

Quantifying the Impact of Insecticides on Food Web Structure of Rice-Arthropod Populations in a Philippine Farmer's Irrigated Field: A Case Study

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Introduction

Rice is grown on 10% of the arable land worldwide and provides one-third of the total calorie supply for two-thirds of the human population (International Rice Research Institute, 1991; Food and Agriculture Organization, 1992). In the middle to late 1960s, the widespread adoption of new high-yield, pest-resistant rice cultivars, nitrogenous fertilizers, and pesticides brought significant increases in rice production (popularly called The Green Revolution (Barker et al., 1985)) in south and southeast Asia. Extensive irrigation systems were built in Asia to capitalize on the insensitivity to the photoperiod of the new cultivars. Eliminating the former fallow period during the dry season removed one form of pest protection and brought new pest problems (Litsinger, 1993). Major outbreaks in the 1970s of the rice brown plant hopper, *Nilaparvata lugens* (Stål), a secondary rice pest before 1964, were traced to overuse of insecticides (Kenmore, 1980; Kenmore et al., 1984; Heinrichs and Mochida, 1984). The pest problems led to integrated pest management (IPM) strategies for tropical rice in the late 1970s that emphasized host plant resistance, cultural practices, and biological control, minimizing the use of pesticides.

In tropical Asia, the most successful example of rice IPM is in Indonesia where an estimated 250,000 IPM-trained farmers use varieties and nonchemical methods to prevent yield losses. Insecticides are used as a method of last resort to control pest outbreaks. The Indonesian model has shown that IPM-

trained farmers produce similar or higher rice yields and enjoy higher farm profits than farmers who do not receive this training (The Indonesian National IPM Program, 1991). Farmers responded favorably to IPM training when conducted at the village level in farmers' field schools.

In view of the importance of rice and the need to develop more stable IPM strategies, entomologists of the International Rice Research Institute (IRRI) in the Philippines, since 1977, have been describing the food web of Philippine irrigated and rain-fed rice fields at and above the waterline. At present, the IRRI cumulative web contains 546 rice-associated taxa (insects, spiders, mites, snails, vertebrates, pathogens, nematodes) and 9319 consumer resource links at 23 sites (Cohen et al., 1994). Among these taxa are 25 putative major and minor pests of Philippine rice (Reissig et al., 1986). Consumer resource links were determined from field observations, exposing eggs and larvae of potential host species in the field to collect immature parasitoids, and predator preference and selectivity tests in the laboratory (Cohen et al., 1994; Reissig et al., 1986).

Many studies have evaluated the effects of insecticides on selected crop insect pests and their principal natural enemies, but few studies have used food webs to study the effects of pesticides on pest-enemy interactions at the community level (Grigarick et al., 1990; Hurlbert et al., 1972). In this report, we describe the impact of insecticide sprays on the food web of rice arthropod populations in sprayed and unsprayed plots of one farmer's

field in central Luzon, the major Philippine rice bowl.

Study Site and Local Climate

The study was conducted during the 1991 dry season within a large synchronously planted area (approximately 100–200 ha) of irrigated farmers' fields at Zaragoza in Nueva Ecija Province, 90 km northwest of Manila, Luzon, 15°30'N and 120°40'E. Zaragoza has cool dry (January–May) and hot wet (July–November) seasons. In Zaragoza, two rice crops are usually planted, one in the wet season and one in the dry, with a fallow period in June. The 1991 rainfall for Zaragoza, registered at the nearby Guimba agrometeorological station (15°39'N, 120°47'E, 66 m above sea level), was 1499 mm, nearly 200 mm lower than the 1986–1991 average of 1685 mm (International Rice Research Institute, 1992). Monthly minimum and maximum temperatures, during 1991, varied by 7–13°C, May being the warmest (36°C maximum temperature) and March and November (20°C minimum temperature each) the coolest months (International Rice Research Institute, 1992).

Materials and Methods

Experimental Design and Data Collection

Two 20m × 50m plots (1000 m² each) were selected from the same farmer's field and randomly designated the sprayed and unsprayed plots. Except for the application of insecticide, the two plots were managed equally. On February 20, 1991, 20-day-old seedlings of IR72, a modern high-yielding rice cultivar with resistance to several insect pests and diseases, were transplanted by hand into both the experimental plots and surrounding fields. Two to four seedlings per hill were planted in a regular 20 cm × 20 cm spacing pattern with fertilizer applied at three stages: basal (60 kg), maximum tillering (30 kg), and panicle initiation (30 kg), at the total rate of 120 kg N (urea) ha⁻¹. Hand harvesting and threshing of the rice crop took place approximately 100 days after transplanting (DT).

Foliar spraying of insecticide in the treated plot occurred on March 20 (28 DT), March

30 (38 DT), and April 10 (49 DT). A 3-m-wide-no-spray zone was established along the perimeter of the sprayed plot to minimize insecticide drift into the control plot because a previous study showed insecticide drift occurred within 3 m of a sprayed border (Litsinger et al., 1987). Standard field dosages of 12.5 gm ai/h (ai=active ingredient) of deltamethrin, a synthetic pyrethroid (Theiling and Croft, 1989; Croft, 1990) were sprayed using a standard 16-l hand-operated knapsack sprayer. Except for an earlier than usual third spray of deltamethrin on 49 DT, the mode and timing of insecticide applications were consistent with normal field practices of local farmers. Arthropod populations were sampled weekly from February 28 (8 DT) to May 30 (99 DT) for a total of 14 sampling dates. The sampling unit was a plastic barrel measuring 45 cm in diameter (0.16 m² area) and 54 cm high with its bottom removed and its top fitted with a fiberglass net sleeve (60 cm long) to prevent escape of highly mobile insects and spiders (Arida and Heong, 1992). For each of the 14 sampling dates, 10 randomly placed samples were taken from each of the two plots for a total of 280 samples. All organisms inside the enclosure were vacuumed using a portable FARMCOP suction device (Cariño et al., 1979). Because arthropod populations in flooded rice increase in both species richness and abundance with crop age (Kenmore et al., 1984; Heong et al., 1991, 1992), sampling duration was increased over the growing season according to the following schedule: transplanted seedling to maximum tillering (2 minutes), maximum tillering to panicle development (3 minutes), panicle development to flowering (4 minutes), flowering to harvest (5 minutes). All arthropod taxa were identified to species or to genus, whenever possible, using the reference collections in the IRRI Entomology Division.

Web Construction and Community Statistics

For both sprayed and unsprayed plots, we constructed first a plot-specific web (a web based only on the species observed in each plot) and then used the web and the sample to construct a set of time-specific webs (using only the species observed on a given sam-

pling date) (Schoenly and Cohen, 1991). We assumed that enemy A ate or parasitized resource B at the site if and only if one life cycle stage of A eats or parasitizes at least one life cycle stage of B in the Philippines web, and species A and B occurred at this site (Reissig et al., 1986). Numbers of taxa and individuals sampled in the plots, over all 14 sampling dates, were higher in the sprayed plot (83 taxa and 29,638 individuals) than in the unsprayed plot (80 taxa and 15,849 individuals).

To assess community wide variation between treatments and sampling dates, we performed three sets of analyses. First, we investigated broad patterns in the percentage abundances of taxa among three trophic groups in the sprayed and unsprayed plots: herbivores (%H), natural enemies of herbivores (%E), and other taxa (%O, detritivore and planktonic taxa). Second, we calculated the magnitude and direction of differences in %H and %E abundances between sprayed and unsprayed webs to quantify ecological effects of sprays. Third, we calculated mean food chain length (μ) of sprayed and unsprayed webs for each sampling date at different abundance thresholds to determine whether sprays reshape food web structure. Mean chain length is defined here as the average length (counting links, not species) of all maximal food chains from a basal species to a top predator (Cohen 1978), calculated using the long-way-up algorithm of Cohen and Luczak (1992).

Results

Because sprayed and unsprayed plots were unreplicated in this study, food web patterns will be described mostly without using formal statistical tests.

Trophic Groups in Sprayed and Unsprayed Plots

On the three prespray dates (8,15,22 DT), sprayed and unsprayed plots harbored similar percentages of herbivores (%H means; 4% and 7%, respectively), natural enemies of herbivores (%E: 6% and 14%) and other (detritivore and planktonic) taxa (%O: 90% and 79%) (Figures 32.1a and 32.1b). In both plots %O declined, whereas %H and %E increased

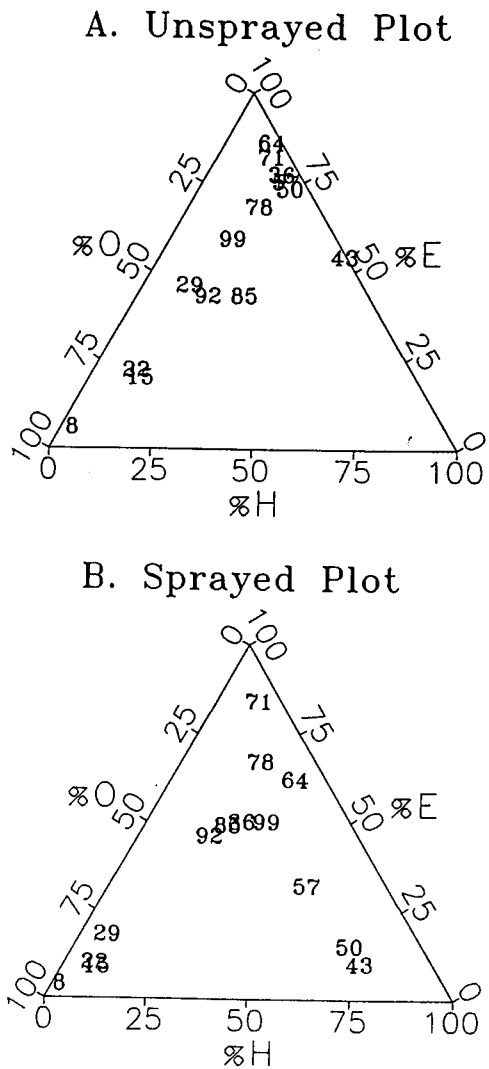


Figure 32.1. Temporal variation in percentage abundances of herbivores (%H), natural enemies of herbivores (%E), and other (detritivorous and planktonic) taxa (%O) sampled on each of 14 sampling dates from a Zaragoza farmer's field in an unsprayed plot (a) and a deltamethrin-sprayed plot (b) during dry season 1991. Numbers in each graph are days after transplanting of rice seedlings (DT). For example, 8 in the lower left corner of the upper triangle means that at 8DT, most individuals were detritivores and planktonic; by 15DT, %H and %E rose while %O fell. Percentages in sprayed and unsprayed plots are based on arthropod counts per 1.6 m² sampling date⁻¹.

over the two-week period. Over the spraying interval (28–49 DT), %H in the sprayed plot exceeded %H in the unsprayed plot (three-date means: 32% and 23%, respectively; Figures 32.1a and 32.1b). Enemy abundances (%E) were much greater in the unsprayed plot than in the sprayed plot (three-date means: 57% and 24%, respectively; Figures 32.1a and 32.1b). Reductions in %O continued in both plots during this three-week period. Over the remaining eight (postspray) dates (50–99 DT), percentage differences in trophic groups gradually lessened between sprayed and unsprayed plots (Figures 32.1a and 32.1b). On 78 DT, %H, %E, and %O in the sprayed and unsprayed plots were nearly identical, suggesting a (roughly) one-month recovery period from deltamethrin sprays.

Ecological Effects of Insecticide Sprays

Farmers can understand the differences between sprayed and unsprayed plots in herbivore and enemy abundances. We estimate that sprays resulted in an additional 4 million herbivores ha^{-1} sampling date $^{-1}$, calculated as the mean of the differences in abundances between sprayed and unsprayed plots per sampling date, multiplied by 6289.3 (to obtain numbers ha^{-1}) and divided by 14 (to obtain numbers ha^{-1} sampling date $^{-1}$). Of 12 putative pest taxa in both plots, the vast majority of additional herbivore individuals in the sprayed plot were three delphacids (*S. furcifer*, *N. lugens* and *T. pusanus*) (Figure 32.2a).

We estimate 1 million fewer natural enemies ha^{-1} date $^{-1}$ in the sprayed plot by mid-season (calculated as the sum of differences in enemy abundances between control and sprayed plots from 8 to 50 DT, multiplied by 6289.3 and divided by 14). The timing of enemy losses partly overlapped the hump of extra herbivores on 36–50 DT (Figures 32.2a and 32.2b). Over this overlapping interval, however, the additional herbivores went unchecked in the sprayed plot because there were fewer enemy individuals. Of the 34 enemy taxa in both plots, the veliid bug *Microvelia atrolineata* (Bergroth) and the mirid bug *Cyrtorhinus lividipennis* Reuter composed the largest fraction of natural enemies that were affected by deltamethrin sprays. By season's end, the sprayed plot netted an esti-

mated 279,000 more natural enemies ha^{-1} date $^{-1}$ than the unsprayed plot. But early season losses increased the likelihood of pest damage in the sprayed plot (Figure 32.2b).

Insecticidal Effects on Food Chain Length

For each time-specific web, mean chain length (μ) was calculated three times: once using all food web taxa (unweighted web), a second time using the most common taxa that captured 90% of the total abundance (90%A web), and a third time using the most common taxa that captured 75% of the total abundance (75%A web). The unweighted versions of the webs from sprayed and unsprayed plots had virtually identical mean chain lengths on nine of 14 sampling dates. There was no systematic pattern to the differences on the other five dates. The 75%A versions contained so few species as to make statistical comparisons of μ impractical (14-date means in sprayed and unsprayed webs: 5.1 taxa in both).

The 90%A webs take species abundances into account, and unlike the 75%A webs, the 90%A webs take a larger number of species into account (14-date means in sprayed and unsprayed plots: 9.1 and 8.6 taxa). Temporal variation in μ for 90%A webs of the sprayed and unsprayed plots is shown in Figure 32.3. On prespray dates, the 90%A webs of the sprayed and unsprayed plots each had food chains up to three links in length: rice-pests-specialist enemies-generalist enemies. Following the first deltamethrin spray, μ in the sprayed plot fell from 2.6 on 22 DT to 2.0 on 29 DT, yielding a web that contained only two-link chains (rice-pests-enemies). Over the same seven-day period, μ in the unsprayed plot increased slightly from 2.4 to 2.6. The date immediately after spraying became the first of six consecutive postspray dates that yielded significant differences in the range of food chain lengths between webs of the sprayed and unsprayed plots. Subsequent sprays on 38 and 49 DT sustained, but did not amplify, the treatment effect first seen on 29 DT.

Over the six postspray dates with significant differences between sprayed and unsprayed plots, six natural enemy species that were present in 90%A webs of the unsprayed plot were absent in 90%A webs of the sprayed

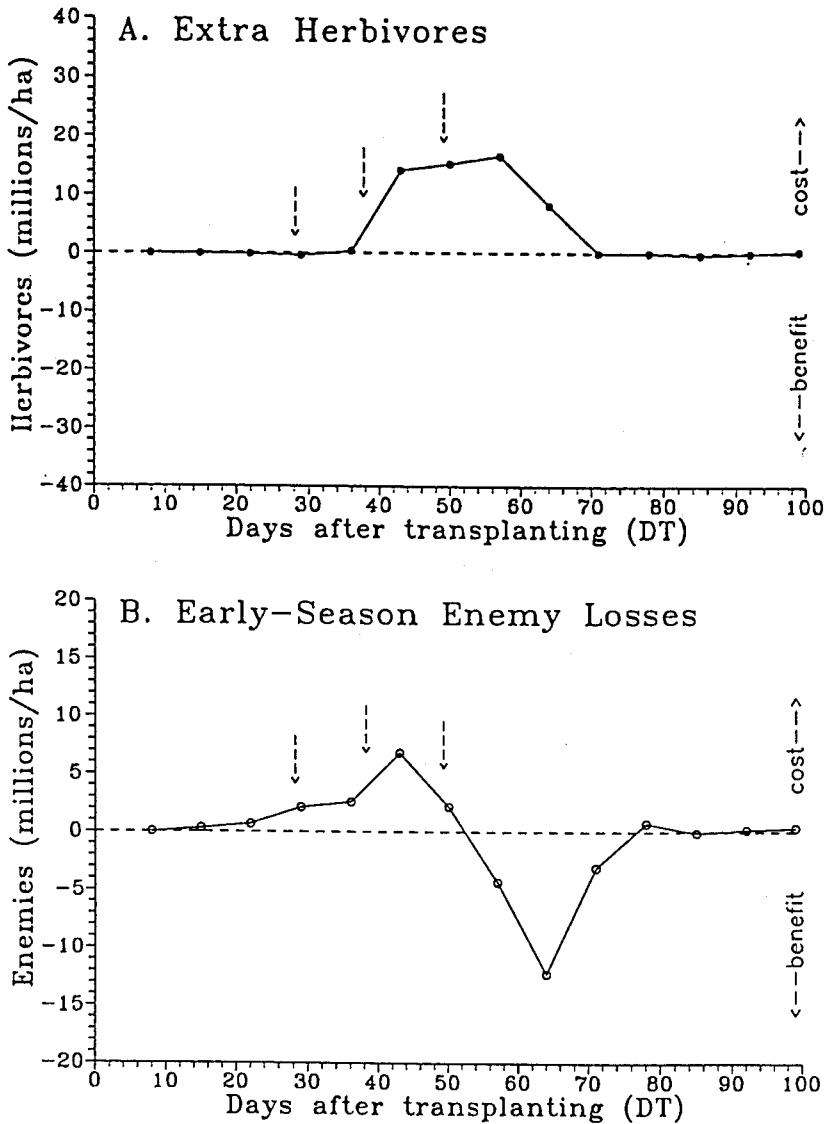


Figure 32.2. Ecological effects of deltamethrin sprays. (a) Extra herbivores (estimated 4 million individuals ha^{-1} sampling date $^{-1}$), and (b) early-season losses of natural enemies (estimated 1 million individuals ha^{-1} date $^{-1}$). Arrows denote dates of deltamethrin sprays.

plot. In decreasing order of occurrence, they were the linyphiid spider *Atypena* (= *Callitrichia*) *formosana* (Oi) (six out of six postspray dates), the mirid bug *C. lividipennis* and the coccinellid beetle *Micraspis* sp. (three out of six dates each), and the lycosid spider *Pardosa* (= *Lycosa*) *pseudoannulata* (Boesenberg & Strand), a second coccinellid beetle *Stilbus* sp. and the tetragnathid spider *Tetragnatha* sp. (one out of six dates each).

Nonparametric tests for medians (Mann-Whitney) and ranges (Kolmogorov-Smirnoff) each revealed significant between-plot differences in μ on 57 and 64 DT (Figure 32.3). The difference between the first postspray date that yielded a nonsignificant between-plot difference in μ (71 DT) and the last spray date (49 DT) is proposed as a measure of recovery time from sprays. Based on food chain lengths, the estimated time to web recovery for Zaragosa plots following

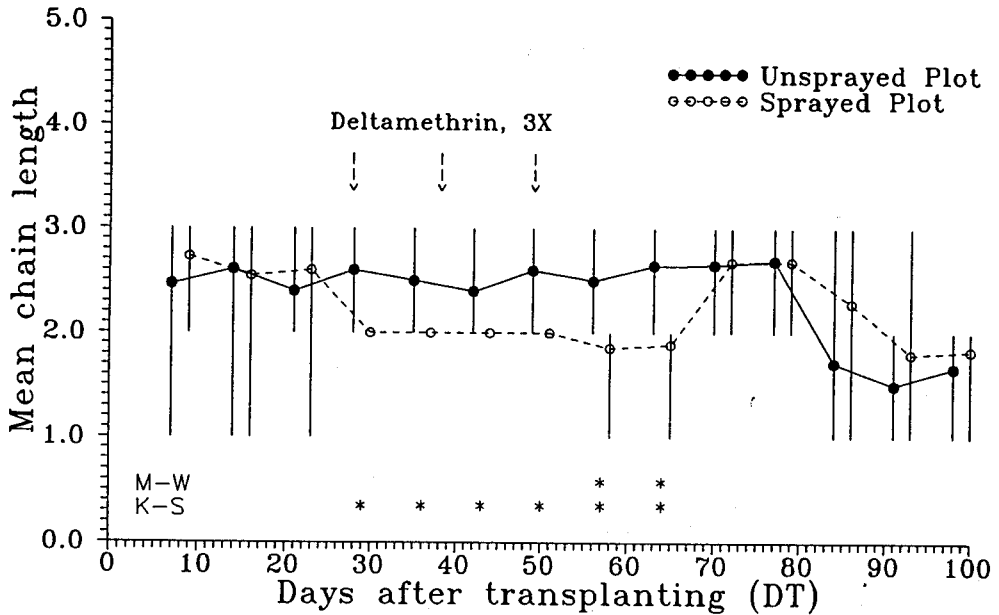


Figure 32.3. Temporal variation in mean food chain length (μ) for unsprayed and deltamethrin-sprayed plots. Vertical lines show the range in food chain lengths for sprayed and unsprayed webs on each sampling date. Calculation of μ is based on the most common taxa whose population sizes made up 90% of the total abundance on each sampling date in sprayed and unsprayed plots. M-W = Mann-Whitney test for medians; K-S = Kolmogorov-Smirnoff test for ranges * $P < 0.05$.

deltamethrin sprays on 28, 38, and 49 DT was 22 days.

Discussion and Conclusions

Biological control seeks to decrease pest populations through habitat manipulation and various management practices to conserve indigenous natural enemies (Smith, 1919; van den Bosch et al., 1982; Waage and Mills, 1992). The common use of insecticides by Filipino farmers kills indigenous natural enemies (Kenmore et al., 1987). Insecticide sprays seek to decrease pest populations, but they also reshape food web structure (van den Bosch et al., 1982) as this case study has shown (Figures 32.1–32.3). In an irrigated Philippine rice field, three applications of deltamethrin caused a dramatic rise in %H, a reduction in μ , a mixed response in %E, and a negligible change in %O. Deltamethrin spraying resulted in local pest outbreaks and increased the likelihood of crop damage. Insect pests of tropical rice inflict crop damage by sucking sap and clogging xylem and phloem tissues, by boring into tillers and feeding on leaves and seeds, and by transmit-

ting rice diseases such as tungro, grassy stunt, and wilted stunt viruses (Litsinger, 1991). During spraying (28–49 DT), several common enemy species that functioned as pest specialists (*Micraspis* sp. and *Stilbus* sp.), generalist insect predators (*A. formosana*, *P. pseudoannulata*, and *Tetragnatha* sp.), and omnivores (*C. lividipennis*) became less abundant. Because rice yield was not directly measured in this study we were unable to determine whether deltamethrin affected crop production.

Pests increased nearly fourfold in the sprayed plot over the unsprayed plot (11,454 and 2994 specimens, respectively). Of 12 putative pest species in both plots, the five cicadellid homopterans (*C. spectra*, *Nephotettix virescens*, *N. nigropictus*, *Balclutha* sp., and *R. dorsalis*), two pyralid lepidopterans (*M. ruralis* and *C. medinalis*), and two dipterans (*Atherigona* sp., and *H. philippina*) had smaller populations in the sprayed plot. These pests were controlled by deltamethrin. However, deltamethrin caused outbreaks in three delphacid populations (*N. lugens*, *S. furcifera*, and *T. pusanus*). This increase has been related to reduced mortality from natural

enemies killed by sprays, higher reproductive rates among pests, and recruitment from surrounding fields (Kenmore et al., 1984; Heinrichs and Mochida, 1984; Reissig et al., 1986; Chelliah and Heinrichs, 1980).

The sizes of natural enemy populations were similar in sprayed and unsprayed plots (9840 and 9216 individuals, respectively). In the sprayed plot, however, natural enemy populations fell during the spray interval and then rebounded following the rise of herbivores. Of the 34 enemy taxa common to both plots, 13 (38%) had overall lower abundances (e.g., *M. atrolineata*, *P. pseudoannulata*, and *Tetragnatha* spp.), 4 (12%) had identical abundances (e.g., *Ophionea* spp.), and 17 (50%) had higher abundances (e.g., *C. lividipennis*) in the sprayed plot than in the unsprayed plot. The broad effects of deltamethrin on nontarget arthropods, particularly natural enemies of pests, are well known (Croft, 1990; Jepson, 1989). This study provides additional evidence that insecticides can sometimes reduce populations of natural enemies.

As in previous studies of Philippine rice communities (Heong et al., 1991, 1992), detritivore and planktonic populations (%O) in Zaragoza plots systematically declined over most of the growing season, from 96% on 8 DT to 10% on 71 DT, and then reached a second smaller peak one week before harvest in both plots (Figure 32.1a and 32.1b). Natural enemies peaked twice, the smaller peak preceding the larger, in both plots (36 DT and 64–71 DT). Herbivores peaked only once on 43 DT in both plots.

It is possible that early-arriving natural enemies prey on detritivores when pest abundances are low, then switch to pests after detritivore populations decline (W. H. Settle, personal communication, June 11, 1993). If this hypothesis is correct, then the early spraying of insecticides, often for the control of highly visible leaf-feeding insects (Escalada et al., 1992; Vo Mai et al., 1993; Heong et al., unpublished manuscript) may be counterproductive. There may be several reasons why most rice farmers spray early. First, farmers overestimate pest damage (Escalada and Heong, 1993a; Lazaro et al., 1993). Second, farmers believe there is an analogy between pesticide applications and therapeutic cures as in medicine (Escalada and Heong,

1993b; Lim and Heong, 1984; Bentley and Andrews, 1991). Third, chemical companies may aggressively promote early insecticide spraying (Escalada and Heong, 1993a). In farmer experiments, there were no significant differences in rice yields between field plots that received early sprays and those that did not (Escalada and Heong, 1993b). Observational studies at farmers' field schools in Central Java show that seedbeds contain large populations of natural enemies (mean abundances: 700 individuals m^{-2}) even during fallow periods in the dry season (Settle, unpublished data). Moreover, leaf removal early in the season, by itself, was insufficient to cause economic loss (Heong, 1993). This finding challenged claims of Philippine farmers that early sprays are necessary to control rice leaf folders (*Marasmia* spp. and *C. medinalis*). Published studies provide compelling reasons to consider suspending prophylactic applications of insecticides for tropical rice (Escalada and Heong, 1993a, 1993b; Heong, 1993) independent of the present study.

In this study, spraying deltamethrin brought increased herbivores ($4 \times 10^6 \text{ ha}^{-1}$ sampling date $^{-1}$) and decreased natural enemies early in the season ($1 \times 10^6 \text{ ha}^{-1}$ date $^{-1}$). Based on trophic groups (Figures 32.1a and 32.1b) and mean chain length μ (Figure 32.3), the estimated time of recovery from deltamethrin varied from 22 to 30 days. These ecological costs and recovery times have practical meaning to IPM workers and farmers. Beyond ecological costs, during the 1992 wet season in central Luzon, farmers spent, on the average, U.S.\$12.18, \$5.01, and \$8.94 ha^{-1} on one to four insecticide, herbicide, and molluscicide applications (based on a 1992 exchange rate of P25.05=US\$1) (Medrano et al., 1993). Associated maintenance, equipment, and labor costs are not included.

In tropical Asia, interest is growing to increase the number of farmers' field schools for nonchemical pest control methods. Village-level IPM using the Indonesian model (The Indonesian National IPM Program, 1991) began in central Luzon only in 1992. The aims of the Philippine program were to determine needs for farmer training, institutional requirements, and constraints to IPM implementation at the village level (Medrano et al., 1993). After reporting no significant

differences in rice yields between different groups of farmers that had and had not received IPM training, Medrano et al. (1993) concluded that insect pest populations posed no economic threat to farmers and pesticides inflicted an unnecessary economic cost. More studies are needed to integrate ecological, agronomic, and economic principles of rice IPM (Medrano et al., 1993; Rola and Pingali, 1993).

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