Species-specific insecticide resistance to imidacloprid and fipronil in the rice planthoppers *Nilaparvata lugens* and *Sogatella furcifera* in East and South-east Asia

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Abstract

BACKGROUND: In 2003 the development of insecticide resistance against neonicotinoids in the brown planthopper (BPH), *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae), was first observed in Thailand and has since been found in other Asian countries such as Vietnam, China and Japan. However, the LD_{50} values of BPH and the whitebacked planthopper (WBPH), *Sogatella furcifera* (Horváth), against both neonicotinoid and phenylpyrazole insecticides have been poorly reported in many Asian countries.

RESULTS: The topical LD_{50} values for imidacloprid in the BPH populations collected from East Asia (Japan, China, Taiwan) and Vietnam in 2006 were 4.3–24.2 µg g^{-1} and were significantly higher than those collected from the Philippines (0.18–0.35 µg g^{-1}). The BPH populations indicated a positive cross-resistance between imidacloprid and thiamethoxam. Almost all the WBPH populations from Japan, Taiwan, China, Vietnam and the Philippines had extremely large LD_{50} values (19.7–239 µg g^{-1} or more) for fipronil, except for several populations from the Philippines and China.

CONCLUSION: Species-specific changes in insecticide susceptibility were found in Asian rice planthoppers (i.e. BPH for imidacloprid and WBPH for fipronil). Insecticide resistance in BPH against imidacloprid occurred in East Asia and Indochina, but not in the Philippines. In contrast, insecticide resistance in WBPH against fipronil occurred widely in East and South-east Asia.

Keywords: *Nilaparvata lugens*; *Sogatella furcifera*; topical application; imidacloprid; fipronil; cross-resistance

1 INTRODUCTION

The brown planthopper (BPH), *Nilaparvata lugens* (Stål), and the whitebacked planthopper (WBPH), *Sogatella furcifera* (Horváth) (Homoptera: Delphacidae), are the two serious pests of rice throughout Asia. The northern limit of breeding area for these species is around the Red River Delta, Vietnam (Fig. 1), where rice (*Oryza sativa* L., their only host plant) is cultivated all year round. Neither of these species is able to overwinter successfully in temperate areas (Japan, Korea and most areas of China), and colonization occurs annually following long-distance migration from overwintering areas.[1]

To control these planthoppers, neonicotinoid and phenylpyrazole insecticides such as imidacloprid and fipronil have been used since the mid-1990s in many East Asian countries and Indochina. Treatment methods of these insecticides vary among countries. In Japan, imidacloprid and fipronil are used exclusively for seedling box treatment to control the rice planthoppers. In Vietnam and China, in contrast, these insecticides are usually sprayed on the rice fields. In any event, the population densities of BPH and WBPH had been relatively low since the mid-1990s when these insecticides began to be used.

In 2003, however, the development of insecticide resistance against neonicotinoids (mainly imidacloprid) in BPH was first observed in Thailand and has since been found in other neighbouring countries such as Vietnam, India and China.[2] From 2005, the BPH and WBPH immigrating into Japan have developed insecticide resistance against imidacloprid and fipronil

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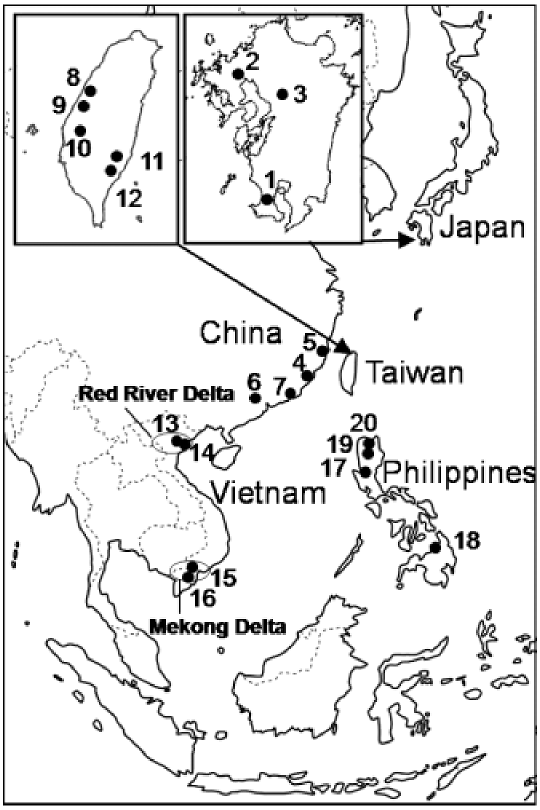

Figure 1. Collection sites of *Nilaparvata lugens* and *Sogatella furcifera* in Asia. Numerals indicate the localities in Table 1.

respectively (Matsumura M *et al.*, unpublished data). However, until now the LD_{50} values of BPH and WBPH against both neonicotinoid and phenylpyrazole insecticides tested by highly accurate methods such as the topical application method[3] have been poorly reported in many Asian countries. Therefore, the insecticide susceptibilities of BPH and WBPH collected from East and South-east Asian countries were determined and compared.

2 MATERIALS AND METHODS

2.1 Insects

Sixteen populations of BPH and 17 populations of WBPH were collected from East Asia (Japan, China, Taiwan), Indochina (Vietnam) and South-east Asia (Philippines) from May to October 2006 (Fig. 1, Table 1). Most populations were collected from paddy fields, but several were collected as individuals that were attracted to lights at night (Table 1). In the latter case, the population was regarded as different from the former even at the same place, because they were newly long-winged immigrants and had thin abdomens.

The collected populations were derived from more than 50 pairs of adults, except for three Philippine populations (ca five individuals in BPH and WBPH of Philippines-AN, and ca 20 individuals in BPH of Philippines-CG). These populations were maintained in the laboratory for 2–5 generations prior to the test using rice seedlings (var. Reihou) at a day length of 16 h and a temperature of 25 °C.

Table 1. Locality and collection date of tested populations of *Nilaparvata lugens* (BPH) and *Sogatella furcifera* (WBPH)

					Insect[b]	
No.[a]	Population	Locality	Lat/Long	Collection date	BPH	WBPH
1	Japan-KG	Minamisatsuma, Kagoshima, Japan	31.28 °N, 130.20 °E	Jul-06-2006	P	P
2	Japan-SGU-A	Ureshino, Saga, Japan	33.5′4 °N, 129.56′4 °E	Jul-13-2006	P	
2	Japan-SGU-B	Ureshino, Saga, Japan	33.5′4 °N, 129.56′4 °E	Sep-04-2006	P	
3	Japan-KM-A	Koshi, Kumamoto, Japan	32.52′26 °N, 130.44′25 °E	Jun-26-2006		P
3	Japan-KM-B	Koshi, Kumamoto, Japan	32.52′26 °N, 130.44′25 °E	Jul-04-2006		L
4	China-FJX	Tongan, Xiamen, Fujian, China	24.44′57 °N, 118.8′4 °E	May-21-2006		P
5	China-FJF	Rongcheng, Fuqing, Fujian, China	25.49′84 °N, 119.23′39 °E	Sep-22-2006	P	P
6	China-GDZ	Dinghu, Zhaoqing, Guangdong, China	23.10′25 °N, 112.33′39 °E	Sep-26-2006		P
7	China-GDS	Chenghai, Shantou, Guangdong, China	23.30′28 °N, 116.49′5 °E	Sep-27-2006		P
8	Taiwan-TC	Dajia, Taichung, Taiwan	24.21′37 °N, 120.37′39 °E	May-30-2006		P
9	Taiwan-CH	Dacun, Changhua, Taiwan	24.0′2 °N, 120.32′17 °E	Oct-16-2006	P	
10	Taiwan-CY	Sikou, Chiayi, Taiwan	23.35′8 °N, 120.24′27 °E	Oct-17-2006	P	P
11	Taiwan-HL	Fuli, Hualien, Taiwan	23.11′33 °N, 121.16′50 °E	Oct-18-2006	P	P
12	Taiwan-TTG	Guanshan, Taitung, Taiwan	23.1′3 °N, 121.10′33 °E	Oct-18-2006	P	P
13	Vietnam-HT	Dai Dong, Ha Tay, Vietnam	21.5′6 °N, 105.34′21 °E	Aug-31-2006	P	
14	Vietnam-HP	An Lao, Hai Phong, Vietnam	20.48′12 °N, 106.34′51 °E	Aug-31-2006	P	P
15	Vietnam-TGL	Long Dinh, Tien Giang, Vietnam	10.24′12 °N, 106.15′11 °E	Sep-03-2006	P	
16	Vietnam-TGH	Hoa Ninh, Tien Giang, Vietnam	10.26′37 °N, 106.20′57 °E	Sep-04-2006	P	P
17	Philippines-NE-A	Munoz, Nueva Ecija, Philippines	15.40′11 °N, 120.53′24 °E	Sep-26-2006	P	P
17	Philippines-NE-B	Munoz, Nueva Ecija, Philippines	15.40′11 °N, 120.53′24 °E	Sep-27-2006	L	
18	Philippines-AN	RTRomualdez, Agusan del Norte, Philippines	9.5′54 °N, 125.32′41 °E	Oct-13-2006	P	P
19	Philippines-CG	Solana, Cagayan, Philippines	17.39′50 °N, 121.41′34 °E	Oct-19-2006	P	P
20	Philippines-IS	Quezon, Isabela, Philippines	17.20′16 °N, 121.36′14 °E	Oct-18-2006		P

[a] See Fig. 1 for the location of the collection sites.
[b] P: From paddy fields. L: Attracted to lights at night.

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2.2 Topical application

The insecticide susceptibility of the planthopper populations was monitored by a standard topical application method[3] on neonicotinoid [imidacloprid (98.5%) and thiamethoxam (98.8%)], phenylpyrazole [fipronil (90.7%)] and O-*sec*-butylphenyl methylcarbamate [BPMC (96.9%)] insecticides. These insecticides were provided by Bayer CropScience KK (Tokyo, Japan), Syngenta Japan KK (Tokyo, Japan), BASF Agro. Ltd (Tokyo, Japan) and Sumitomo Chemical Co. Ltd (Tokyo, Japan). In the case of thiamethoxam, the test was conducted only for the BPH populations.

Within 7 days of emergence, long-winged female adults were anaesthetized with carbon dioxide for about 5 s prior to treatment. A 0.08 μL droplet of acetone solution of insecticide was applied topically on the dorsal surface of the thorax with a hand microapplicator (Burkard Manufacturing Company Ltd). The treated insects were kept at a day length of 16 h and a temperature of 25 °C, with rice seedlings in a transparent plastic box (5 cm diameter, 10 cm high). Mortality was determined 24 h after treatment for all insecticides. In the case of fipronil on WBPH, mortality was also determined 48 and 72 h after treatment because mortality was less than 50% at 24 h after treatment in some populations. All the tests were conducted on 2–5 generations after collection. More than 45 females were used for each concentration. Tests were carried out on 5–6 concentrations. The average body weight of the tested insects was 2.41 ± 0.06 (mean ± SE) mg for BPH and 1.56 ± 0.04 mg for WBPH.

2.3 Statistical analyses

The LD_{50} value, 95% confidence interval and slope of regression line were calculated by Bliss's probit method.[4] Control mortality was corrected for by using Abbott's formula[5] for each probit analysis. The chi-square test was used to test for heterogeneity ($P = 0.05$). The Mann–Whitney U-test was used to compare the difference in LD_{50} values and slopes of regression lines between East Asian plus Indochina (Japan, China, Taiwan, Vietnam) and South-east Asian (the Philippines) populations.

3 RESULTS

3.1 BPH

In the case of imidacloprid, the LD_{50} values for the BPH populations collected from East Asia (Japan, China, Taiwan) and Vietnam were 4.3–24.2 $\mu g\,g^{-1}$ body weight and were remarkably larger than those collected from the Philippines (0.18–0.35 $\mu g\,g^{-1}$ body weight) ($P < 0.01$, Mann–Whitney U-test) (Table 2). The slopes of the regression lines of East Asian and Vietnam populations (0.9–1.9) were significantly smaller than those of the Philippine populations (2.1–3.0) ($P < 0.01$, Mann–Whitney U-test) (Table 2). The East Asian and Vietnam populations had significantly larger LD_{50} values (0.27–2.16 $\mu g\,g^{-1}$) for thiamethoxam compared with those from the Philippines (0.41–0.62 $\mu g\,g^{-1}$) ($P < 0.05$, Mann–Whitney U-test) (Table 2), although the difference in the slopes of regression lines between the two regions was not significant ($P > 0.05$, Mann–Whitney U-test). There was a significant positive relationship between the LD_{50} values of imidacloprid and thiamethoxam in all the Asian populations ($r = 0.72$, $P < 0.01$, including one outlier of Japan-KG) (Fig. 2, Table 2).

In contrast to the two neonicotinoids, all the Asian BPH populations had much smaller LD_{50} values (0.06–0.65 $\mu g\,g^{-1}$) for fipronil, and no difference was found among locations ($P > 0.05$, Mann–Whitney U-test). The slopes of regression lines for fipronil were larger than 2, except for the two southern Vietnam populations (0.9 for Vietnam-TGL and Vietnam-TGH) (Table 2).

For BPMC, the LD_{50} values were larger (>30 $\mu g\,g^{-1}$) in several Vietnam and Philippine populations than those in other populations, but there was no significant difference among countries ($P > 0.05$, Mann–Whitney U-test). A large difference in LD_{50} values was found among the Philippine populations (4.9–43.2 $\mu g\,g^{-1}$) (Table 2).

3.2 WBPH

In WBPH, almost all the populations collected from Japan, Taiwan, China, Vietnam and the Philippines had very much larger LD_{50} values (19.7–239 $\mu g\,g^{-1}$ body weight or more at 24 h after treatment) for fipronil than had several populations from the Philippines (0.3–5.9 $\mu g\,g^{-1}$) and China (3.0 $\mu g\,g^{-1}$) (Table 3). At 48 and 72 h after treatment, the LD_{50} values decreased, but some were still large at 48 h after treatment (Table 3). The slopes of the regression lines were <1, except for one Philippine population (Philippines-IS) at 24 h after treatment.

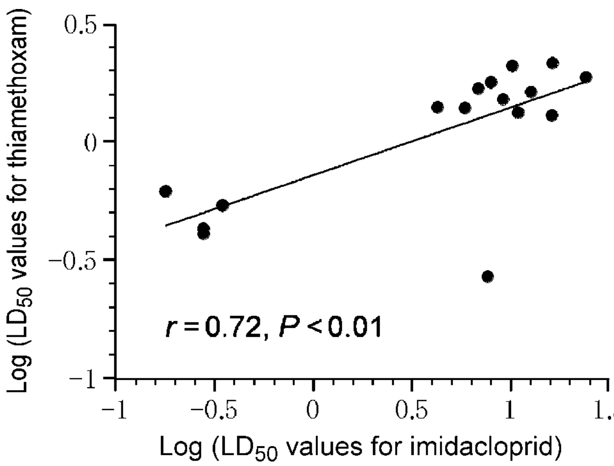

Figure 2. Relationship between LD_{50} values for imidacloprid and those for thiamethoxam in *Nilaparvata lugens* collected in Asia in 2006.

Table 2. The LD_{50} values ($\mu g\,g^{-1}$) of *Nilaparvata lugens* populations collected in 2006 in Asia [a,b]

	BPMC		Imidacloprid		Fipronil		Thiamethoxam	
Population	LD_{50}	b	LD_{50}	b	LD_{50}	b	LD_{50}	b
Japan-KG	22.3 (18.8–26.4)	2.9	7.7 (4.7–13.8)	0.9	0.06 (0.05–0.07)	3.3	0.27 (0.20–0.36)	2.6
Japan-SGU-A	27.0 (23.0–31.8)	3.2	4.3 (2.9–6.4)	1.2	0.15 (0.12–0.17)	3.5	1.40 (1.06–1.93)	1.4
Japan-SGU-B	21.7 (18.6–25.4)	3.3	16.4 (11.6–23.4)	1.4	0.13 (0.11–0.18)	2.1	2.16 (1.52–3.53)	1.1
China-FJF	14.6 (12.5–17.2)	3.4	11.0 (6.8–20.4)	1.0	0.05 (0.04–0.06)	2.9	1.33 (1.06–1.68)	2.3
Taiwan-CH	13.8 (11.3–16.8)	2.5	8.0 (6.0–10.9)	1.9	0.11 (0.09–0.15)	2.1	1.79 (1.43–2.30)	1.9
Taiwan-CY	19.4 (16.7–22.9)	3.6	12.8 (9.1–18.1)	1.3	0.11 (0.08–0.13)	2.5	1.63 (1.25–2.17)	1.5
Taiwan-HL	23.3 (19.8–27.4)	3.0	10.3 (6.6–16.0)	1.2	0.45 (0.37–0.55)	2.2	2.10 (1.75–2.56)	2.6
Taiwan-TTG	15.2 (12.6–18.1)	2.7	6.9 (4.8–10.5)	1.2	0.10 (0.08–0.13)	2.1	1.68 (1.30–2.26)	1.6
Vietnam-HT	17.4 (14.7–20.4)	3.2	9.2 (6.3–13.4)	1.3	0.13 (0.10–0.15)	3.5	1.52 (1.28–1.81)	2.7
Vietnam-HP	18.4 (15.5–21.7)	3.0	5.9 (4.3–8.1)	1.6	0.15 (0.13–0.19)	2.6	1.39 (1.11–1.75)	2.0
Vietnam-TGL	26.0 (22.3–30.4)	3.3	24.2 (17.1–35.1)	1.4	0.37 (0.23–0.64)	0.9	1.88 (1.46–2.34)	1.9
Vietnam-TGH	32.3 (27.6–37.7)	3.5	16.3 (11.9–22.6)	1.5	0.65 (0.43–1.18)	0.9	1.30 (1.05–1.65)	2.3
Philippines-NE-A	14.5 (12.3–17.3)	2.9	0.28 (0.22–0.35)	2.2	0.10 (0.08–0.12)	2.4	0.43 (0.33–0.56)	1.6
Philippines-NE-B	4.9 (3.9–6.1)	2.0	0.18 (0.14–0.23)	2.1	0.16 (0.13–0.21)	2.2	0.62 (0.47–0.84)	1.4
Philippines-AN	30.6 (25.9–36.4)	2.9	0.35 (0.29-0.41)	2.6	0.09 (0.07–0.11)	2.6	0.54 (0.42–0.71)	1.7
Philippines-CG	43.2 (36.1–53.0)	2.6	0.28 (0.22–0.33)	3.0	0.08 (0.06–0.10)	2.2	0.41 (0.32–0.52)	1.8

[a] LD_{50} value and its 95% confidence interval in parentheses were shown with ($\mu g\,g^{-1}$), and slope of regression line (b) were shown.
[b] All the LD_{50} values were determined 24 hours after treatment.

In the case of imidaclopirid, all the WBPH populations had small LD_{50} values (0.11–0.34 $\mu g\,g^{-1}$) and large slopes of regression lines (2.7–4.6), except for one population in Japan (Japan-KM-A) (1.06 $\mu g\,g^{-1}$) (Table 3). In the case of BPMC, the LD_{50} values for WBPH ranged from 6.1 to 26.6 $\mu g\,g^{-1}$ (Table 3). There were no significant differences in LD_{50} values and slopes of regression lines for the three insecticides between East Asian and South-east Asian WBPH populations ($P > 0.05$, Mann–Whitney *U*-test).

4 DISCUSSION

Imidacloprid has been widely used since the early 1990s to control rice planthoppers in East Asia and Indochina. The topical LD_{50} values of imidacloprid for BPH were in the range 0.09–2 $\mu g\,g^{-1}$ from 1992 to 2003 in Vietnam, China and Japan.[6–11] The slopes of the regression lines for BPH in these countries were in the range 2.0–2.5 until 2001.[6,11] In the present study, however, the East Asian and Vietnam BPH populations in 2006 had remarkably higher LD_{50} values and much smaller slopes of regression lines (Table 2) than those before 2003. In contrast, the BPH populations collected in the Philippines in 2006 had similar LD_{50} values and slopes of regression lines for imidacloprid (Table 2) compared with those in East Asian populations before 2003.[6–11] These results suggest that insecticide resistance against imidacloprid occurred only in East Asia and Indochina but not in the Philippines.

In contrast to BPH, no significant differences in LD_{50} values for imidacloprid were found among Asian WBPH populations, except for one Japanese population (Table 3). The LD_{50} values in 2006 were similar to those in Japanese and Chinese populations collected in 1992–2001 (0.02–0.33 $\mu g\,g^{-1}$).[7,11] These results suggest that no insecticide resistance against imidacloprid occurred in WBPH in Asia. However, the monitoring of insecticide susceptibility of WBPH against imidacloprid should continue because one Japanese population had a slightly higher LD_{50} value than the others (Table 3).

Although the LD_{50} values for thiamethoxam were not so large, the BPH populations indicated a positive cross-resistance between imidacloprid and thiamethoxam (Table 2, Fig. 2). In the case of dinotefuran, another neonicotinoid insecticide, the BPH populations collected in 2005–2007 in Japan showed no insecticide resistance (Matsumura M *et al.*, unpublished data). Thus, cross-resistance with imidacloprid might not occur with all neonicotinoid insecticides.

Almost all the Asian WBPH populations collected in 2006 had large LD_{50} values and extremely small slopes of regression lines (<0.6) for fipronil at 24 h after treatment (Table 3). The LD_{50} values were still large at 48 h after treatment. Although no topical LD_{50} values for fipronil in the field WBPH populations have been published previously, these results suggest that insecticide resistance of WBPH against fipronil occurs widely in East Asian and South-east Asian countries.

On the other hand, all the Asian BPH populations had much smaller LD_{50} values for fipronil (Table 2), suggesting that no insecticide resistance against fipronil occurred in BPH in Asia. However, the low slope of regression lines for fipronil was found in two southern Vietnam BPH populations (Table 2). In addition, the LD_{50} values of these two populations are slightly larger than others. Thus, the monitoring of insecticide susceptibility to fipronil in BPH should be continued in this region.

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Table 3. The LD_{50} values ($\mu g\, g^{-1}$) of *Sogatella furcifera* populations collected in 2006 in Asia [a,b]

	BPMC		Imidacloprid		Fipronil					
					24h		48h		72h	
Population	LD_{50}	b	LD_{50}	b	LD_{50}	b	LD_{50}	b	LD_{50}	b
Japan-KG	21.1 (17.7–26.1)	3.0	0.34 (0.29–0.40)	3.4	22.5 (11.5–51.6)	0.6	1.58 (0.86–2.62)	0.8	0.74 (0.45–1.13)	1.5
Japan-KM-A	24.6 (21.2–28.5)	3.7	1.06 (0.91–1.25)	3.9	23.9 (11.5–61.5)	0.5	0.32 (0.03–0.95)	0.4	0.02 (0.00–0.13)	0.5
Japan-KM-B	9.6 (8.2–11.3)	3.3	0.12 (0.10–0.14)	3.1	29.5 (15.8–64.9)	0.6	3.0 (2.0–4.5)	1.1	0.81 (0.57–1.10)	1.7
China-FJX	6.1 (4.9–7.2)	3.2	0.11 (0.10–0.13)	3.1	3.0 (1.1–6.6)	0.5	0.66 (0.27–1.22)	0.7	0.31 (0.18–0.44)	1.8
China-FJF	19.1 (16.2–22.7)	3.1	0.21 (0.18–0.25)	3.6	>284[c]	0.3	11.9 (5.2–28.4)	0.5	0.97 (0.44–1.76)	0.8
China-GDZ	20.0 (17.4–23.2)	4.8	0.10 (0.08–0.11)	3.7	>270[c]	0.4	13.5 (7.4–28.4)	0.9	3.7 (2.0–6.5)	0.8
China-GDS	24.3 (21.0–29.6)	4.1	0.15 (0.13–0.17)	3.4	>243[c]	0.2	17.6 (8.2–46.1)	0.5	0.65 (0.28–1.23)	0.8
Taiwan-TC	15.5 (13.2–18.4)	3.6	0.33 (0.28–0.39)	3.0	19.7 (9.0–53.5)	0.5	3.4 (1.6–6.6)	0.6	0.60 (0.36–0.88	1.4
Taiwan-CY	25.2 (21.8–29.9)	3.9	0.19 (0.16–0.22)	3.6	>310[c]	0.2	9.1 (3.4–24.3)	0.4	0.41 (0.16–0.71)	1.0
Taiwan-HL	22.3 (19.4–25.4)	4.4	0.12 (0.10–0.14)	3.2	239 (85.5–1,549)	0.5	52.8 (33.2–92.8)	1.0	2.8 (1.3–5.3)	0.6
Taiwan-TTG	25.0 (21.3–29.3)	3.5	0.13 (0.12–0.16)	3.5	>277[c]	0.4	55.8 (29.0–139)	0.6	2.1 (1.0–3.9)	0.6
Vietnam-HP	12.2 (10.7–13.9)	4.4	0.18 (0.16–0.21)	3.5	>252[c]	0.2	44.6 (19.9–109)	0.5	4.5 (2.0–8.7)	0.5
Vietnam-TGH	26.6 (23.3–30.5)	4.3	0.18 (0.15–0.21)	3.0	>501[c]	– [d]	237 (143–482)	1.1	20.7 (12.9–34.7)	0.9
Philippines-NE-A	24.3 (21.3–27.9)	4.7	0.27 (0.24–0.32)	4.6	>346[c]	0.4	18.5 (6.7–63.3)	0.4	0.97 (0.47–1.65)	0.9
Philippines-AN	11.1 (9.7–12.8)	4.3	0.20 (0.17–0.23)	3.3	>283[c]	0.4	6.4 (3.8–10.5)	0.8	0.81 (0.45–1.28)	1.0
Philippines-CG	11.8 (10.3–13.5)	4.5	0.20 (0.17–0.23)	3.9	5.9 (3.0–11.5)	0.6	0.23 (0.09–0.46)	0.6	0.04 (0.01–0.10)	0.9
Philippines-IS	23.6 (19.3–29.6)	2.7	0.16 (0.14–0.20)	2.7	0.30 (0.24–0.42)	1.7	0.14 (0.07–0.23)	0.7	0.06 (0.02–0.11)	0.7

[a] LD_{50} value and its 95% confidence interval in parentheses were shown with ($\mu g\, g^{-1}$), and slope of regression line (b) were shown.
[b] All the LD_{50} values were determined 24 hours after treatment except for Fipronil (24,48, and 72 hours).
[c] LD_{50} value was not determined because mortality was lower than 50% in all the treatments. The value shown as maximum dose treated.
[d] Slope was not calculated because the test for heterogeneity was significant ($P < 0.05$).

In the case of BPMC, the LD_{50} values of BPH and WBPH in 2006 were similar to those in Japan, China and Vietnam in 1992–2001 (8.8–26 $\mu g\,g^{-1}$ for BPH and 5.1–28 $\mu g\,g^{-1}$ for WBPH).[6–8,11] No significant differences were detected between countries.

The present study revealed a species-specific change in insecticide susceptibility in Asian rice planthoppers (i.e. BPH for imidaclopirid and WBPH for fipronil). Imidacloprid has been used commonly to control BPH in later stages of rice in Vietnam and China (around May to early June in winter–spring rice cropping in northern Vietnam). Fipronil has been used commonly to control the rice leaf folder, *Cnaphalocrocis medinalis* (Guenée), and the rice stem borers in an early stage of rice in Vietnam and China (around early April in winter–spring rice cropping in northern Vietnam). Spraying fipronil early in the season could also be more effective on WBPH than on BPH, because WBPH increases earlier than BPH in the rice-growing season. This could be a possible reason why insecticide resistance against fipronil occurred only on the WBPH species. The overuse of insecticides is often the precursor to the development of insecticide resistance,[12] and many Asian countries rely heavily on a limited number of compounds for planthopper control.[13,14]

The present study suggests that insecticide resistance of BPH against imidacloprid does not occur in the Philippines. This is because BPH outbreaks have not occurred recently and imidacloprid has not been commonly used in the Philippines. In contrast, fipronil has been used widely to control rice stem borers in the Philippines. For this reason, the insecticide susceptibility of WBPH against fipronil in the Philippines was as low as those in East Asia and Vietnam.

The species-specific insecticide resistance against different insecticides might also result from the difference in mode of action of the insecticides. Liu *et al*.[15] found that a nicotinic acetylcholine receptor (nAChR) mutation confers target-site resistance to imidacloprid in BPH. However, this target-site resistance in BPH was only selected in the laboratory and never found in a field strain. Although the target site of fipronil (GABA receptors) is different from that of imidacloprid (see review by Raymond-Delpech *et al*.[16]), no detailed information is available for the mechanism of resistance to fipronil in WBPH. Further comparative studies on the mode of action of neonicotinoid and phenylpyrazole insecticides against BPH and WBPH would be needed to explain the species-specific development of insecticide resistance against neonicotinoid and phenylpyrazole insecticides as well.

In the Mekong Delta of southern Vietnam (Fig. 1), outbreaks of two BPH-transmitted virus diseases, rice ragged stunt virus (RRSV) and rice glassy stunt virus (RGSV), have occurred since 2005,[17] resulting in the heavy use of insecticides to control BPH. The present study showed that the LD_{50} values in two southern Vietnam BPH populations tended to be larger than those in the other locations for BPMC, imidacloprid and fipronil (Table 2). Thus, the status of insecticide susceptibility in BPH against these insecticides in southern Vietnam and neighbouring countries such as Thailand should continue to be monitored carefully.

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REFERENCES

1 Kisimoto R, Synoptic weather conditions inducing long-distance immigration of planthoppers, *Sogatella furcifera* Horváth and *Nilaparvata lugens* Stål. *Ecol Entomol* **1**:95–109 (1976).

2 Harris R, Monitoring of neonicotinoid resistance in *Nilaparvata lugens* and subsequent management strategies in Asia Pacific. *Proceedings of the International Workshop on Ecology and Management of Rice Planthoppers*, Hangzhou, China, 16–19 May 2006, Zhejiang University, p. 2 (2006).

3 Fukuda H and Nagata T, Selective toxicity of several insecticides on three planthoppers. *Jpn J Appl Entomol Zool* **13**:142–149 (1969).

4 Bliss CI, The calculation of the dosage–mortality curve. *Ann Appl Biol* **22**:134–167 (1935).

5 Abbott WS, A method of computing the effectiveness of an insecticide. *J Econ Entomol* **18**:265–267 (1925).

6 Endo S and Tsurumachi M, Insecticide susceptibility of the brown planthopper and the white-backed planthopper collected from southeast Asia. *J Pestic Sci* **26**:82–86 (2001).

7 Ping X, Endo S, Suzuki K and Ohtsu K, The insecticide susceptibility of the brown planthopper, *Nilaparvata lugens*, and white-backed planthopper, *Sogatella furcifera*, collected from China and Japan. *Kyushu Pl Prot Res* **47**:54–57 (2001).

8 Nagata T, Kamimuro T, Wang YC, Han SG and Noor NM, Recent status of insecticide resistance of long-distance migrating rice planthoppers monitored in Japan, China, and Malaysia. *J Asia-Pacific Entomol* **5**:113–116 (2002).

9 Nagata T and Kamimuro T, Joint survey on insecticide susceptibility of the migratory rice planthoppers in Asian countries. *Plant Prot* **56**:488–491 (2002).

10 Liu Z, Han Z, Wang Y, Zhang L, Zhang H and Liu C, Selection for imidacloprid resistance in *Nilaparvata lugens*: cross-resistance patterns and possible mechanisms. *Pest Manag Sci* **59**:1355–1359 (2003).

11 Liu Z, Wang Y, Han Z, Li G, Deng Y, Tian X, *et al.* Comparision of the susceptibilities of *Nilaparvata lugens* and *Sogatella*

furcifera from three areas to ten insecticides. *J Nanjing Agric Univ* **26**:29–32 (2003).

12 Heinrichs EA, Impact of insecticides on the resistance and resurgence of rice planthoppers, in *Planthoppers: Their Ecology and Management*, ed. by Denno RF and Perfect TJ. Chapman and Hall, New York, NY, pp. 571–598 (1994).

13 Nagata T, Monitoring on insecticide resistance of the brown planthopper and the white backed planthopper in Asia. *J Asia-Pacific Entomol* **5**:103–111 (2002).

14 Sun JZ, Fan JC and Xia LR, Studies on the insecticidal activity of imidacloprid and its application in paddy fields against the brown planthopper, *Nilaparvata lugens* (Homoptera: Delphacidae). *Acta Entomologica Sinica* **39**:37–45 (1996).

15 Liu Z, Williamson MS, Lansdell SJ, Denholm I, Han Z and Millar NS, A nicotinic acetylcholine receptor mutation conferring target-site resistance to imidacloprid in *Nilaparvata lugens* (brown planthopper). *PNAS* **102**:8420–8425 (2005).

16 Raymond-Delpech V, Matsuda K, Sattle BM, Rauh JJ and Sattelle DB, Ion channel: molecular targets of neuroactive insecticides. *Invert Neurosci* **5**:119–133 (2005).

17 Chien HV, Cuong LQ and Thiet LV, Community level of brown planthopper associated virus disease managements: use of 'synchronized cropping season and brown planthopper escape strategy'. *Proceedings of the International Workshop on Forecasting and Management of Rice Planthoppers in East Asia: Their Ecology and Management*, Kumamoto, Japan, 4–5 December 2007, National Agricultural Research Centre for Kyushu Okinawa Region, pp. 10–19 (2006).