) a
Mead	4	818	0.88 ± 0.07 a	4.22 (1.38 - 9.40) b	121 (43.8 - 957) b
Alma	4	1600	0.83 ± 0.06 a	0.79 (0.23 - 1.73) ab	22.7 (11.7 - 109) ab
North Platte	4	1300	0.96 ± 0.07 a	0.75 (0.42 - 1.20) a	16.1 (10.0 - 29.2) a
Clay Center	4	900	1.08 ± 0.10 a	1.10 (0.54 - 1.82) ab	17.1 (10.7 - 29.2) a
Laboratory	4	1020	1.05 ± 0.09 a	0.80 (0.50 - 1.16) a	13.3 (9.41 - 20.3) a

[a] Values followed by the same letter within a column for a single sampling time are not significantly different ($P > 0.050$).
[b] Significance of differences determined by likelihood ratio test for parallelism (Savin et al. 1977).
[c] Significance of differences determined by likelihood ratio test for equality followed by pairwise comparisons using nonoverlapping fiducial limits (Savin et al. 1977).
[d] ng CryIA (b) protein/cm^2

in susceptibility of field populations have been observed (Sawicki 1987, ffrench-Constant and Roush 1990). Further investigation is required to establish that differences in susceptibility are genetically controlled and not the result of insufficient sampling or other unidentified factors. However, it is important to document the extent of this variability throughout the known range of ECB to establish a diagnostic *B. thuringiensis* concentration or dose (i.e., an LC_{99}) that could be used in more extensive resistance monitoring programs. Further, baseline susceptibility, as documented here, provides a basis for determining if resistance is developing as a result of increased exposure to *B. thuringiensis* toxins as might be expected with increased use of *B. thuringiensis* formulations and introduction of transgenic corn. Such information is essential to developing resistance management strategies designed to maintain the efficacy of these environmentally sound and economically important management options.

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INTRODUCING OUR NEW EDITOR

Julie L. Todd

Dr. Julie L. Todd is the new Editor of the *Journal of Agricultural Entomology* (JAE). She is replacing Dr. Howard W. Fescemyer who has served as the Interim Editor since Dr. Bob Cartwright resigned in July 1995. Julie is located at Iowa State University in Ames, Iowa. She is excited about her new role as Editor of *JAE* which will help her pursue a career as a science editor. I am sure we will want to congratulate Julie on this new endeavor.

Julie received a B.S. in biology (1983) and a M.S. in ecology (1985) from Kent State University in Kent, Ohio. She received her Ph.D. in entomology (1989) from The Ohio State University in Columbus, Ohio. Her M.S. research in Dr. Benjamin Foote's laboratory at Kent State University concentrated on determining the mechanisms affecting the community organization of acalypterate Diptera within wetland habitats. Julie conducted her Ph.D. research with Dr. Skip Nault at the Ohio Agricultural Research and Development Center in Wooster, Ohio. This research focused on elucidating the visual, chemical, and structural plant characteristics that were being used by *Dalbulus* leafhoppers to find and accept hosts. During her Ph.D. research, she traveled throughout Mexico to observe the behavior of *Dalbulus* leafhopper species on maize and its wild relatives, the teosintes and the gammagrasses. Her discoveries during studies of the intraplant movements of leafhoppers in relation to maize phenology have led to a better understanding of the nonpest, evolving pest, and pest status of species in the *Dalbulus* complex. Her discoveries have also contributed to the development of a new phylogeny of this leafhopper genus.

Julie has been working with Dr. Tom Baker as a Postdoctoral Research Associate in the field of neuroethology of insect olfaction since 1989. She pioneered the use of the cut-sensillum extracellular recording technique in Baker's laboratory, the only laboratory in the United States that uses this technique for single-neuronal recording. Julie stands alone among researchers outside of Europe in coupling the cut-sensillum technique with cobalt staining of physiologically identified olfactory neurons. The cobolt stain neurons can then be tracked to their areas of arborization into antennal lobe glomeruli in the brain. Coupling olfactory neuron physiological with neuron morphology is a powerful approach that is advancing our understanding of first-order neuronal processing of sex pheromones and host odors in moths.

Julie has been a member of the Entomological Society of America since 1983. She also holds membership in Sigma Xi and the Tri Beta Biological Honor Society. Julie received the William E. Krauss Directors Award for Excellence in Research for the best doctoral dissertation in agriculture by a student at the Ohio Agricultural Research and Development Center in 1989. Her studies on the population growth and spatial distributions of *Dalbulus* species on maize from the seedling stage through maturation and senescence have helped to explain the observed field associations of various species, and

to indicate which species may evolve into maize pests. Julie was a visiting scientist in Dr. Bill Hansson's laboratory at the University of Lund in Sweden from 1993-1994. While in Dr. Hansson's laboratory, she learned the techniques necessary for staining moth peripheral receptors so that their pathways into the brain could be visualized. She used this experience to obtain funding from The American-Scandinavian Foundation for her research proposal on the antennal lobe projections of male cabbage looper moths. The American-Scandinavian Foundation is an organization that supports collaborative research between American and Scandinavian scientists.

Julie has much experience in publishing and editing research articles. She is a freelance editor for the Iowa State University Press. Julie has published 14 articles in peer reviewed journals such as the *Journal of Chemical Ecology, Environmental Entomology,* and *Entomologia experimentalis et applicata.* Her knowledge and experience in entomology covers a broad range as evidenced by her research described above. I am sure Julie will use her talents to the fullest as the new Editor of JAE. Please join me in welcoming Julie to this new position, and work with her to make JAE one of the best of its kind.

Respectfully submitted with help from Julie,
Howard W. Fescemyer
Business Manager and Interim Editor of JAE

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