Habitat Manipulation to Reduce Papaya Fruit Fly (Diptera: Tephritidae) Damage: Orchard Design, Use of Trap Crops and Border Trapping

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ABSTRACT We designed 2 papaya groves to test the concepts of trap cropping and border trapping to control Toxoptera curvicauda. Intensive fruit sampling in grove 1 indicated that the degree of fruit infestation decreased as the distance from the native vegetation (source of flies) increased. Rows planted 10 m away from the main block of papaya trees (trap crop) exhibited the greatest degree of puncture damage and larval infestation in both experimental groves. Fruit damage was highest after the rainy season was over and was spatially aggregated. We conclude that designing a papaya grove in such a way that a trap crop consisting of plants located 10 m from the main block of trees (and entirely surrounding it) can reduce fly damage significantly. If pheromone-baited fly traps are hung in these peripheral rows, the trap crop effect can be enhanced, and as a result, damage to the commercial block of trees can be reduced even further. Such a fly management scheme should allow growers to avoid or drastically reduce pesticide applications. We discuss our findings in relation to current knowledge of T. curvicauda behavior and make suggestions for further improvement and large scale testing of the management scheme we propose.

KEY WORDS Toxoptera curvicauda, Tephritidae, pest management, habitat manipulation, trap crops, border trapping

Carica papaya L., commonly known as papaya, is native to tropical America but is currently grown in all tropical regions of the world (Moreno 1980, Sanor 1986). Female trees start to bear fruit at 6–14 mo of age and produce fruit during 2–4 yr if no viral infections are present (Solano-Alvarez 1976). The commercial value of the fruit is high and large plantations can be found in Florida, Mexico, Belize, Guatemala, Costa Rica, Brazil, Thailand, and India. In Mexico ~25,000 ha are planted, currently producing ~700,000 metric tons of fruit per year (estimate based on SARH 1984). Infestations by the papaya fruit fly, Toxoptera curvicauda Gerstaecker, and the presence of plant virus infections are 2 of the more important phytosanitary problems commercial papaya growers face in southern Florida in the United States, Mexico, and in a number of Central American countries (Quezada 1980, Landolt 1985, Aluja 1993).

The papaya fruit fly is a multivoltine insect native to tropical America. Immatures and adults can be found almost throughout the year. Typically, the female thrusts her ovipositor through the pulp of unripe papaya fruit (~5–12 cm in diameter) and deposits 10 or more eggs among seeds in the central cavity of the papaya. Larvae feed on the seeds and lining of the seed cavity, and upon completion of development, exit the fruit and drop to the ground to pupate in the soil. Larval development requires ~15–17 d, whereas pupal development requires 2–6 wk depending on temperature and humidity of the soil (Knab and Yohns 1914, Mason 1922, Weems 1969, Landolt 1983, Peña et al. 1986). Even though it was usually believed that T. curvicauda only infested papaya (Carica papaya L.), recent studies have shown that its host range is much broader. Fruit such as Conolobus soroitus Gray, C. niger R. Br., C. ertanthus Dece., Morrenia adorata Lindl. (all Asclepiadaceae), and Jacaratia mexicana (A.DC.) (= Frelia mexicana Johnston) (Caricaceae) are important reservoirs of this pest (Baker et al. 1944, Leyva-Vazquez 1990, Castrejon-Ayala and Camino-Lavin 1991, Landolt 1994). These native hosts represent reservoirs from which adults move to infest papayas grown in backyard gardens and commercial groves. When provided a choice, T. curvicauda prefers to attack papaya cultivars which produce small fruit (such as the Hawaiian Solo cultivar or wild Carica papaya). This in contrast to cultivars such as Cera Amarilla or Cera Roja that bear large fruit (Aluja et al. 1994). T. curvicauda adults exhibit a distinct diel pattern of activity, moving back and forth between native vegetation and papaya groves.
Control of the papaya fruit fly has been historically restricted to insecticides used singly or in combination with toxic baits (Mason 1922, Wolfenbarger 1962, Aluja 1993). Because adult papaya fruit flies do not require protein to complete ovarian maturation (Landolt 1984b), it is recommended that baits be prepared with brown sugar and an insecticide as opposed to the more common protein-insecticide combination used with other pestiferous tephritids (Sharp and Landolt 1984). Mason (1922) recommended destruction of all infested fruit in groves and isolating plantations by removing all wild plants within a radius of at least 3.2 km from commercial groves. This scheme, even though effective, faces limitations of scale and practicality. Landolt (1984a), based on a series of behavioral observations, proposed that bait sprays be applied when flies are most active in papaya plantations and concentrated on those areas most frequented by flies (i.e., plantation borders). This author also proposed the use of seedless and thick pulp cultivars to reduce damage by T. curvicauda. Landolt and collaborators (Chuman et al. 1987; Landolt and Heath 1988, 1990; Landolt and Reed 1990; Landolt et al. 1985, 1991, 1992) identified the male sexual pheromone of T. curvicauda and developed a trap to monitor populations. Recently, more efficient trap designs were tested in commercial groves in Guatemala and Mexico (Heath et al. 1996).

Vegetational designs and other habitat manipulation practices such as cover crop manipulation, crop row spacing, shelterbelt management, and trap cropping have been extensively studied in annual crops (e.g., Altieri 1983, McPherson and Newsom 1984, Baliddawa 1985, Herzog and Funderburk 1986, Hokkenen et al. 1986, Andow 1991, Hokkenen 1991, Margolis 1993, Srinivasan et al. 1994, Brewer and Schmidt 1995) and less intensively in perennial crops (e.g., Corbet 1976, Tedders 1983, Flaherty et al. 1983, Prokop 1984, Ingels et al. 1994, Hendricks 1995). Studies of this nature are hindered by the fact that fruit trees are perennial, thus making it more difficult to test experimentally the impact of orchard design, inter-orchard fruit species composition, or trap crops. Papaya plantings offer such an opportunity. Even though they are not strictly perennial, trees bear fruit for at least 2–4 yr. Based on the observations on T. curvicauda behavior in nature by Landolt (1984a), Aluja and Liede (1986) proposed a theoretical management scheme based on trap cropping. Our aim here was to test this scheme.

Materials and Methods

Study Site. The research was conducted at the Centro de Desarrollo de Productos Bioticos (CEPROBI), Instituto Politecnico Nacional (IPN), located on the riverbanks of the Rio Yaupepec in San Isidro Yaupepec, Morelos, Mexico, at 19° 10’ northern latitude and 99° 05’ western longitude. The altitude is 1,100 m, and mean annual rainfall and temperature are 1,050 mm and 22°C, respectively. The climate is defined as semi-arid, humid (García 1981). There are 2 rainy seasons separated by dry periods. The 1st rainy season is in June and the 2nd is in October–November (Castrejón-Ayala 1987). Native vegetation surrounding the study site has been characterized as deciduous dry forest (Soria 1985).

Experimental Papaya Groves. We planted 2 experimental groves. Grove 1 during 1991, and grove 2, during 1994. The physical layout of the groves is shown in Fig. 1. Grove establishment and maintenance is described in Aluja et al. (1994). In grove 1, we planted 6 plots of papaya trees (40 by 25.5 m each) in a total area of 1.0 ha. Plots were separated by alleys (10 by 25.5 m of open space with grasses and weeds) and consisted of a trap crop (2.5 by 25.5 m each) and a main block consisting of 2 and 15 rows of trees, respectively (see Fig. 2 A and B for details). Each main block measured 701 m² (27.5 by 25.5 m). In both the trap crop and the main block, there were 10 papaya trees per row. Distances between trees and between the trap crop and the main block were 2.5 and 10 m, respectively. Because we did not know before planting the grove the direction from which T. curvicauda individuals would approach it, we alternated the position of the trap crop among the 6 plots (in plots 1, 3, and 5 it was planted in the E side [adjacent to native vegetation] and in plots 2, 4, and 6 it was planted in the W side) (see Fig. 1 for details).

Grove 2 was planted (after work in grove 1 was discontinued) to validate the concept of trap cropping tested in grove 1 and to test various trap types and trap designs aimed at incorporating a border trapping component to the trap cropping scheme (also see Heath et al. 1996). The grove was ~1.2 ha in size and consisted of a main block of trees (1,385 trees planted in ~5,000 m² of land) and a trap crop (2 rows [152 trees in each row] planted 10 m away from the main block) (see Fig. 2 D for details). Distance between trees was 3 m. Because of a severe drought combined with viral infection, trees in this grove died ~12 mo after planting.

Fruit Sampling. In grove 1, once plants reached a height of ~1.8 m (~8 mo after transplant), 5 fruit in every tree were sampled every other month. Fruits were picked at random. If a chosen fruit was <10 cm or had already fully ripened, it was discarded and another fruit selected at random. Fruit were cut in half and the presence of larvae was recorded. Because the 2nd grove was planted to test various trap designs for T. curvicauda monitoring and control (see Heath et al. 1996), we did not cut fruit from trees, but instead counted the number of oviposition insertions in fruit. All fruit in every tree were inspected. This task was made easy by the fact that when females insert their ovipositor in a fruit, a distinctive trail of hardened latex remains.

Analysis of Data. To facilitate analysis and presentation of data, we divided all plots of grove 1 into
subunits (see Fig. 2B and C for details). Plots were divided into 4 sections. One section (trap crop) consisted of 2 rows of trees and the other 3 of 5 rows each (Fig. 2B). With the exception of plot 1, trees in section 1 were closest, and in section 4 farthest from the native vegetation. In plot 1, distance to the native vegetation was similar in all sections. We also divided plots into the first 2 rows and the rest of the plot (Fig. 2C). The first 2 rows were always those adjacent to the unperturbed native vegetation (see location of grove 1 in Fig. 1). Finally, we compared fruit infestation at both ends (i.e., E and W sides) and the central part of the plots.

To determine if the level of fruit infestation decreased as distance from native vegetation increased, we performed an analysis of covariance (ANCOVA) (Statistical Graphics 1991). Before formal analysis, we applied an angular transformation (arcsine) because the raw data were proportions. In our model, we used the effect of sampling dates as a blocking factor and distance as the covariate. We tested for multiple slopes in the regression using the interaction between distance and sampling dates.

To compare the degree of infestation in the first 2 rows (those closest to unperturbed native vegetation) against the remainder of the plot in grove 1 and the number of fruit with oviposition punctures in the trap crop and in the main block in grove 2, we used a chi-square test (Sokal and Rohlf 1981).

Results

Fruit infestation patterns are shown in Figs. 3–8. On a seasonal basis, fruit infestation was highest during the months of September to February (Fig. 3). The highest levels of infestation in grove 1 were detected in plots 1 and 2 (Fig. 4) and in plot sections closest to the perturbed and unperturbed native vegetation adjacent to the grove (all sections in plot 1 and section 1 of plots 2–6) (Fig. 5A). The ANCOVA indicated that both distance (covariate in model) and sampling date (blocking factor in model) were highly significant ($F = 79.47; df = 1, 147; P < 0.00001$ and $F = 4.87; df = 7, 147; P < 0.0001$ for distance and dates). The distance × sampling date interaction was not significant ($F = 1.03; df = 7, 140; P = 0.413$). The regression analysis clearly showed that as distance from native vegetation increases, the number of infested fruit per tree decreases. Given that the distance × sampling date
interaction was not significant, and that the only difference between sampling dates was the infestation level, we illustrate the pattern observed using only 1 sampling date (December 1992) (Fig. 5B). This pattern becomes even more apparent when a comparison is made between the first 2 rows (those closest to the native vegetation adjacent to the grove) and the rest of the plot (Fig. 6) ($\chi^2 = 197.2, P < 0.001$) (see Fig. 2C for details on plot subdivision).

The pattern of infestation in the trap crop during 3 different sampling periods (July and October 1992 and February 1993) is illustrated in Fig. 7. Note that the trap crop closest to the unperturbed native vegetation was the most infested (plots 1, 3, and 5).

Finally, when comparing the number of punctured fruit in grove 2, a significantly higher proportion of fruit was punctured in the trap crop rows than in the main block of trees (chi-square test with Yates correction for continuity, $\chi^2 = 12.9, P < 0.001$) (Fig. 8).

**Discussion**

Our results clearly show that the pattern of *T. curviscunda* fruit infestation is aggregated both in space and time. Highest levels of infestation were detected between September and February and always in grove sectors closest to the adjacent perturbed and unperturbed native vegetation. We also demonstrate that a trap crop completely ringing the main block of trees in an experimental grove can be an effective mechanism to reduce fruit damage by the papaya fruit fly.

**Relationship of Fly Behavior and within Field Infestation Patterns.** The highest proportion of infested fruit in grove 1 was found in border rows adjacent to native vegetation. Aluja et al. (1967) have shown that papaya fruit fly adults move back and forth between patches of native vegetation and papaya groves. Furthermore, these authors showed that when not in native vegetation, flies are sighted most often in papaya trees in the periphery of groves (adjacent to native vegetation). A similar pattern of behavior has been also reported in fruit flies infesting olives, cucurbits and mangoes: *Bactrocera oleae* (Guisay et al. 1990), *B. frontalis* (Becker) (Steffens 1983), *B. cucurbitae* Coquillett (Nishida and Bess 1950, Kazi 1976), and *A. obliqua* (Aluja and Birke 1993). For *T. curviscunda*, this pattern can vary depending on the structure of the grove (monocrop versus mixed grove), type of papaya cultivar
**Fig. 3.** Seasonal pattern of fruit infestation (infested fruit per tree). Values for each sampling period represent the average (±SE) of all fruit sampled in grove 1.

**Fig. 4.** Between-plot distribution of fruit infestation (infested fruit per tree) in grove 1. Values for each plot represent the average (±SE) of all fruit sampled independent of sampling date.
Fig. 5. (A) Distribution of fruit infestation by plot and section number (see Fig. 2C for details on plot subdivision into 4 sections). (B) Pattern of fruit infestation as affected by distance from native vegetation (source of flies).
planted, and the age of the papaya grove. If the grove is a true monocrop (1 species, 1 cultivar), then most individuals are indeed sighted in the periphery (Aluja et al. 1997). If it is a monocrop but with different cultivars planted, the pattern changes. If rows of a highly preferred papaya cultivar (e.g., 'Hawaiian Solo') are planted between rows of other less preferred varieties (e.g., 'Cera Amarilla'), almost all fruit in every tree of the preferred cultivar is infested, whereas levels of infestation in the less preferred cultivar are lower (Aluja et al. 1994). Finally, if other tree species are interplanted between papaya trees (e.g., mango, avocados), then flies also use the nonhost species as shelter sites from which they then displace to papaya trees. In this case, a proportion of individuals is sighted in the periphery of the grove and the rest in papaya trees next to shelter sites located within the grove (Aluja et al. 1997). In conclusion, within-grove fly distribution and the concomitant fruit infestation patterns are not only contingent on fly movement patterns between groves and native vegetation but also on grove structure. It is important to consider this when designing papaya fruit fly control tactics.

**Implications of Our Findings for T. curvicauda Management and Control.** In general terms, the implications of our findings for papaya fruit fly management are clear: Trap cropping/border trapping schemes are, we suggest, potentially viable alternatives to the large scale use of insecticides. Nevertheless, there are several questions that need to be addressed before making recommendations to growers: size of grove, economic feasibility, and the possibility of further refinement of the management scheme proposed here (e.g., optimal distance between trap crop and main block [i.e., size of alley], feasibility of placing a plant that is repellent to adult papaya fruit flies in the alley separating the trap crop and the main block of trees, effect of placing pheromone traps in both the trap crop and the periphery of the main block of trees, and feasibility of using a highly susceptible papaya cultivar, such as Hawaiian Solo, as a trap crop [see Aluja et al. 1994]). In conjunction with these validation studies, economic feasibility and grower acceptance assessments are also needed. As mentioned before, feasibility, we suggest, will be contingent on fly population size, size of grove, papaya cultivar planted, degree of capitalization by grower, and quality standards imposed by local markets. Grower acceptance will strongly depend on degree of capitalization, pesticide use restrictions, and on value of noninsecticide treated fruit. For example, in large scale, commercial operations, leaving an alley between the trap crop and the main block of trees could not be cost effective because of the large surface left unplanted. In such cases, we feel that a more economically feasible alternative would be to leave the alley out (Fig. 9) and to place the trap crop and a large

**Fig. 6.** Distribution of fruit infestation dividing experimental units of grove 1 into 2 parts (2 rows closest to native vegetation and rest of plot; see Fig. 2C for details on plot subdivision). Difference highly significant (χ² = 197.2, P < 0.001).

**Fig. 7.** Within-plot distribution of fruit infestation in grove 1 when considering 2 extremes (2 rows of trees each) and central part of plot (13 rows of trees). Numbers represent percentage of total fruit infested in each of 3 sections (values in each plot add to 100%). Three sampling periods chosen to illustrate patterns.

**Fig. 8.** Level of damage (proportion punctured fruit) measured in trees located in trap crop zone and in main block of trees in grove 2. See Figs. 1 and 2D and Materials and Methods section for details on design and structure of this grove. Difference highly significant (chi-square with Yates correction for continuity, χ² = 12.9, P < 0.001).
number of pheromone-baited traps in the periphery of groves. In addition to this, we recommend the application of toxic bait-sprays or insecticide alone also in the periphery.

Habitat manipulation, with some exceptions (see reviews by Dempster and Coaker 1974, Cromartie 1981, Altieri 1983, Baliddawa 1985, Herzog and Funderburk 1986, Hukkanen 1991, Andow 1991, and Prokopy 1994) has only been tested experimentally with annual crops. As more information on fly behavior becomes available, prospects for the use of environmentally friendly fruit fly management approaches are increasing (Aluja 1994, 1996). We hope that our study will encourage more research in this area.

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