STRATEGIES FOR
THE DEVELOPMENT OF
AN INTEGRATED APPROACH TO
RICE BROWN PLANTHOPPER CONTROL

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In the last 10 years, the brown planthopper (BPH) *Nilaparvata lugens* (Stal) (Hom., Delphacidae) and the two virus diseases it transmits have become serious constraints to rice production in South and Southeast Asia. Dyck and Thomas (1979) estimated that recent losses of rice due to the BPH and grassy stunt (GS) disease in Asia amounted to about US$300 million.

Four major genes that impart resistance to the BPH were identified in the rice germplasm at IRRI. When resistant cultivars (IR26, IR28, IR29, IR30, and IR34) with the *Bph 1* gene were released, BPH problems almost disappeared in farmers' fields in some countries of Asia but those cultivars were not resistant to the BPH in India and Sri Lanka. Furthermore, they were at first resistant but after about 2 years became susceptible to the BPH in the Solomon Islands, Philippines, and Indonesia.

Thus, resistant cultivars are threatened by the development of biotypes of the BPH. Chemical control is also not a panacea in the protection of the rice plant against the BPH. Thus, integrated control should be considered for the control of the BPH (Mochida 1978, 1979; Dyck et al 1979; Heinrichs et al 1979b).

TAXONOMY, DISTRIBUTION, BIOLOGY, AND FACTORS ASSOCIATED WITH BPH OUTBREAKS

Fifteen species belong to the genus *Nilaparvata* (Table 1). Among *Nilaparvata* spp. the BPH is the only species that attacks the rice plant and causes economic damage (Mochida et al 1978). It is widely distributed in South, Southeast, and East Asia (Fig. 1).

Biology
The BPH has three stages — egg, nymph, and adult. The developmental period of the various stages depends on the temperature and food source. The ideal temperature is 25° -30° C. The BPH completes a life cycle about every month in tropical wetland areas when a suitable food source is present (Mochida et al 1978). When

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Table 1. *Nilaparvata* spp. and their distribution (Mochida, unpubl.)

Nilaparvata sp	Distribution
N. albotristriata	Australia, Micronesia, New Caledonia.
N. angolensis	Angola.
N. bakeri	Japan, S. Korea, Formosa, Philippines, Sri Lanka.
N. caldwelli	Puerto Rico.
N. camilla	Sudan
N. castanea	China.
N. chaeremon	Sri Lanka.
N. diophantus	Portuguese, Guinea, Senegal.
N. lineolae	China.
N. lugens	From India to Japan, Pacific Is., Australia to Japan.
N. maeander	Sudan, Guinea.
N. muiri	China, Japan, S. Korea.
N. myersi	New Zealand.
N. nigritarsis	Natal, Sudan (Abyssinia).
N. wolcotti	Puerto Rico.

dryland and wetland rice fields are compared, BPH populations are frequently highest on wetland rice. Water management affects BPH population growth to some degree (Mochida 1978, Dyck et al 1979).

The BPH has two wing-forms, macropterous and brachypterous. Macropterous adults can fly over long distances with the movement of air masses. No studies on long-distance migrations have been reported in the tropics but it is suspected that long-distance migration does occur.

Macropterous adults appear to have a key role in initiating oubreaks of BPH on
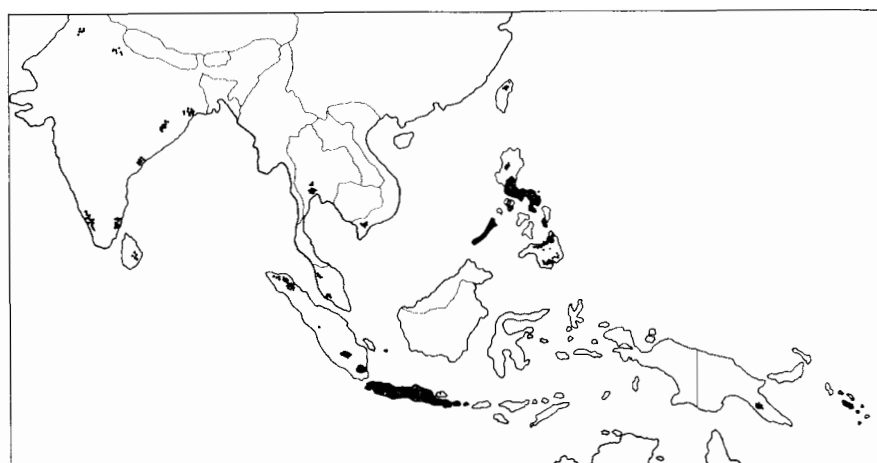
1. Locations where BPH caused serious damage to rice in 1965-76 (Mochida et al 1977, modified).

rice in the tropics (Mochida et al, unpubl.). The fact that higher densities during the nymphal stage increase the relative proportion of macropterous adults in delphacids was first reported in the smaller brown planthopper (SBPH) *Laodelphax striatellus* (Fallén) by Murata (1930). Later, Kisimoto (1956) showed that the occurrence of BPH wing-forms depends on the population density and food conditions during the nymphal stage, and that poor food conditions produced higher proportions of macropterous adults. Cheng (1977) and Cheng and Chang (1979) indicated, however, that brachypterous adults appeared even on BPH-resistant rice cultivars in Taiwan.

Suenaga (1963) calculated theoretically the maximum total number of oocytes produced within a BPH female as 1.728- 1,984. He recorded the maximum number of eggs deposited by 1 female on rice seedlings as 1,474. Less than 100 eggs female was estimated in the field at IRRI, but in the greenhouse the number of eggs produced by a female was estimated at less than 200 on a susceptible cultivar. Pelita I-1 (Mochida et al, unpubl.). The preoviposition period is shorter in brachypterous females than in macropterous females when temperature is low (Mochida et a1 1978).

The main host plant of the BPH is *Oryza sativa* but several *Oryza* species serve as host plants for the BPH in tropical Asia. Eight species, for example, are found in Indonesia — *O. granulata, O. longiglumis, O. meyeriana, O. minuta, O. officinalis, O. ridleyi O. rufipogon,* and *O. sativa. Oryza* species such as *O. australiensis, O. barthii, O. brachyantha, O. latifolia, O. nivara, O. punctata,* and *O. rufipogon* may become potential host plants. At least two allied species of the genus *Nilaparvata* are known on *Leersia* spp. (Gramineae). Correct identification of both delphacids and plant species are needed for further studies on host plant relationships (Mochida and Okada 1971, 1979).

Factors associated with BPH outbreaks
Several factors have been suggested as encouraging BPH outbreaks, but they may not be the same in different countries,

Cropping of modern high-yielding rice cultivars susceptible to BPH. Mochida and his coworkers (1977, unpubl.) reviewed the literature to determine the relationships between the time of introduction of modern cultivars and the time of BPH outbreaks as recorded in Indonesia, Malaysia, Solomon Islands, and some parts of India. Most of the outbreaks occurred after modern cultivars without BPH resistance were first grown. The population growth of BPH was greater on modern cultivars without resistant genes than on some local cultivars (Mochda 1978, Dyck et a1 1979).

Nitrogen fertilizers. High fertilizer rates are favorable to the development of BPH populations (Abraham 1957, Dyck et al 1979). Figure 2 shows the results of tests in Indonesia. In many Asian countries, synthesized N-fertilizers are usually applied to modern cultivars but not to traditional cultlvars. The amount of N-fertilizer applied to the rice crop has increased considerably in recent years. In Indonesia, for example, consumption of urea used mainly for rice, estimated at 405 million tons in
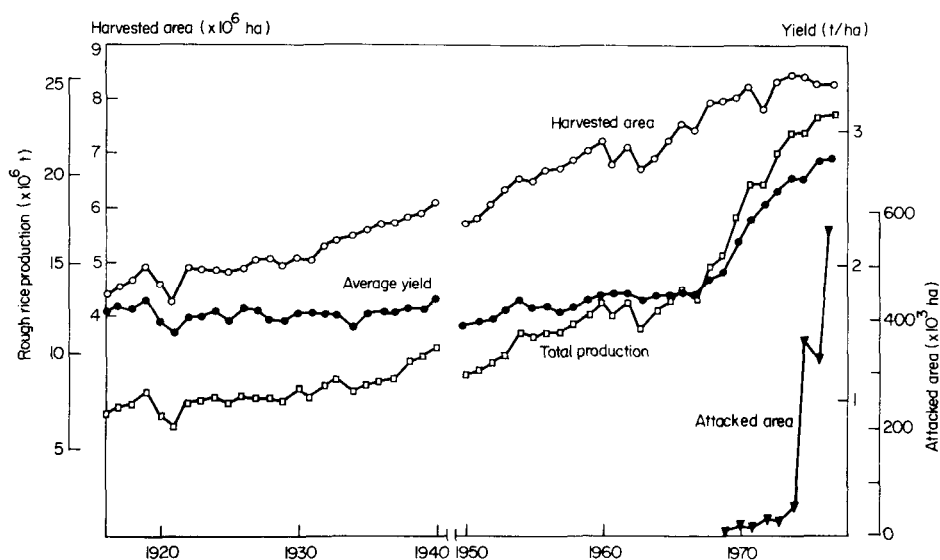
2. The total harvested area of lowland and upland rice, average yield, total rough rice production, and BPH-attacked area of rice fields in Indonesia in 1916–77 (Mochida 1978).

1971-72, reached 919 million tons in 1977-78 (Mochida 1978).

Irrigation. In some countries the area of irrigated land for rice production has increased. Irrigation affects the BPH in two ways. First, irrigation occasionally changes rice cropping patterns. Because rice is the main host of BPH, irrigated double or continuous rice cropping provides a suitable host plant throughout the year. Where rice is cropped only once a year, on the other hand, most BPH cannot survive for the dry period because of lack of a host. Second, water content of soil or water management is related to the BPH population growth (Mochida 1978, Dyck et al 1979).

Application of insecticides and resurgence. Generally, it is believed that application of insecticides to the rice crop results in a decrease of the populations of the natural enemies of the BPH. However, the kinds of insecticides and the amounts applied to the rice crop are considerably different in various countries.

There are indications that insecticide-induced BPH resurgence has caused some outbreaks. The role of insecticides in inducing resurgence is discussed in detail in a later section on chemical control.

Coverage of rice plants per unit of area. The number of BPH nymphs per hill and the number of tillers per hill are occasionally positively correlated. There are also positive correlations between the number of nymphs and hill density per square meter and between density of nymphs and the number of tillers per square meter (Dyck et al 1979). The number of tillers per square meter can change due to cultivars and cultural practices such as fertilizer application, spacing, and planting methods.

If modern BPH-susceptible rice cultivars produce many tillers when fertilizers, especially nitrogen, are applied at high levels, modern rice cropping would be expected to increase the density of BPH.

Mochida et al (1977, 1978) and Mochida (1978, 1979) indicated that the recent outbreaks of BPH in Indonesia were probably associated with the enlargement of irrigated rice fields, double or continuous rice cropping with high-yielding BPH-susceptible cultivars, and application of N-fertilizers. Mochida (1978) pointed out that such outbreaks have been occurring since about 1970, when average rice yields started to increase, and have been occasionally seen in rice-bowl areas with high yields (Fig. 2, 3).

Although numerous cultural practices affect BPH populations, it has not been possible to experimentally manipulate cultural practices such that BPH would cause hopperburn, except through the application of resurgence-inducing insecticides. Entomologists disagree regarding the causes of BPH outbreaks but agree that BPH is an extremely important pest, which can only be properly controlled through an integrated pest management approach.

DEVELOPMENT OF COMPONENTS FOR THE MANAGEMENT OF BPH POPULATIONS

Rice yield losses caused by BPH and the two virus diseases fluctuate considerably locally, seasonally, and annually. Mochida (unpubl.). over a 5-year period, compared the rice yields in untreated plots with those in plots intensively treated with
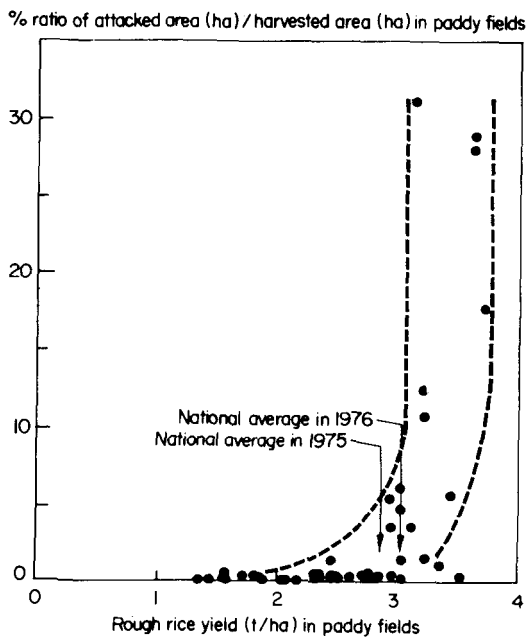
3. Relationship between the average rice yields in each province and the area of rice fields attacked by the brown planthopper in Indonesia in 1975 and 1976 (Mochida 1978).

insecticides. Yield losses of a susceptible cultivar (Pelita I–1), four resistant cultivars with the *Bph 1* gene (IR26, IR28, IR30, and IR34), and one resistant cultivar with the *Bph 2* gene (IR32) due to all insect pests were 49.4, 29.1, and 26.4%, respectively. The yield losses in the resistant cultivars were primarily due to BPH, although hopperburn did not occur.

Dispersal and migration of BPH seem to occur frequently in continuous rice-cropping areas, especially with staggered cropping. Continuous movements into the field make it difficult to control the BPH with chemicals. When BPH population was high, frequent applications of effective insecticides were not sufficient to prevent the yield losses of Pelita I-1 due to the BPH (Mochida et al 1977), grassy stunt, and ragged stunt (Mochida et al 1978). Chemical control is effective but it is expensive and its cost is increasing at a faster rate than the price of rice.

It is apparent that no one control technique is by itself entirely satisfactory. The most rational approach to control the BPH is to integrate the various pest manage-ment components such as varietal resistance and cultural methods in which insecti-cides are applied according to the insect population, as measured by an efficient monitoring program.

Economic injury levels and economic thresholds
Knowledge of the relationships between the yield loss caused by BPH and BPH population densities is important. In the Philippines, Dyck and Orlido (1977) identified critical stages for plant damage (Table 2). In the greenhouse, there was usually no significant reduction in grain weight when maximum BPH densities were about 25 BPH/hill in either the second or third generation. In the field, 50-60 BPH/hill at harvest produced no apparent loss in grain yield. Thus, Dyck and Orlido recommended an economic injury level of 1 BPH tiller or about 25 BPH / hill as a rough guide for practical BPH control throughout a crop period. In Taiwan, Yen and Chen (1977) showed that 25 BPH/ hill was a practical control threshold. In Indonesia, greenhouse experiments indicated that all the young plants of Pelita I-1, a susceptible cultivar, were killed within 2 weeks, when 10 macropterous adults/ hill attacked within a week after transplanting (CRIA-IRRI, Sukamandi, unpubl.). In Sukamandi fields, more than 200 adults plus nymphs/hill appeared on 3 cultivars — IR26, IR32, and Kencana (without any major resistant gene) — for a 2-week period at 10-14 weeks after transplanting, but all rice plants of the 3 cultivars survived. However, three other susceptible cultivars were hopperburned (Mochida et al 1979).

In Japan, Nomura (1949) indicated a relationship between the number of BPH adults swept by a net and the loss of grain as:

Adults/100 strokes	Loss of grain (%)
500	25
1000	40
1500	55
2000	70
2500	85

Table 2. Grain yield response of IR22 in the greenhouse to direct damage caused by various densities of BPH nymphs caged for 2 weeks on plants of different ages (Dyck and Orlido 1977).

Insects caged[a] (no./tiller)	Yield[b] (g/hill)							
	26-39 DS	40-53 DS	54-67 DS	68-81 DS	82-95 DS	96-109 DS	110-123 DS	124-137 DS
0.0 (Control)	34	21	20	15	14	16	14	14
0.1	21*	22	20	18	17	13	11	12
0.2	29	20	17	12	12	8*	9	14
0.5	20*	24	17	15	12	16	13	14
1	21*	15	16	11	14	16	11	14
2	21*	21	15	14	13	16	13	15
5	5*	20	16	13	10	13	14	14
10	0*	21	21	12	10*	13	13	12
25	0*	6*	20	11	10*	13	9	16
50	0*	0*	15	11	5*	10	11	16

[a] Where number is less than 1, 1 insect/tiller was caged for a fraction of 2 weeks, e.g. 1 insect/tiller for 2.8 days (0.2 × 14). [b] * means significantly lower than the control at the 5% level. DS = days after seeding (plant's age at infestation). Each plant was infested for not more than 2 weeks throughout its entire growth.

Suenaga (1959a) recommended the application of insecticides when there are more than 10 adult BPH/hill at tillering stage and more than 50/hill after heading stage. Kisimoto (1978) indicated that, when there are more than 20-30 immigrant adults/100 hills, hopperburn will be expected in later generations. Yokoyama (1979) recommended insecticide application when more than 20 adults/ 100 hills occur about 1 month after the peak of immigrant adults (or tillering stage), and when more than 10 adults 100 hills occur during the postbooting to heading stage.

Population monitoring
Population monitoring is necessary for preventing the outbreaks of BPH. Various sampling techniques have been developed.

Although various sophisticated techniques for sampling BPH populations have been developed, most are research tools and are not required in a practical pest management program. The simple technique of tapping the plant and estimating the number of insects provides adequate information to enable a farmer to decide whether or not an insecticide application is needed. The need today is to teach the farmers how to sample and identify the BPH and to make a control decision based on economic injury levels.

Biological control
Natural enemies of the BPH and their use as control agents have received little emphasis until recently. Numerous predators, parasitoids, and pathogens attack the BPH. Chiu (1979) listed 19 hymenopterous species as egg parasites, 16 insect species as parasitoids of nymphs and adults, 21 insects and 16 spiders as predators, and 7

species of pathogens. In addition, a mite, two coccinellids (*Harmonia octomaculata* and *Microspis lineata*), and a dryinid *(Digonatopus javanus)* were recorded as natural enemies in Indonesia (CRIA-IRRI, Sukamandi, unpubl.).

Among the egg parasites, *Anagrus* and *Oligosita* are the most common at IRRI. Parasitism averages about 25% (V. A. Dyck, IRRI, pers. comm.). Among the predators, the spider *Lycosa pseudoannulata* and the vellid bug *Microvelia atroli-neata,* and the mirid bug *Cyrtorhinus lividipennis* are common. However, the effectiveness of the latter two species as biological control agents is still under study.

The use of insect pathogens as BPH control agents is an area relatively untouched. IRRI and Boyce Thompson Institute (Ithaca, New York, USA) scientists recently initiated a program to identify suitable pathogens and determine their efficacy against field populations of BPH. Fungi such as *Entomophtora* and *Metarrhizium* have potential in BPH control.

Although natural enemies have been shown to exert a significant effect on the regulation of BPH populations, biological control agents cannot yet be manipulated in a pest management program. Today, only a few examples of the use of biological control agents exist. The nematode *Agamermis unka* was introduced from Japan into the Solomon Islands in 1966 for BPH control (Suenaga and Mochida 1969). Ducks are used to control the BPH in most of southern China and have been shown to be effective as BPH predators in IRRI experiments (V. A. Dyck, IRRI, pers. comm.). Conservation and augmentation, however, are areas of potential value as the key natural enemies are identified and more is learned about their biology and ecology.

V. A. Dyck, IRRI (pers. comm.), suggests that in biological control of BPH:

- Ducks can be used to suppress BPH populations but they should be herded in fields where the BPH needs to be controlled, not in fields with low BPH density.
- Where practical, natural biological control agents should not be destroyed through the excessive use of insecticides.
- Based on previous ecological studies, it should be possible to predict the future pest density if the current pest and natural enemy (especially predator) densities are known.
- Fungal pathogens suggest that microbial insecticides be developed in the future.

Chemical control

Throughout Asia, insecticides are an important component in the control of BPH. especially where resistant varieties are not available. However, several factors complicate the use of insecticides in the control of this pest.

- The BPH feeds at the base of the plant near the water level, where it is difficult to be reached directly by insecticides.
- The BPH is a phloem feeder, and systemic insecticides are expected to move primarily through the xylem. Insecticide accumulates in the leaf tips and little of it accumulates in the leaf sheath area.
- Of the various rice planthoppers and leafhoppers, BPH is generally the most difficult to kill with insecticides. Thus, many insecticides effective against other

hoppers are not sufficiently effective against the BPH.
- It is extremely difficult to control the adults migrating from adjacent outbreak areas. Even when fields are sprayed, the insects are capable of laying eggs before they are killed. Many insecticides do not kill the eggs and when eggs hatch, the residual activity of the insecticide is not sufficient to kill the nymphs and, thus, additional applications are required. Timing of application is critical.
- With the high reproductive rate, the BPH rapidly develops resistance to insecticides.
- Many insecticides applied at sublethal rates cause resurgence. Because many farmers use sublethal rates, these insecticides have caused severe problems for farmers.

In this section on chemical control, we discuss some of the progress made in the last decade in overcoming the difficulties mentioned above and suggest areas where additional studies are needed to better cope with the BPH problem in the 1980s.

Effective insecticides. Insecticides active against BPH have been identified among those evaluated at IRRI and in national programs (Heinrichs et al 1978, 1979a; Heinrichs 1979; Moriya 1977; Cheng and Liu 1978). The Philippines recommends 10 insecticides for BPH. In Taiwan, 30 insecticides have been registered with the government for use in BPH control. In Taiwan, most of the insecticides are carbamates, with carbofuran granules and MIPC, Hokbal, propoxur, and BPMC sprays being the most effective. Moriya (1977) found that the BPH in Japan was more susceptible to carbamate than to organophosphorus compounds in LD_{50} studies.

Application methods. In Japan, Korea, and Taiwan, dust formulations are commonly used for BPH control but in the tropics granules and foliar sprays are the most common. A survey in Central Luzon, Philippines, found that 27% of the insecticides used for rice insect control was applied as granules and 73% as foliar sprays (W. H. Reissig, unpubl. data).
- *Foliar sprays.* Because the BPH feeds at the base of the plant and is not highly active, it is difficult to contact directly with insecticide.

  In the Philippines, high spray volumes of 1,000 liters/ha are recommended for BPH control when the canopy has closed but a field experiment using Perthane indicated no difference in control among volumes from 190 to 950 liters/ha (IRRI 1978). A greenhouse test comparing the effect of spray volumes of several insecticides on BPH control indicated that for most insecticides, all volumes provided similar initial control but the highest spray volume provided the longest residual toxicity (Fig. 4).

  Application of high volumes (300- 1,000 liters ha) of water, as required in the commonly used knapsack sprayer, is extremely laborious. As a result, farmers use too little water and frequently underdose. Studies at IRRI have indicated that the deposition of insecticide at the BPH feeding site with the ultralow volume (ULV) applicator is similar to the application with a knapsack sprayer (Pickin et al 1980). High wind speeds, however, cause drifting of the small droplets emitted by the ULV sprayer. Recently developed electrostatic sprayers

4. Effect of 3 spray volumes on BPH mortality. Mortality readings were taken at 24 hours after insects were caged on treated plants. Three groups of insects were caged at 1, 7, and 14 days after treatment. All insecticides were applied at 0.75 kg a.i./ha, except carbofuran, which was applied at 0.25 kg a.i./ha. IRRI greenhouse. 1979 (Heinrichs and Valencia, unpubl data).
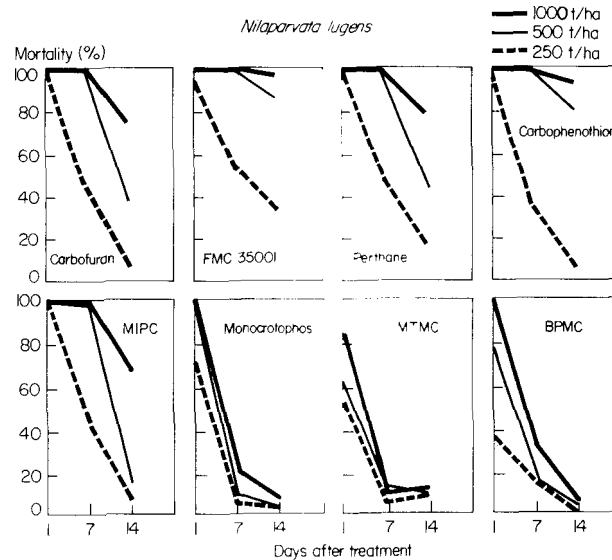
that add an electrical charge to the droplets, which is opposite to the charge of the rice plant, show promise in overcoming the drift problem because the droplets are attracted to the plant.

Insecticides applied as foliar sprays, when exposed in the field, have extremely short residual activity. Microencapsulation of insecticides may provide a means of slow release, thus increasing residual activity and also decreasing the hazard to the applicator.

• *Paddy water application of granules.* The use of a granular formulation, which can easily be broadcast by hand, eliminates many of the application problems encountered with foliar sprays. Granules, however, are expensive and the number of effective insecticides in granular formulations is limited. Carbofuran and diazinon granules have been commonly used for BPH control. Carbofuran is highly effective at 0.5 kg a.i./ ha in the greenhouse.

• *Root-zone application.* Insecticides that are highly active when applied in the root zone of the rice plant are being sought but only a few have been identified (Table 3). Root-zone application provides much longer residual activity than foliar sprays and broadcast of granules (Fig. 5). Root-zone application is more effective against the green leafhopper *Nephotettix virescens* than against the BPH. Another disadvantage of the root-zone method is that application is most convenient at or shortly after transplanting. However, under normal circumstances, the BPH moves into the field about 30 DT, after which the residual activity of a soil incorporation is too low for adequate BPH control. To extend the period of control, we are evaluating various slow-release formulations.

Table 3. Activity of granular insecticides applied in the root zone of rice plants at 1.0 kg a.i./ha for brown planthopper *Nilaparvata lugens* control. IRRI greenhouse, 1978.

Insecticide		Mortality[a] (%)		
		1 DT	7 DT	14 DT
FMC 27289	2.5 G	23 abc	60 abc	85 ab
Carbofuran	3 G	15 abc	38 bc	98 ab
Bendiocarb	5 G	15 abc	30 cd	70 b
FMC 35001	2.5 G	10 bc	15 cd	63 b
Isazophos	3 G	5 c	60 abc	80 ab

[a]Av, 4 replications, each consisting of 10 insects caged on treated plants. Means followed by a common letter are not significantly different at 5% level.
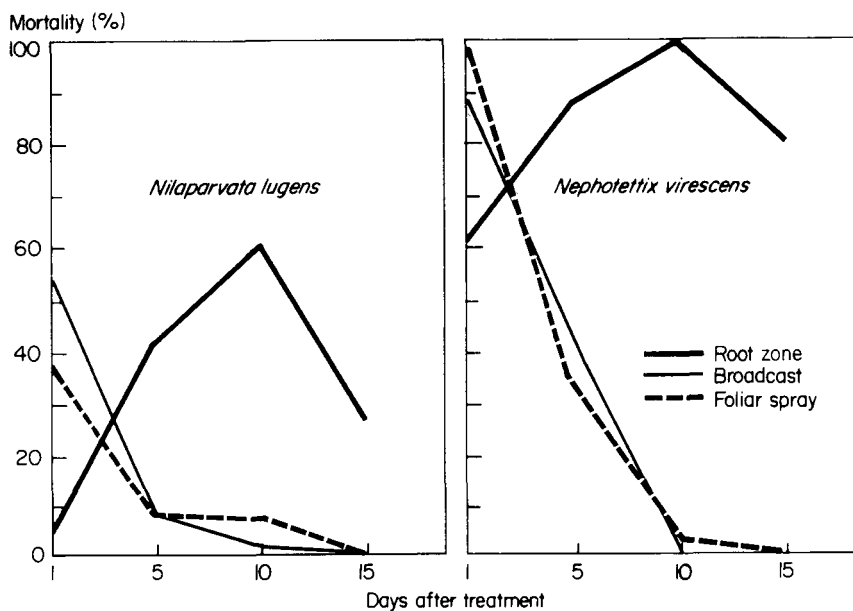
5. Field evaluation of 3 methods of isazophos application at 0.5 kg a.i./ha. In the root-zone treatment, insecticide was placed in a gelatin capsule and inserted into the soil near the roots; in the broadcast method, granules were broadcast into the paddy water. Mortality readings were taken 48 hours after hoppers were caged on treated plants and adjusted using Abbot's formula. Variety IR22. IRRI, 1979.

Modes of insecticide action

The effectiveness of the various insecticides depends on their modes of action. According to Moriya (1977), the killing action of an insecticide can occur through
- the chemical's direct application to the body of the BPH;
- contact of the BPH with the insecticide as it moves over the residue;
- BPH ingestion of insecticide present in the plant system (systemic insecticide); and

• fumigation by insecticide vapors.

The most effective insecticides are active throughout all the above actions. Some insecticides are not highly active as contact insecticides but are effective against BPH feeding on sprayed plants (Fig. 6). Perthane and carbofuran, both highly effective against BPH, have a high degree of fumigant action as a foliar spray. Granules applied to the paddy water also act as a fumigant. Studies in Japan by Koyama and Tsurumachi (1968) indicate that diazinon granules also mainly act as a fumigant.

The population density of BPH is usually higher a week after insecticide application than a week before, when applications are poorly timed and many eggs within the leaf sheath tissue hatch and survive because the toxicity of the insecticide dissipated within a few days after application. Thus, insecticides with ovicidal action are desired for more effective BPH control. Carbofuran and triazophos have been shown to be ovicidal as foliar sprays and as paddy water applications in greenhouse studies (Heinrichs and Valencia, unpubl.).

Antifeedant compounds hold much promise for BPH control. The insecticide chlordimeform has an antifeedant action against BPH (Hirata and Sogawa 1976). Both chlordimeform and Perthane are highly effective antifeedants for BPH con-
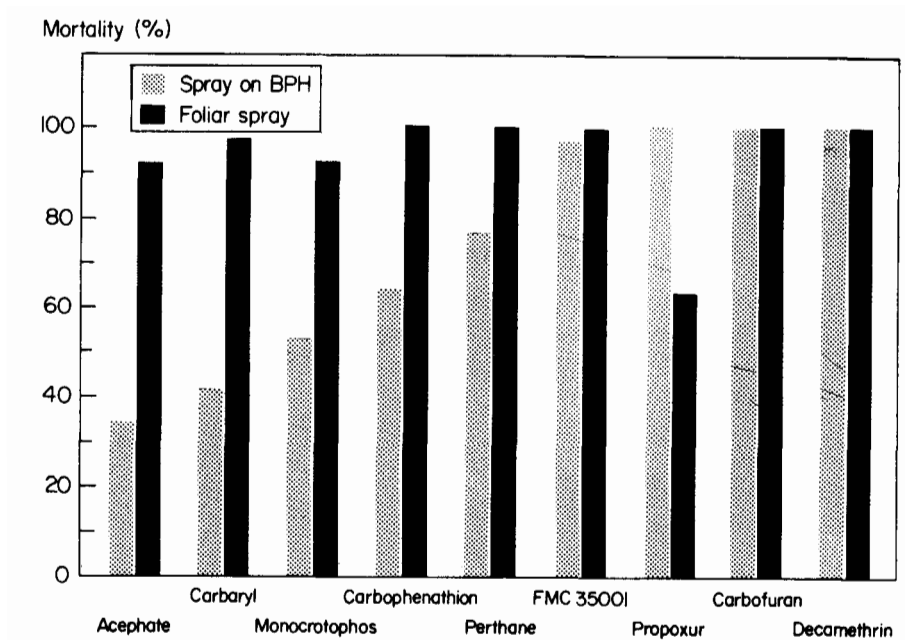
6. Mortality of the *Nilaparvata lugens* when sprayed directly in the Potter's Spray Tower or when placed on sprayed plants at 1 day after treatment, both with a 0.04% spray. Mortality in the Potter's Spray Tower test was recorded 48 hours after treatment and in the foliar spray test at 48 hours after caging insects on treated plants. Values adjusted using Abbott's formula. IRRI greenhouse, 1977.

trol. The fungicide guazatine triacetate (Panoctine) also had antifeedant activity in IRRI tests (Heinrichs and Valencia, unpubl.). Botanical compounds such as trans-aconitic acid (Koh et al 1977) and neem (*Azadirachta indica*) oil (R. C. Saxena, pers. comm.) have been shown to reduce BPH feeding activity. Neem oil, however, has not been shown to be effective in the field because its residual activity is short.

Timing of application
Proper timing of insecticide application is important to achieve maximum control of the BPH. It is best to apply insecticide when most of the nymphs are in the third to fourth instar because most of the eggs deposited by adults of the past generation have hatched and few eggs have been laid by adults of the next generation.

In studies conducted in a farmer's field in the Philippines (Heinrichs and Aquino, IRRI, unpubl.), application of insecticides for BPH control was timed according to:
- the life cycle of the BPH,
- the number of BPH per hill, and
- a calendar-based schedule.

The highest yield of 7.03 t/ha was obtained when Perthane was applied at the peak population of the first- and second-generation nymphs (based on the life cycle). Yield losses due to BPH were low when a spray was applied once, when the population reached 10 or 16/hill. The benefit-cost ratio for insecticide use was highest (10.7) on the treatment sprayed when the population was 10 BPH/hill, whereas it was only 2.4 in the treatment sprayed 4 times on a calendar basis. The studies showed that fields should be monitored weekly and insecticides applied only when the economic threshold is reached.

Insecticide resistance
Resistance of the BPH to insecticides is primarily a problem in countries where insecticides have been extensively used. However, in Japan, the BPH has not developed resistance to as high a degree as has the green leafhopper *Nephotettix cincticeps* (Nagata 1979) because, it is believed, the BPH cannot overwinter and the migrants that come in early summer apparently have not had much exposure to insecticides. That would be the case if the BPH is coming from mainland China, as reported. Nagata (1979) reported that the level of resistance increased twentyfold from the immigrant generation to the fifth generation.

In Taiwan the BPH was recently reported to have developed resistance to MIPC and MTMC (Lin et al 1979). At IRRI, where diazinon and carbofuran had been extensively used, the BPH developed resistance (Heinrichs 1979). Throughout tropical Asia, however, because of the limited use of insecticides, selection pressure is low and resistance does not appear to be a problem at this time. But, with the increase in continuous cropping and national production programs that promote insecticide use, BPH resistance to insecticides may become a problem in the future.

Insecticide-induced BPH resurgence
The reasons for the 1972-75 BPH outbreaks throughout tropical Asia is not known,

but many entomologists have implicated the changes in cultural practices that have accompanied the change from local to high-yielding cultivars. However, as previously indicated, it has been difficult to significantly increase BPH populations by manipulating cultural factors. On the other hand. applications of certain insecticides have been observed to cause unusual increases in BPH populations.

Most of the hopperburned fields reported, or actually observed by Heinrichs, in the Philippines and other countries have had a history of insecticide applications before the occurrence of an outbreak.

In the routine field evaluation of insecticides at IRRI, it is frequently observed that after certain insecticides have been applied, the BPH population dramatically increases. Hopperburn results while the BPH population remains low in the untreated check. A significant increase in BPH populations after treatment with insecticides, compared with that in an untreated area, is termed insecticide-induced resurgence (Fig. 7). Insecticide-induced BPH resurgence has also been observed in Bangladesh, India, and Indonesia. Although the role of insecticide in promoting the major 1972-75 BPH outbreaks throughout Asia is not known, insecticides have been suggested as the major cause by Kenmore (1979). Numerous insecticides have the potential to induce resurgence (Chelliah 1979). The list includes insecticides that may provide control at recommended rates but induce resurgence at sublethal rates. Because of the feeding location of the BPH and the short residual activity of the insecticides, the BPH is frequently exposed to sublethal rates.

National rice production programs designed to increase rice yields have encouraged an increase in insecticide use in rice. In the Philippines, methyl parathion was used in the Masagana 99 program. Methyl parathion applied at recommended rates of 0.75 kg a.i./ha is highly active as a resurgence-inducing insecticide (Fig. 7).

7. Four sprays of methyl parathion at 0.75 kg a.i./ha caused marked resurgence of BPH population on IR22. IRRI, 1977 dry season.
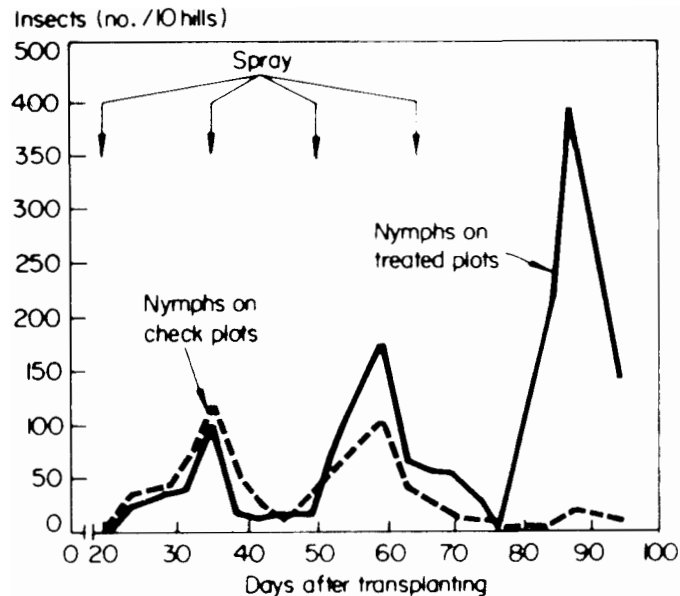
Because of its resurgence and hazard to humans, it was removed from the list of recommended insecticides in the Philippines in 1978. In reviewing the insecticides included in the national rice production program in Indonesia, known as the Bimas Program, as listed by Soenardi (1978), it is of interest to note that at least half of the insecticides recommended may cause BPH resurgence.

Evaluation studies at IRRI indicate that there is no apparent class distribution among insecticides causing resurgence since some of the carbamates, phosphates, and synthetic pyrethroids cause resurgence. Field studies are currently under way to screen the recommended rice insecticides for their resurgence potential. The basic mechanism in insecticide-induced BPH resurgence is not understood. Various hypotheses have been proposed. These are:
- selective removal of natural enemies. Studies on the relationship between natural enemies and BPH resurgence have been inconclusive;
- selective removal of competitive species;
- change in the physiology of the plant, which enhances its nutritional value to the BPH;
- increase in growth of the plant, which has an effect on the ecology of the insect;
- control of a BPH pathogen; and
- direct effect of the insecticide on the insect to increase its feeding and reproductive rate. Intensive greenhouse studies have shown that sublethal rates of certain insecticides significantly increase the feeding and reproductive rate of the BPH (Chelliah et al 1980).

Varietal resistance

Varietal resistance to the BPH was first reported from India. A systematic search of the world germplasm collection for BPH resistance began at IRRI in 1966 (Pathak and Khush 1979). Development of an efficient screening system greatly accelerated the identification of resistant sources in programs at IRRI and in Korea, Japan. Taiwan, Thailand, Indonesia, India, Sri Lanka. and the Solomon Islands (Choi 1979). About 37,000 accessions from the world collection have been evaluated at IRRI since 1966 and nearly 300 varieties with high level of BPH resistance have been identified (Table 4). Some accessions have multiple resistance to the BPH, green leafhopper, and WBPH (Heinrichs, unpubl.).

Through genetic analysis of selected varieties, four genes for resistance have been identified (Table 5). Many of those varieties are being used as resistance sources in national programs (Table 6) and BPH-resistant varieties have been released for commercial cultivation in China, Indonesia, Korea, Philippines, Solomon Islands, Taiwan, Thailand, and Vietnam, Bangladesh, India, and Sri Lanka have advanced BPH-resistant lines for possible release in the near future.

Attempts to identify the various biotypes on the basis of characters other than the reaction of differential varieties, as indicated by feeding damage or by the insect's feeding activity on differential varieties, have not been successful.

IR26 (*Bph 1* gene), the first BPH-resistant variety released in the Philippines, was found susceptible when first grown in India. After IR26 had been grown in Indone-

Table 4. Origin of cultivars in the IRRI germplasm collection with resistance to the brown planthopper *Nilaparvata lugens.* IRRI, January 1980.

Origin[a]	Cultivars/accessions	Total varieties (%)
Oryza sativa[b]		
Australia	1	0.4
Bangladesh	4	1.6
Burma	1	0.4
China	1	0.1
India	47	18.2
Nepal	1	0.4
Nigeria	2	0.8
Sri Lanka	197	76.4
Taiwan	3	1.2
Thailand	1	0.4
Total	258	
Wild rice species[c]		
Africa	1	3.7
Australia	2	7.4
Costa Rica	2	7.4
Gambia	4	14.8
Guatemala	1	3.7
India	15	55.6
Taiwan	1	3.7
U.S.A.	1	3.7
Total	27	

[a] Sources from which IRRI received seeds. The variety may have originated in another country and come to IRRI from the country indicated. [b] 37,000 varieties have been evaluated. [c] 93 accessions have been evaluated.

Table 5. Brown planthopper-resistant varieties and genes identified for that resistance (Khush 1977, Lakshminarayana and Khush 1977).

Bph 1	bph 2	Bph 3	bph 4
TKM 6[a]	ASD$_7$	Rathu Heenati	Babawee
Mudgo	Ptb 18	Ptb 19	Gambada Samba
MTU 15	H 105	Gangala	Hotel Samba
CO 22	ASD$_9$	Horana Mawee	Kahata Samba
	Palasithari 601	Muthumanikan	Thirissa
	H 5	Kuruhondarawala	Sulai
		Mudu Kiriyal	Vellai illankali
			Heenhoranamawee
			Kulu Kuruwee
			Lekam Samba
			Senawee

[a] Resistance gene is marked by an inhibitory gene.

Table 6. Varieties used as sources for gall midge and brown planthopper resistance in breeding programs of various countries (Animal Institute, Academy of Science, China, 1979).

Bangladesh	India	Indonesia	Sri Lanka	Thailand	IRRI

Kuluhondara-wala
Suduru Samba
Balamawee
Gangala
	Ptb 21
	Ptb 33
	ARC6650
	Leb Mue
	  Nahng
	Rathu Heenati
	CR57-Mr-1523
	ARC1125
	ARC6650
		ASD 7
		Ptb 33
		Rathu Hee-
		  nati
		Babawee
			Ptb 33
			ARC6650
			Heen Rath-
			  kunda
			Suduru Samba
			CR57-Mr-1523
				Eswarakora
				Ptb 21
					Mudgo
					ASD7
					Ptb 21
					Ptb 33
					Rathu Heenati
					Babawee
					Suduru Samba

sia and in the Philippines for about 2-3 years, there were reports of high BPH populations causing hopperburn. This indicated that selection pressure resulted in a shift in the BPH population to an abundance of a virulent biotype. Farmers in the Philippines then shifted from IR26 to IR36 (*bph 2* gene). IR26. however, is grown on more than a million hectares in China (G. S. Khush, pers. comm.). The Chinese used IR26 as a restorer parent in 90% of the 5 million ha of hybrid rice grown in 1979.

Laboratory studies have documented the rate at which the wild strain, biotype 1, can adapt to a resistant variety (Pathak et al 1980). Within 7 generations, biotype 1 became adapted to the resistant varieties Mudgo (*Bph 1* gene) and ASD 7 (*bph 2* gene), as indicated by survival studies (Fig. 8). With 3 generations per crop this would be 3-4 years under a 2 crops/year system. Additional studies indicated that rate of adaption, based on feeding activity and fecundity on the resistant varieties. varied between Mudgo and ASD 7. Biotype 1 adapted at a more rapid rate to feeding on ASD 7 and was more fecund on Mudgo.

Development of BPH-resistant varieties was accelerated through the establishment of the International Rice Brown Planthopper Nursery (IRBPHN) in the International Rice Testing Program. Results of the 1979 IRBPHN at IRRI indicate that advanced breeding lines from the various national programs have resistance to two or three of the biotypes at IRRl (Table 7). Some of the lines are expected to have two major genes for BPH resistance whereas all commercial varieties still have only one major gene.

Breeders are incorporating into rice hybrids multiple resistance to insect and disease pests. Some IR varieties have resistance to the BPH and the green leafhopper *N. virescens,* but, so far, no IR variety has resistance to the WBPH. However, elite breeding lines under evaluation have resistance to the three BPH biotypes, green leafhopper, and WBPH. The Korean breeding program has developed cultivars with resistance to the green leafhopper *Nephotettix cincticeps,* BPH, SBPH, and WBPH.

Although farmers in the Philippines have been growing IR36 for 3-4 years, there have still been no confirmed reports of BPH damage. IRRI studies indicated that

8. Survival of newly emerged nymphs of biotype-1 BPH up to 13 days after release on susceptible TN1 and resistant varieties Mudgo (*Bph 1* gene) and ASD 7 (*bph 2* gene) from 1-7 generations. Biotype I is a wild strain originally collected in the field and reared on TN1 for at least 10 years. IRRI 1979 (Pathak et al 1980).
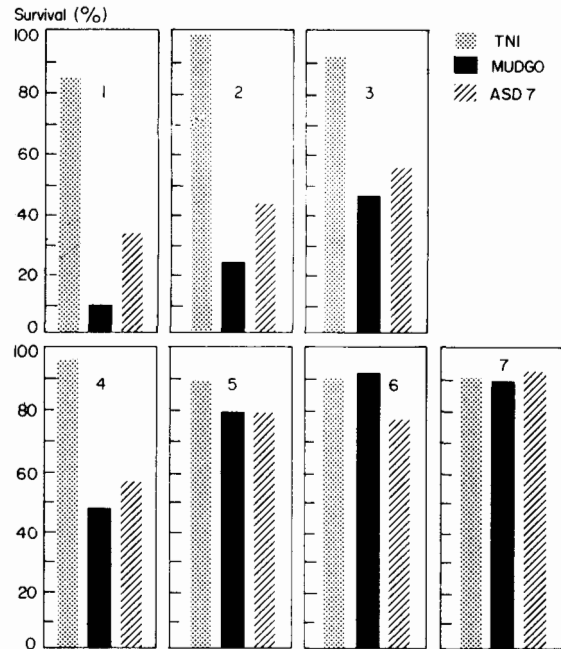
IR36 may possess minor genes, in addition to the major *bph 2* gene. The minor genes appear to be active in imparting resistance in plants after the seedling stage. This is indicated by the difficulty in maintaining a biotype 3 population on 30- to 40-day-old plants; the biotype 3 population thrives on ASD 7, even though it has the same major gene as IR36. Because minor genes, which impart moderate resistance, may provide horizontal resistance to all biotypes and exert less selection pressure for biotype development, methods are being developed to screen for this type of resistance.

Moderate resistance is difficult to detect by the common seedbox-screening technique used to evaluate 7- to 10-day-old seedlings, which are usually rated susceptible. It is clearly observable, however, in screenhouse or field studies, where planthopper activity generally occurs on older plants. TNl, Triveni, IR26, and Mudgo are all susceptible to biotype 2 in seedbox screening but they show distinct differences in resistance when evaluated as older plants (Fig. 9).

Although IR26 and Mudgo have the same major gene for resistance, *Bph 1,* Mudgo is always more resistant in IRRI field trials than IR26. Triveni, having no known major gene, is always more resistant in field screening than TNl. Tolerance, the ability of a plant to survive and grow despite insect feeding, may be one of the mechanisms operating in the field. Mudgo and Triveni are able to tolerate BPH

Table 7. Degree of resistance of selected entries in the 5th International Rice Brown Planthopper Nursery (IRBPHN) to brown planthopper biotypes at IRRI, 1979.

Entry	Cross	Source	Reaction[a] in greenhouse to			Field[b]
			Biotype 1	Biotype 2	Biotype 3	
CR57-11-2	IR8/Ptb 27	India	R	R	R	R
Kanto PL 2	Reiho/F8269//Tsukushibare	Japan	R	S	R	S
Kav 10661-1	Triveni/IR2071	India	R	R	R	R
Milyang 44	YR657-153/IR26	Korea	R	S	R	S
YR1805-52B	—	Korea	R	R	R	R
IET5122	Vijaya/Ptb 21	India	R	R	R	R
B28508-SI-2-1	B541B-KN-91-3-1/IR2011-15-4-1-2	Indonesia	R	R	R	R
RD9	LY*2/TN1/W1256//RD2	Thailand	R	S	R	S
IR13543-66	R. Heenati/IR3403-267-1//IR34	IRRI	R	R	R	R
IR13240-6-3	IR30S/Babawee//IR2071-625-1-252	IRRI	R	R	R	R
IR13429-47-3	IR4432-53-33/Ptb 33//IR2071-625-1	IRRI	R	R	R	R
Mudgo (check)		India	R	R	R	R
ASD 7 (check)		India	R	S	S	MR
Rathu Heenati (check)		Sri Lanka	R	R	R	R
Babawee (check)		Sri Lanka	R	R	R	R
Ptb 33 (check)		India	R	R	R	R

[a]R = resistant, MR = moderately resistant, S = susceptible. [b]Predominantly BPH biotype 2.
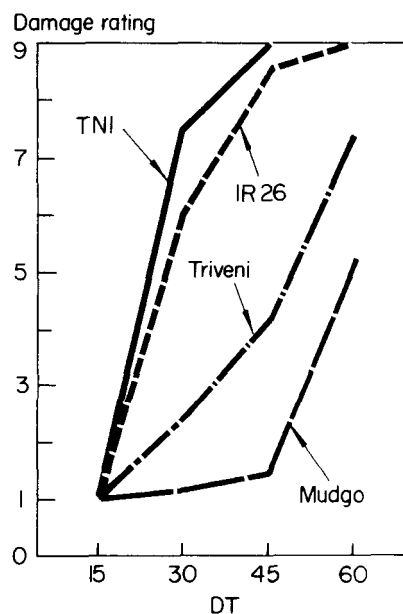
9. Damage ratings of varieties exposed to BPH biotypes 1 and 2 in a screenhouse. 1 = slight damage. 9 = all plants dead. The varieties are all susceptible to biotype 2 when evaluated as 7- to 10-day-old seedlings in the seedling bulk technique. IRRI 1979 (Dang Thanh Ho, unpubl. data).

populations without being as severely damaged as TN1 and IR26 (Fig. 10). Mudgo appears to have, in addition to tolerance, another mechanism that influences the growth and development of the insect (Fig. 11). Survival of the virulent biotype 2 is lower and its developmental period longer on Mudgo than on IR26 and TN1.

Cultural control

Because of the development of BPH resistance to insecticides, as reported from Japan (Nagata and Moriya 1969, Nagata 1979, Nagata and Djatnika 1980) and Sri Lanka (Fernando 1975), resurgence (Heinrichs et al 1979b), the difficulty of controlling outbreak populations with insecticides (Mochida et al 1977, 1978), and the selection for virulent biotypes (Khush 1979, Mochida 1979, Stapley et al 1979), there is interest in developing cultural control techniques.

Fallow, crop rotation, and sanitation. Although some *Oryza* spp. can serve as potential host plants (CRIA-IRRI, Sukamandi, unpubl.; Oka 1979), the main host of the BPH is rice in the field. Accordingly, BPH populations are expected to be reduced by fallow, crop rotation, and sanitation.

BPH (no./hill)
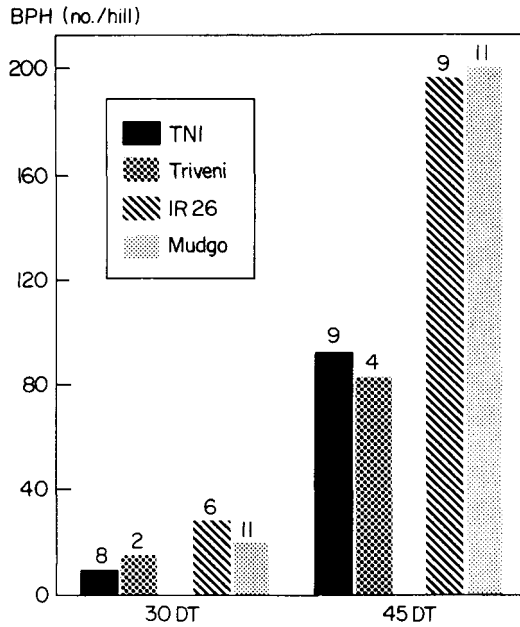
10. Population of brown plant-hoppers and damage ratings (bars) on varieties exposed in the screenhouse to a mixture of biotype 1 and 2 hoppers at 30 and 45 days after transplanting (DT). 1 = slight damage. 9 = all plants dead. All varieties are equally susceptible in the seedbox screening of 7- to 10-day-old seedlings. IRRI 1979 (Dang Thanh Ho, unpubl. data).
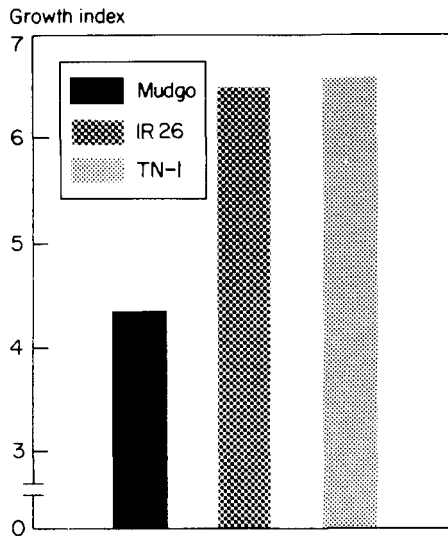
Growth index

11. Growth index of BPH biotype 2 on 30-day-old plants of three rice varieties. All varieties are susceptible to biotype 2 in the seedling bulk screening test. Growth index - % survival of nymphs to adult stage ÷ days of development of newly hatched nymphs to the adult stage. IRRI 1979 (Pathak et al 1980).

The growing period of rice cultivars generally ranges from 78 to 230 days but that of some cultivars in Kalimantan, Indonesia, is about 330 days. After harvest, ratoon plants and seedlings frequently develop from dropped grain. When rice is harvested by the panicles with an *ani-ani,* or small knife, rice plants occasionally survive for

several weeks. Staggered rice cropping, commonly observed in some areas with adequate irrigation, provides BPH with host plants throughout the year. Thus, fallowing of cultivating crops other than rice should be done simultaneously over large areas and continued at least for 2 months. BPH populations are reduced by destroying living stubble, ratoon plants, and seedlings during the dry season. Sanitation, though difficult in many small farmers' fields in Asia, and fallowing have been successfully used in controlling BPH in the mechanized, commercial rice production areas in the Solomon Islands (MacQuillan 1974).

Water management. Studies indicate that irrigation water is associated with the population growth of BPH, as reviewed by Dyck et al (1979) and Heinrichs et al (1979b). In Japan, many farmers withhold irrigation water for about 1-3 weeks in the middle of the summer. Some farmers supply water to rice by intermittent irrigation. Farmers believe that midsummer drainage and intermittent irrigation accelerate removal by plants of fertilizer nutrients from the paddy soil and promote the development of the rice root system, and, thus, rice plants grow vigorously and suffer less from the injury of insects and diseases.

Early-maturing cultivars. Early-maturing breeding lines are being evaluated at IRRI, and results indicate that the cultivars have a great deal of potential in the cultural control of BPH. Lines that can be harvested 75 days after transplanting are available. The third BPH generation, which occurs about 80 days after transplanting, usually causes hopperburn in the tropics. The early lines are harvested before the third-generation nymphs occur and thus escape damage (Fig. 12).

Integrated pest control

As intensive studies now in progress provide basic information on BPH ecology and the role of insecticides, resistant cultivars, and cultural control methods, advances in the integration of these various control components will be made for more effective and economic regulation of BPH populations. Two areas that show promise are:
- the identification and use of selective insecticides, and
- integration of moderate resistance with chemical and biological control.

Studies on the selective toxicity of insecticides to natural enemies and the BPH are receiving more emphasis because of information about the relative importance of the various biocontrol agents in BPH control. Laboratory studies have shown that commercial insecticides vary in their toxicity to natural enemies and the BPH. Some insecticides have a high relative toxicity to the spider *Lycosa pseudoannulata* and the mirid bug *C. lividipennis,* whereas others are relatively more toxic to the BPH (Fig. 13). Additional studies are needed to permit use of selective toxicity data in drawing up control recommendations.

IRRI has recently begun studies to determine the compatibility of moderate resistance with chemical and biological control. BPH that survive on moderately resistant cultivars are smaller and appear less vigorous than BPH on susceptible cultivars. Are these insects more susceptible to insecticide than those on a susceptible variety? If so, lower rates would provide control and thus chemical control would provide greater economic returns. In IRRI studies, carbofuran was more toxic to
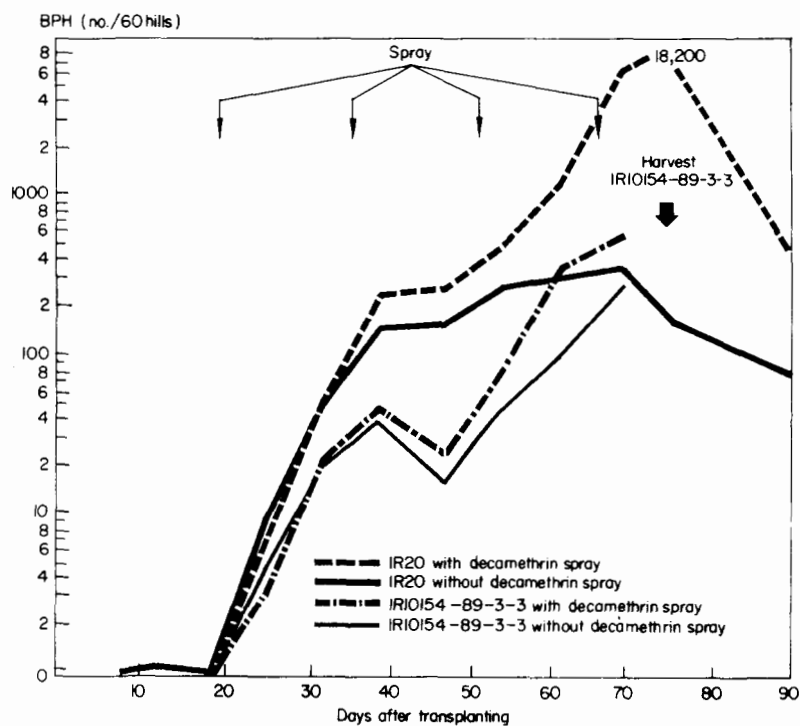
12. Brown planthopper populations on two BPH-susceptible cultivars with and without four applica-
tion, of a resurgence-inducing insecticide. IR20 is of intermediate duration while IR10154-89-3-3 is
early maturing. IRRI, 1979 wet season (Heinrichs and Arceo, unpubl. data).

BPH feeding on a moderately resistant cultivar than to BPH feeding on a susceptible
one (E. A. Heinrichs, F. Medrano, and L. Fabellar, unpubl.). Moderate resistance
has also been shown to increase the efficiency of the spider *L. pseudoannulata*
feeding on BPH (Fig. 14). These initial studies indicate that combining moderately
resistant varieties (which exert less selection pressure for biotype shifts) with biologi-
cal and chemical control is a promising means of BPH control.

STRATEGIES FOR AN INTEGRATED APPROACH
TO BROWN PLANTHOPPER CONTROL

When the BPH outbreaks of 1973-75 first occurred in the Philippines, many farmers
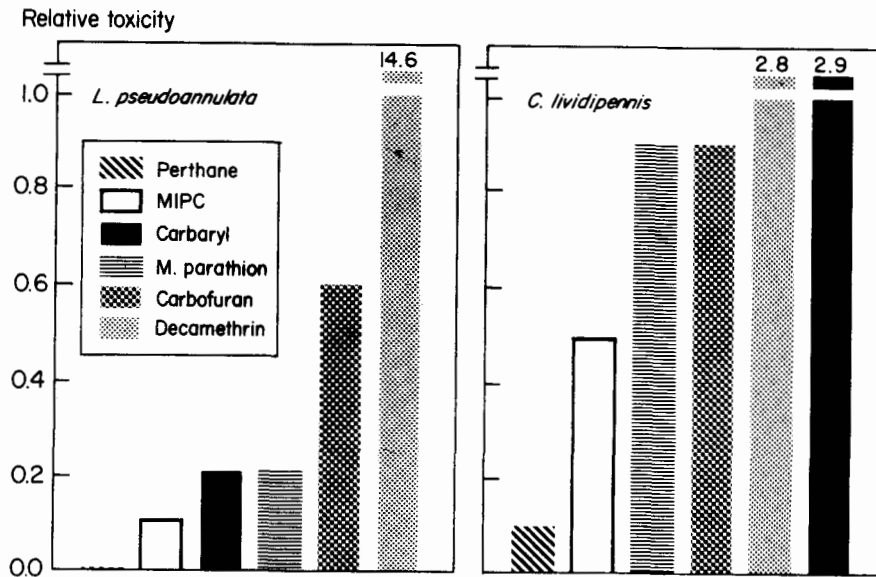
Relative toxicity

13. Relative toxicity of insecticides applied topically to the brown planthopper *N. lugens* to its predator, the spider *Lycosa pseudoannulata* or the mirid bug *Cyrtorhinus lividipennis.* Relative toxicity = LD_{50} of hopper — LD_{50} of predator. A relative toxicity 1.0 indicates the insecticide is relatively more toxic to the predator. The absence of LD_{50} on *Lycosa* up to 5.000 ppm Perthane indicates its low toxicity to the predator. IRRI laboratory, 1979 (Heinrichs and Fabellar, unpubl.).

were not aware of this pest. Today, through the efforts of extension programs, farmers have been taught to recognize the BPH and to apply control measures before the pest reaches damaging levels. There have been significant advances in the development of components for BPH management. The development of these components has been rapid and their use effective.

Many national rice breeding programs have given priority to the BPH problem, and BPH-resistant, high yielding varieties are successfully being grown or are nearing release in most endemic areas. The availability of additional major genes for resistance and the potential for use of minor genes indicate that varietal resistance will continue to be a major BPH control component in many countries in Asia.

No single control component, however, is in itself a panacea. The BPH is a dynamic insect and is capable of responding to resistant varieties through the selection for biotypes, to insecticides by the development of resistant strains, and possibly even to biological control agents. Recently the BPH has been reported to be the transmission agent of a newly identified rice virus disease, wilted stunt (Chen et al 1978), for which no known sources of varietal resistance have yet been identified.

The BPH will continue to threaten rice production. The force of scientists that has
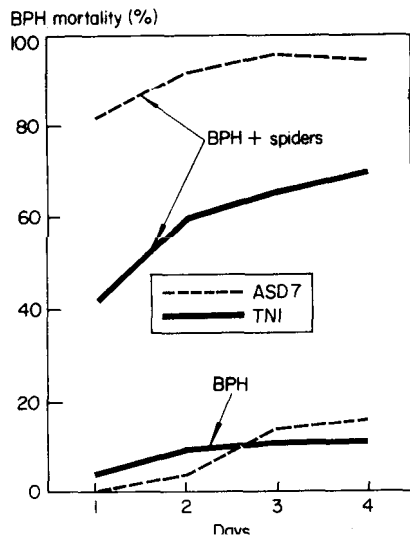
14. Efficiency of the spider *Lycosa pseudoannulata* when feeding on BPH on a resistant (ASD 7) and a susceptible (TN1) variety. Ratio of BPH to spiders was 20:1. IRRI 1979 (Kartohardjono et al, unpubl. data).

been mobilized throughout Asia must continue and even expand their cooperative efforts in the development of control programs that integrate varietal resistance, chemical control, cultural practices, and biological control to effectively control this pest in the 1980s.

Research strategies
We suggest that the following be included in any strategies developed for BPH research.

Strategies for chemical control
1. Continued work to determine the minimum effective rates of commercial insecticides.
2. Continued research on the volume of spray solution needed for effective control using recommended insecticides at various plant growth stages.
3. Development of insecticides that:
    • are selectively more toxic to the BPH than its major natural enemies,
    • do not induce resurgence,
    • are ovicidal, and
    • have fumigant action.
4. Development of botanical insecticides that can be produced by farmers.
5. Broadening the search for formulations of plant extracts, such as neem oil, which have more stability under field conditions.
6. Search for insecticide formulations that are less hazardous to humans and that provide slow release and increased residual activity.
7. Development of application equipment that can put foliar spray droplets in the

feeding site of the insect.

8. Socioeconomic research and linkage with extension to teach farmers to monitor their fields and apply insecticides only when economic thresholds are reached.

9. Research on insectistatics (Levinson 1975) or chemicals dependent upon the alienation of the normal function of physiologically active compounds, such as hormonal imbalances, nutritional and metabolic disturbances, prevention of mating, antifeedant, etc.

Strategies for varietal resistance

Research strategies for developing varietal resistance to BPH should include:

- the development of new techniques to identify moderately resistant cultivars and the use of moderately resistant cultivars in the breeding program;
- identification of additional major genes for resistance and the incorporation of two or more of those genes into a cultivar;
- characterization of the biotypes in the various rice-growing regions through reactions on differential cultivars (development of isogenic lines will facilitate this study);
- determination of the biochemical bases for resistance and development of a technique to obtain sap from the phloem, the feeding site of the BPH, as a way to greatly facilitate biochemical studies;
- achieving an understanding of the genetic basis for virulence among biotypes; and
- integration of moderate resistance with chemical and biological control in the field.

Strategies for biological control

Research should determine if establishment of exotic natural enemies, release of reared natural enemies, and manipulation of the environment (through cultural or chemical means) to enhance natural enemy action are feasible.

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