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Estimating the immigration source of rice planthoppers, *Nilaparvata lugens* (Stål) and *Sogatella furcifera* (Horváth) (Homoptera: Delphacidae), in Taiwan

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Abstract

Since overwintering populations of brown planthopper (*Nilaparvata lugens*) and white-backed planthopper (*Sogatella furcifera*) in Taiwan are very low based on field observations, immigrant planthoppers have become the most important source of serious damage to rice crops (*Oryza sativa*). Backward trajectory analysis was conducted using trap catch data from 1990 to 2005 to estimate the source of immigrant planthoppers, taking into account the emigration periods and weather conditions, and showed that southern China, Vietnam and the Philippines (Luzon Island) were possible source areas. Southern China was found to be the most important source of emigration. Of all the immigration cases tested, the sources from southern China were estimated to be about 77% in the first rice crop and 65% in the second rice crop. Vietnam came second with about 37% and 56% in the first and second rice crops, respectively. Typhoons were the most important weather factor, inducing mass emigrations from China and Vietnam. Since the population properties are known to differ among the emigration regions and Taiwan, careful monitoring of these insects in the emigration sources and Taiwan is needed in order to establish better pest management practices.

Key words: Rice planthopper; *Nilaparvata lugens*; *Sogatella furcifera*; migration; Taiwan

INTRODUCTION

Rice is a staple food crop in Taiwan, and is grown twice a year. The first rice crop is planted starting from January in the south to early March in the north, and is harvested from mid-May to early July. The second rice crop is planted starting in late June in the south to early August in the north, and is harvested between mid-October and the end of November.

The brown planthopper (abr. BPH, *Nilaparvata lugens* (Stål)) and the white-backed planthopper (abr. WBPH, *Sogatella furcifera* (Horváth)) have been recorded as important pests of rice in Taiwan since 1912 (Nitobe, 1912). Planthoppers caused only sporadic damage prior to 1960; however, once damage occurred, it often became a severe infestation (Cheng, 1978). Both BPH and WBPH can breed to the 3rd or even 4th generation during a single rice crop period. The population density in the first rice crop season is generally low due to the very low overwintering population as well as the low temperatures during the early stage of rice growth (Chu and Yang, 1984; Cheng, 1990). In general, planthoppers are rarely observed in paddy fields before April, and their infestation of rice plants in the first rice crop is usually negligible. On the other hand, during the growth period of the second crop, the population of these insects increases rapidly from their low initial density, and cause

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considerable damage to rice plants in the mid- to late part of the growing season of the second crop (Cheng, 1978, 1984). Damage to the second crop was especially severe from the 1960s to 1980s (Cheng, 1978, 1984).

Triggered by finding BPH and WBPH far from land over the Pacific Ocean in 1967 (Asahina and Tsuruoka, 1968), intensive studies on their ability to sustain long-distance migration have been conducted (e.g. Kisimoto, 1971; Ohkubo and Kisimoto, 1971). It is believed that the two species migrate from northern Vietnam to southern mainland China from March to June, and then move further into middle and northern China, Japan and Korea between June and July (Kisimoto, 1971, 1976; Seino et al., 1987; Sogawa et al., 1988; Sogawa, 1997).

In order to develop an effective strategy for managing these migratory species in Taiwan, the immigration of BPH and WBPH into southern Taiwan has been monitored since 1983 (Liu, 1984). It was found that these planthoppers are able to carry out overseas migrations to Taiwan under specific weather conditions, such as a frontal system, typhoons, subtropical highs and southwestern airflows (Liu, 1988; Liu et al., 1989; Cheng and Lu, 1990). Among these various weather conditions, tropical cyclones (typhoons) are the most important weather factor, inducing mass immigrations into Taiwan (Liu et al., 1989; Cheng and Lu, 1990). Based on these studies, the conditions suitable for migration of these pests into Taiwan can be summarized as follows: mass immigration may occur when the air temperature at the 850 hPa level is higher than 17°C, and the southwesterly to northwesterly airflows reach a wind speed between 9 and 19+ km/h on the 850 hPa weather chart, extending from southern China to Taiwan, or when southerly to southeasterly airflows extend from northern Luzon to the western coast of Taiwan, suggesting that there are two possible directions of migrations (Cheng and Lu, 1990; Cheng, 1997).

Previous studies have provided a clear picture of the ecology of the species; however, no studies were been conducted to estimate the source of immigration into Taiwan. As a result, knowledge on the immigration source has been limited. In order to estimate possible sources of these migrations, this study performed backward trajectory analysis (Otuka et al., 2005) on the data from trap catches of BPH and WBPH that were recorded using airborne net traps and suction light traps in the Chiayi area in southwestern Taiwan. Immigrants were generally detected from April to October and mainly from July to August (Cheng and Lu, 1990). The number of early immigrants (from late April to early May) and late immigrants (from July to August) greatly affects the abundance of the population in the first and second crop seasons, respectively (Cheng, 1990; Cheng and Huang, 2004; Huang et al., 2007); therefore, trap catches from both April to May for the first crop, and from July to August for the second crop were analyzed.

MATERIALS AND METHODS

Trap data at Sikou. Two tow-net traps and two suction-type light traps were placed at latitude 23.58 deg. north and longitude 120.40 deg. east at Sikou Experimental Farm of the Chiayi Agricultural Experiment Station in Sikou township, Chiayi county, southwestern Taiwan (Fig. 1). The light traps were about 235 m apart, and each light trap consisted of a 30 watt cycloid fluorescent lamp with a top cover, and a 30 cm diameter suction fan with a double entrance net bag, 60 cm in depth, attached to the lamp, 10 cm apart. The suction-type light trap was set on top of a pole, 1.8 m above the ground. Each tow-net trap had a 1 m diameter ring with a 2 m deep tow net mounted at the top of a pole, 10 m above the ground. The catch in each trap was collected every morning at 8:00 am (local time) all year round, and the species were identified and their number recorded by well-trained staff. Trap catches from late April to early May were closely correlated to the highest population density in the first crop, and those from July to August to the highest population density in the later stage of the second crop (Cheng, 1990; Cheng and Huang, 2004; Huang et al., 2007). Therefore, trap catch data in these 2 periods from 1990 to 2005 were used for the source estimation, except for the catch in late May (after May 21) because local rice planthoppers from harvested paddy fields in the southern region could possibly be caught by traps during that time.

Although the net trap can capture windborne immigrants directly, it is not suitable for detecting small immigrations when the wind speed is not large enough to open the tow net. On the other

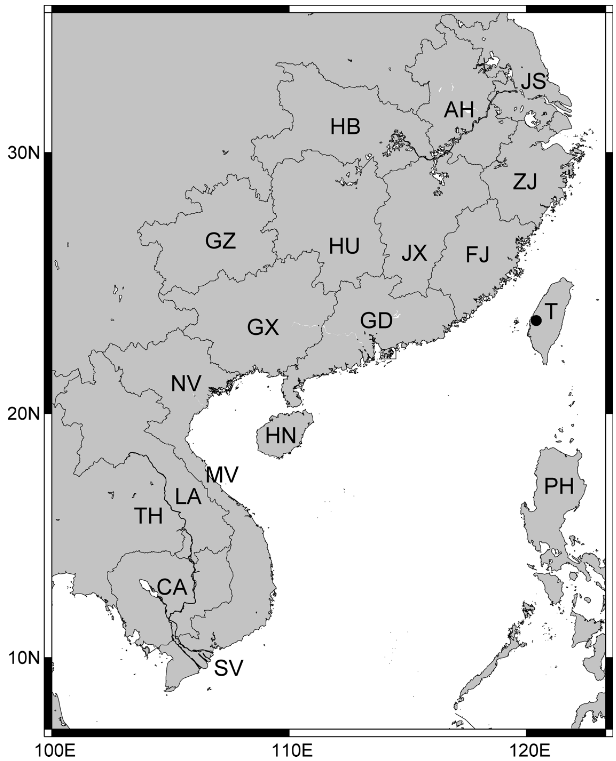

Fig. 1. Taiwan and surrounding regions. Codes such as T, GD, PH indicate the name of the region or country (see the annotations in Table 1). Solid circle shows the location of traps in Sikou, southwestern Taiwan.

hand, in addition to mass immigrations, the suction-type light trap can also capture smaller immigrations by attracting the insects with lights. Since the catch number with the net trap from April to May is generally very small, catches both by the tow-net traps and by suction-type light traps were used to determine the level of immigration. On the other hand, the number of net trap catches from July to August is generally large enough to determine immigration events; therefore, only the catch data of net traps were used to analyze the later season. Only data where the catch of WBPHs or BPHs in any trap was greater than 10 adults per day were used for source estimation. For July and August, the data from when the net trap was lowered due to a typhoon and insects were caught by light traps at the same time were also included, because it was highly probable that an immigration event had occurred under such windy conditions.

Backward trajectory analysis. Backward trajectory analysis (BTA) was conducted to estimate any possible emigration source for the catches in Sikou. Backward trajectories of BPHs and WBPHs were calculated using a three-dimensional BTA model employing wind fields simulated by a weather forecast model MM5 (Otuka et al., 2005). In the BTA model, it was assumed that planthoppers moved at the same velocity as the wind during migration (Otuka et al., 2005). The starting times of the backward trajectories were set every hour within a 24 h period of each catch date. For each starting time, 20 backward trajectories were calculated using different initial heights ranging from 100 to 2,000 m at an interval of 100 m above the trap site.

The backward trajectories were terminated at three different times; at dusk, 11:00 Coordinated Universal Time (UTC) 2 days before the catch (2 DB), at dawn, 20:00 UTC, and at dusk, 11:00 UTC, one day before the catch (1 DB). Dawn and dusk are times when planthoppers are assumed to fly out of their source areas (Ohkubo and Kisimoto, 1971; Lai, 1982). These terminal times were the three values closest to the catch date. They were used not only because they made the flight durations shorter, but also because the calculated trajectories using these terminal times could reach the possible source areas. Terminal points of the trajectories were distributed over a region based on their starting time and height (terminal point distribution), and were plotted on a map to determine the possible source areas.

In the estimation of the immigration sources from April to May, the southern Chinese provinces of Hunan, Jiangxi, Fujian, Zhejiang, Hubei, Anhui, and Jiangsu were excluded, because the immigration of planthoppers to these provinces occurs later than May, and the density of their emigrating populations is generally low (Li et al., 1996). The southern provinces of China, such as Hainan, Guangxi, and Guangdong, were set as source candidates, as well as Vietnam and the Philippines. Tropical regions, such as Vietnam, Hainan and the Philippines, are areas where rice planthoppers can overwinter (Sogawa, 1993b). The other southern Chinese provinces above are areas where immigration occur early, generally from March to April (Otuka et al., 2007; Guangdong Plant Protection General Station, 2009; Guangxi Zhuang Autonomous Region Plant Protection General Station, 2009). If terminal points were distributed over none of the source candidates, then the possible source was estimated to be Taiwan.

RESULTS

Trap catches at Sikou

The daily catch data in the first and last months are shown in Tables 1 and 2, respectively. For the catch in April and May, no BPHs were captured in the net trap (Table 1). Many BPHs were captured in the light trap in May 1991, and no WBPHs were captured during that same time period. The catch number of WBPHs in both traps has become dominant since 1997 over that of BPHs. The net trap catches in April occurred only during 3 days in 1998, and the others occurred in May. The catch numbers of WBPHs in the net trap were relatively small, with a maximum of 48 on 20 May 1997. The largest catch, 202, of WBPHs in the light trap was recorded on 9 May 2001.

In the catch records from July to August, the catch numbers of BPHs and WBPHs were similar in 1992 and 1996 (Table 2). For example, the number of insects was captured in the same order for both species on 28 July 1996; however, after three years of smaller catches from 1997 to 1999, after 2000, the catch number of WBPHs was larger than that of BPHs. This is similar to the abundance of WBPHs since 1997, shown in Table 1. The catch number exceeded 100 in some cases, such as on 28 July 1996 and 21 July 2005, when a typhoon came close to Taiwan, indicating that typhoons are a major cause of mass immigrations for the second rice crop (Table 2).

Estimated source for the first rice crop

Table 1 shows the regions over which the terminal points of the backward trajectories were distributed for the first crop season in 1991 to 2004. The terminal points generally traveled further from Taiwan when the terminal time was set further back under windy conditions. Figure 2 shows three examples of the time series of terminal point distribution for catches on 20 May 1997, 9 May 2001 and 5 May 1998. Figure 2a shows an example whose terminal points reached over Hainan, Guangdong and Guangxi. Three figures in the middle row (Fig. 2b) show terminal points reaching over Guangdong at dusk (11:00 UTC) on the previous day (1 DB), Guangxi at dawn on the previous day, and Hainan and Vietnam at dusk 2 days before the catch date (2 DB) (Fig. 1 and Table 1). Three figures in the bottom row in Fig. 2c shows were the terminal points reached as far as Luzon, the Philippines. The estimated sources were grouped into five groups: Taiwan, Vietnam, the Philippines, the southern provinces of China including Guangdong, Guangxi and Hainan, and other Chinese provinces, such as Fujian, Zhejiang, and others. The reason for dividing the Chinese provinces into two groups has already been described in the section of Backward Trajectory Analysis. Countries in the Indochina Peninsula, except Vietnam, were excluded because knowledge on the ecology of rice planthoppers in these countries was very limited. The column 'Estimated source' in Table 1 shows the source regions estimated by backward trajectory analysis. Southern China was estimated to be the source in 77% (23 cases) of all cases, except for domestic catches (T in Table 1), and in 48% of these Southern China cases, Vietnam was also identified. Vietnam was estimated to be the source region in 37% of these cases. Seven cases (23%) occurred when winds came from the Philippines.

Estimated source for the second cropping season

The estimated sources for the second crop season are shown in Table 2. Figure 3 shows examples of the terminal point distribution for the three largest catches on 28 July 1996, 6 July 2004 and 21 July 2005. These catches were recorded under windy conditions by typhoons located around Taiwan. Figure 3a shows an example in which immigrants were estimated to come from southern China and the middle of Vietnam. An example is shown in Fig. 3b, in which terminal points were distributed over southern Vietnam, Cambodia etc. This example suggests direct immigration from southern Vietnam across the South China Sea. An example in which immigrants were estimated to come from the mainland China by a typhoon is shown in Fig. 3c.

Fifty-three cases were analyzed. China, Vietnam and the Philippines were estimated to be the source 22, 19 and 7 times, respectively. Southern Vietnam was found to be the possible source in eight cases. China was identified in 65% of all cases, except for domestic catches (T in Table 2), and in 50% of these Chinese cases, Vietnam was also identified. Vietnam and the Philippines were identified in 56 and 21% of all cases, respectively. China and Vietnam were estimated to be the source of four mass immigrations greater than 100 in 1996, 2001, 2004

Table 1. Trap catches in Sikou, southwestern Taiwan and estimated sources with the backward trajectory analysis for the first rice crop

Catch date	Net trap[a]		Light trap[a]		Regions where terminal points were distributed[b]			Estimated source[d]
	WBPH	BPH	WBPH	BPH	Dusk 1 DB[c]	Dawn 1 DB	Dusk 2 DB	
30-Apr-91	0	0	18	0	GD, FJ	GD	—	SC
1-May-91	0	0	0	25	T	GD, FJ	GD	SC
12-May-91	0	0	0	10	T	T	T	T
13-May-91	0	0	0	39	FJ, GD, T	GD, T	GD, T	SC
17-May-91	0	0	0	56	FJ	FJ	FJ, ZJ	T
18-May-91	0	0	0	13	T	T	T	T
24-Apr-92	0	0	18	3	—	—	GD, HN	SC
19-May-97	40	0	8	0	GD, T	GD, HN	GD, HN	SC
20-May-97	48	0	10	0	GD	GD, HN	GD, GX, HN	SC
13-Apr-98	2	0	24	0	—	PH	PH	PH
14-Apr-98	7	0	17	2	GD	GD, GX	HN, GX, GD	SC
15-Apr-98	8	0	23	2	T, FJ, GD	GX, GD, HN	NV, GX, GD, HN	SC, V
1-May-98	1	0	19	6	—	PH	PH	PH
5-May-98	10	0	56	11	PH	PH	PH	PH
6-May-98	2	0	37	3	—	PH	PH	PH
7-May-98	0	0	18	2	—	PH	PH	PH
11-May-98	1	0	22	4	PH	—	—	PH
19-May-98	0	0	17	8	T	—	—	T
1-May-99	0	0	28	0	T	—	—	T
2-May-99	0	0	26	0	—	—	—	T
30-Apr-00	0	0	46	0	GD, HN, NV	NV, MV, GX, HN	NV, MV, LA, TH	SC, V
2-May-00	0	0	39	0	GD, FJ	HN, GD, GX, HU, JX, FJ	MV, GX, HN, GD, HU, JX, FJ	SC, V
4-May-00	2	0	17	0	FJ, GD	FJ, JX, HU, GX	FJ, JX, HU, GX	SC
13-May-00	0	0	16	0	T, FJ	FJ	ZJ, AH, JX	T
8-May-01	3	0	54	3	GD	GX, HN, GD	NV, MV, HN, LA	SC, V
9-May-01	1	0	202	3	GD	GX, GD	NV, MV, GX, HN, GD	SC, V
10-May-01	22	0	8	2	GD	GD, GX, JX	GD, GX, NV	SC, V
11-May-01	21	0	0	0	—	HN	MV, LA	SC, V
8-May-02	0	0	64	2	—	—	—	T
9-May-02	3	0	20	0	—	—	—	T
10-May-02	17	0	0	2	—	PH	PH	PH
16-May-02	1	0	32	0	GD, HU	GD, GX, HN	HN, NV, GX	SC, V
17-May-02	11	0	31	0	GD, FJ	GX, HU, JX, FJ	HU	SC
18-May-02	0	0	32	0	HN, GD, T	MV, LA, HN, GD, T	MV, LA, HN, GD, FJ, T	SC, V
19-May-02	0	0	45	1	JX, FJ, T	HB, HU, JX, FJ, T	HB, HU, JX, FJ, T	T
20-May-02	3	0	38	0	T	HN, GD, FJ, T	GD, FJ, HN, MV	SC, V
19-May-03	19	0	27	0	T, FJ, JX	GD, JX, HU, FJ	GD, JX, HU, FJ	SC
20-May-03	38	0	31	1	T, FJ	FJ, JX	JX, FJ, HU	T
10-May-04	7	0	13	0	HU, GD	GX, GD, GZ	NV, GX, GD, GZ	SC, V
11-May-04	12	0	43	2	—	GD	GD, JX	SC
20-May-04	10	0	26	1	FJ, GD	GD, GX, JX, FJ	FJ, GD, JX, GX	SC

[a] The sum of catches, either in net traps or light traps in Sikou, southwestern Taiwan. Catch data were extracted when the catch of WBPH or BPH in a trap of any type was more than 10 per day. Underlined numbers indicate when the catch in the net trap was more than 10 per day. See Fig. 1 for the location of the traps.

[b] NV: northern Vietnam (>20°N), MV: middle of Vietnam (13 to 20°N), GX: Guangxi, GD: Guangdong, JX: Jiangxi, HN: Hainan, HU: Hunan, HB: Hubei, FJ: Fujian, JS: Jiangsu, ZJ: Zhejiang, AH: Anhui, GZ: Guizhou, T: Taiwan, PH: the Philippines, LA: Laos, —: over the sea.

[c] Terminal time of the backward trajectories. DB: day(s) before the catch date.

[d] SC: southern China, including GX, GD and HN, V: Vietnam, PH: the Philippines, T: Taiwan.

Table 2. Trap catches in Sikou, southwestern Taiwan and estimated sources with backward trajectory analysis for the second rice crop

Catch date	Net trap[a]		Regions where terminal points were distributed[b]			Estimated source[d]	Remark[e]
	WBPH	BPH	Dusk 1 DB[c]	Dawn 1 DB	Dusk 2 DB		
8-Jul-92	45	28	HN, MV, LA	MV, SV, LA, TH	SV, CA, TH	C, V	
5-Jul-94	50	22	PH	PH	PH	PH	
7-Jul-94	23	0	T	T	T	T	
8-Jul-94	13	2	—	—	—	T	
9-Jul-94	40	16	—	—	—	T	
10-Jul-94	ND	ND	—	—	—	T	Typhoon, BPH:6
11-Jul-94	55	0	—	—	—	T	
14-Jul-94	55	1	PH	—	—	PH	
16-Jul-94	14	36	T	T	T	T	
17-Jul-94	23	0	T	T	T	T	
18-Jul-94	55	15	T	T	T	T	
19-Jul-94	39	12	T	—	—	T	
23-Jul-94	22	0	—	—	MV	V	
2-Jul-95	38	0	—	—	PH	PH	
3-Jul-95	45	5	—	SV	SV, CA	V	
5-Jul-95	31	0	—	—	—	T	
6-Jul-95	23	0	—	—	—	T	
27-Jul-96	75	35	GD	GD, HN, MV, LA	GD, MV, LA, TH	C, V	Typhoon
28-Jul-96	448	621	HN	GD, HN, MV, LA, TH	GD, HN, MV, LA, TH	C, V	
29-Jul-96	40	90	—	—	HN, MV, LA, PH	C, V, PH	
30-Jul-96	15	20	T	—	—	T	
31-Jul-96	31	39	—	—	—	T	Typhoon
1-Aug-96	40	34	—	—	—	T	
2-Aug-96	51	32	HN, GD, HU, JX, ZJ	MV, LA, GX, GD, HU, JX, ZJ	MV, LA, GX, GD, HU, JX, ZJ	C, V	
3-Aug-96	24	25	PH	—	MV, HN, GD	PH, C, V	
4-Aug-96	10	11	—	—	—	T	
5-Aug-96	11	12	—	—	—	T	
18-Jul-00	31	2	SV	—	—	V	
12-Jul-01	202	29	FJ, GD	FJ, GD	FJ, GD	C	Typhoon
13-Jul-01	99	9	GD	GD, HN	GD, HN	C	
14-Jul-01	53	4	—	—	HN	C	
31-Jul-01	13	29	GD	GD	HN, GD	C	Typhoon
4-Jul-02	ND	ND	—	—	—	T	Typhoon, WBPH:8
19-Jul-02	26	0	MV	SV, MV, CA, LA	SV, CA, LA	V	
2-Jul-04	22	0	—	PH	—	PH	Typhoon
3-Jul-04	ND	ND	GX, GD, HN, HU, JX, FJ	GX, GD, JX, FJ, ZJ	FJ, ZJ	C	Typhoon, BPH:975, WBPH:10,674
4-Jul-04	ND	ND	GX, GD, HU, JX, FJ	NV, LA, GX, GD, HN, HU, HB, JX, FJ, ZJ	TH, LA, NV, MV, GX, HU, HB, JX, AH, FJ, ZJ	C, V	Typhoon, BPH:879, WBPH:3,581
5-Jul-04	ND	ND	GD, GX, HN, JX, FJ	NV, HN, GX, GD, JX, HU, HB	NV, MV, LA, TH, SV, HN, GX, GD, HU, JX, HB	C, V	Typhoon, BPH:863, WBPH:3,321
6-Jul-04	296	6	—	MV, SV, CA, LA	SV, MV, CA, LA	V	
7-Jul-04	177	0	—	MV, SV, CA	SV, MV, CA	V	
8-Jul-04	139	1	—	MV, LA, TH	MV, LA, TH, CA	V	
9-Jul-04	106	2	—	HN	MV, LA	C, V	
25-Aug-04	ND	ND	FJ, ZJ	FJ, ZJ	GD, FJ, ZJ	C	Typhoon, BPH:4, WBPH:73
26-Aug-04	46	0	ZJ	—	—	C	Typhoon

Table 2. (Continued)

Catch date	Net trap[a]		Regions where terminal points were distributed[b]			Estimated source[d]	Remark[e]
	WBPH	BPH	Dusk 1 DB[c]	Dawn 1 DB	Dusk 2 DB		
27-Aug-04	70	0	GD	GD, GX, HU, JX	GX, HU, JX, AH, JS	C	
30-Aug-04	19	0	MV, SV, CA, LA, TH	MV, SV, CA, TH, LA	SV, CA, LA, TH	V	
20-Jul-05	ND	ND	ZJ	PH	PH	C, PH	Typhoon, BPH:18, WBPH:58
21-Jul-05	203	162	GX, GD, HU	NV, GX, HU, JX, HB, AH, ZJ	NV, LA, GX, ZJ, AH, JX, HB, HU	C, V	
22-Jul-05	140	85	—	GD, GX, HN, MV	GX, HN, MV, LA, TH, CA	C, V	
23-Jul-05	43	10	—	—	—	T	
24-Jul-05	20	3	T	T	—	T	
6-Aug-05	14	33	GD, JX, FJ	GD, JX, HN, AH	GD, HN, JX, HB	C	
7-Aug-05	13	33	GD, JX	HN, GD, HU, JX	HN, GX, GD, JX, HU, HB, AH	C	

[a] The sum of catches in net traps in Sikou, southwestern Taiwan. Catch date was extracted when catch of WBPH or BPH in a net trap was more than 10 par day. ND: no data with the net unmounted due to strong winds. See Fig. 1 for the location of the trap.

[b] NV: northern Vietnam (>20°N), MV: middle of Vietnam, SV: southern Vietnam (<13°N), GX: Guangxi, GD: Guangdong, JX: Jiangxi, HN: Hainan, HU: Hunan, HB: Hubei, FJ: Fujian, JS: Jiangsu, ZJ: Zhejiang, AH: Anhui, GZ: Guizhou, T: Taiwan, PH: the Philippines, CA: Cambodia, TH: Thailand, LA: Laos, —: over the sea.

[c] Terminal time of the backwaed trajectores. DB: day(s) before the catch date.

[d] C: China, V: Vietnam, PH: the Philippines, T: Taiwan.

[e] Typhoon: A typhoon passed over or near Taiwan. Total catch number of BPH and WBPH in two light traps is shown in case of ND.

and 2005. One characteristic result is that the trajectories were covered at high speeds due to a typhoon. In some cases, the terminal points reached as far as Vietnam or the Philippines, even at dusk the previous day.

DISCUSSION

Possible migration sources in first and second crop seasons were found to be China, Vietnam and the Philippines. Early in the season, when westerly or southwesterly winds prevailed, three southern regions, Guangdong, Guangxi and Hainan, were frequently identified as possible migration sources to Taiwan (Table 1). When the wind speed was high, north and central Vietnam also became possible sources.

Especially in the second cropping season, the wind speed became very high when a typhoon was present near or over Taiwan. In fact, more than 100 insects per day were caught by net traps in the immigration events in 1996, 2001, 2004 and 2005 (Table 2). In these events, the typhoons approached Taiwan from the southeast between Luzon Island and Taiwan, and crossed over Taiwan or passed adjacent to the south of Taiwan, moving in a northwesterly direction. When these typhoons moved into the west to Taiwan, the wind direction changed, with winds coming from the mainland, based on the weather data. These westerly to southwesterly winds brought many immigrants, as in the cases on 28 July 1996 or 12 July 2001 and etc. Therefore, a typhoon approaching from the southeast towards Taiwan in the second cropping season could bring mass immigration and should be paid careful attention.

Among the catch dates in Table 1, some insects were captured in mid-April in 1998. In early spring, March and April, rice planthoppers from northern Vietnam are believed to immigrate into Guangxi. For example, 5,976 rice planthoppers in 2005 and 15,016 in 2006 were captured in light traps in Guangxi from 1 March to 20 April (Otuka et al., 2008), and the first rice crop in Guangxi is transplanted from late March to early April. Thus, generally, there is insufficient time for these immi-

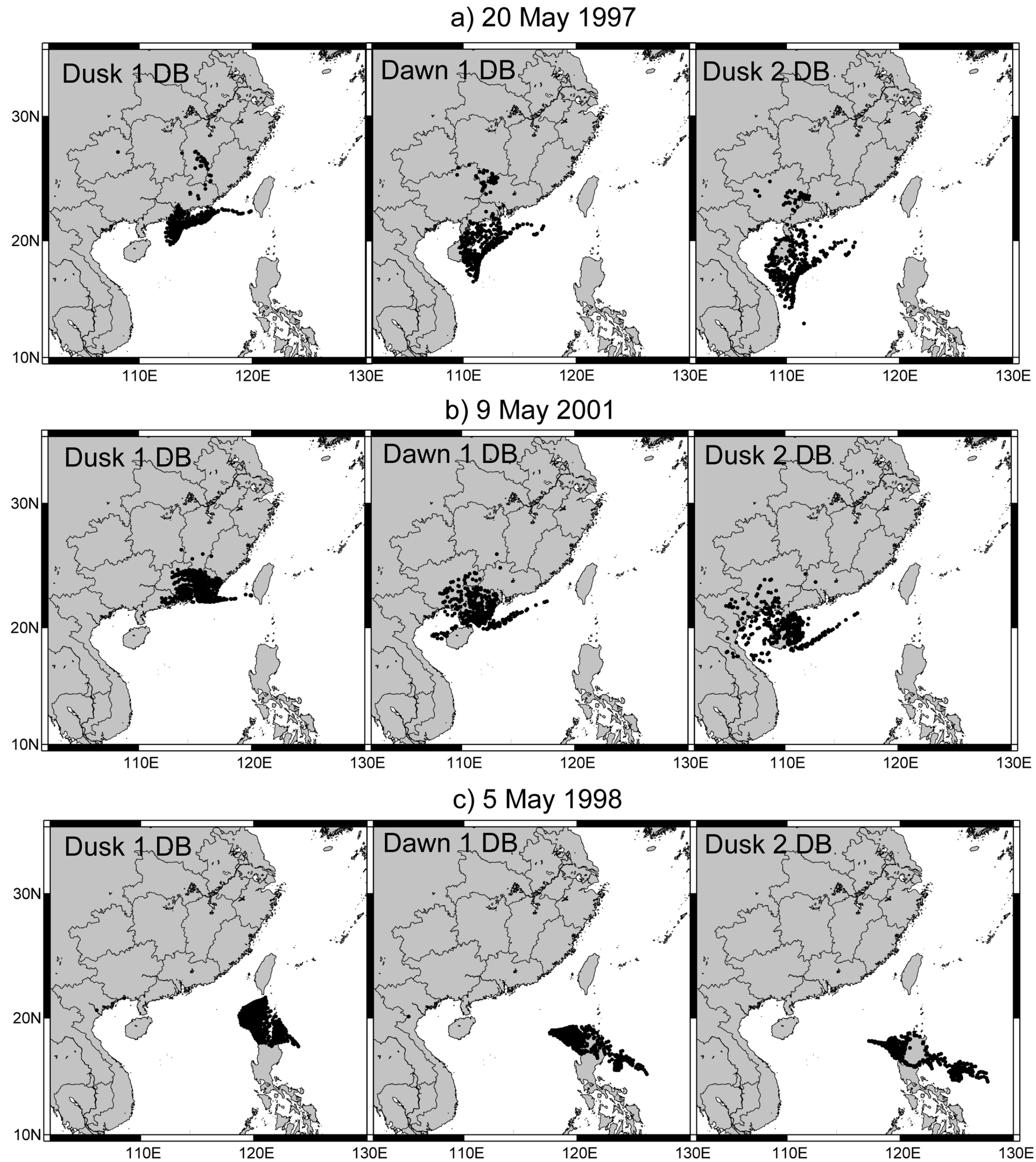

Fig. 2. Distribution of the terminal points of the backward trajectories which started over Sikou, southwestern Taiwan on a) 20 May 1997, b) 9 May 2001, and c) 5 May 1998. Annotations such as Dusk 1 DB, Dawn 1 DB indicate when backward trajectories were terminated. DB denotes the day(s) before the catch date. The starting time of trajectories on a catch date ranged over 24 h at intervals of 1 h. Since trajectories have different flight durations depending on their starting times, the terminal points are distributed mainly in the wind direction. Terminal points over the sea were disregarded for source estimation because the sea cannot be a source.

grants to multiply on rice plants by mid-April, and the density of rice planthoppers is expected to be small; therefore, Guangxi was not a major source of immigration into Taiwan in mid-April (Table 1). The Red River Delta (RRD) in Vietnam and Hainan province are overwintering areas of BPHs and WBPHs for the East Asian Population (Cheng et al., 1979; Sogawa, 1993a, b), where rice is cultivated in winter and spring. The first rice crop is also cultivated on Luzon Island, the Philippines, as discussed below. Therefore, it is possible that Hainan, northern Vietnam and the Philippines are

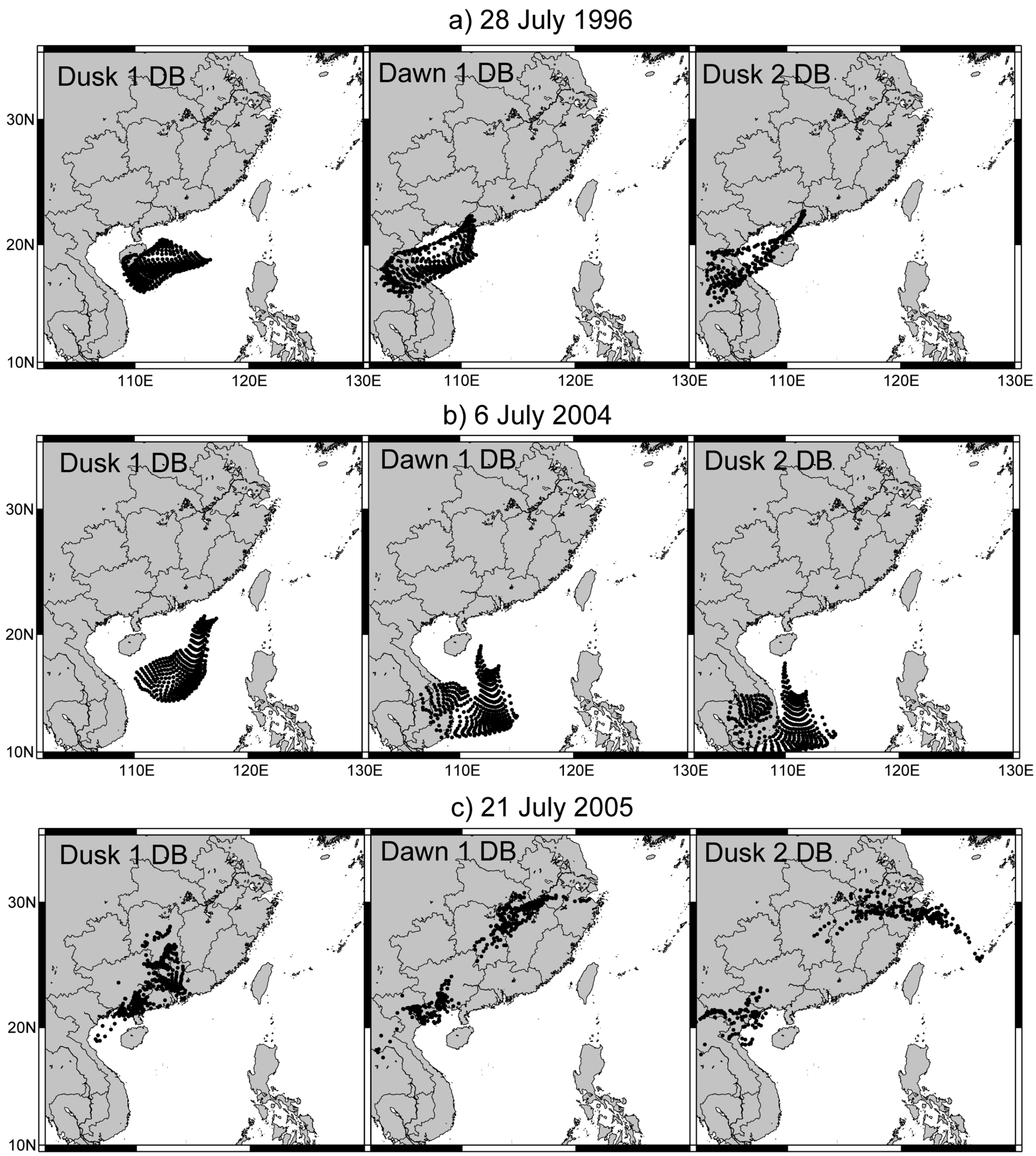

Fig. 3. Distribution of the terminal points of the backward trajectories which started over Sikou, southwestern Taiwan on a) 28 July 1996, b) 6 July 2004, and c) 21 July 2005. Examples of source estimation for large catches in the summer (Table 2). The same annotations were used as in Fig. 2.

sources in April. If early migrations in April are long-distance migrations, then the distances from Hainan or northern Vietnam to western Taiwan is about 1,100 or 1,400 km, respectively. These distances are comparable to the migration distances from southern China to Kyushu, western Japan in later migrations during the *Bai-u* rainy season (about 1,400 km).

In May, the winter-spring rice crop is grown to its mature stage in RRD. This first rice crop is transplanted from January to February, and is harvested from May to June (Otuka et al., 2008). In early May, when rice plants are in their milky stage, or later, when the density of rice planthoppers in the paddy fields increases, the emigration trend tends to peak (Otuka et al., 2008). During these later times, immigrations into southern China also increase, as described previously (Otuka et al., 2008). These migrations are the major portion of the first-step migration of the East Asian Population (Otuka et al., 2008). In southern China, Guangxi, Guangdong and Hunan, the next generation of immigrants that arrives in China in April are an emigrating generation, so when they emerge (Li et al., 1996), these regions become possible sources for emigration towards Taiwan. The source in May was found to be southern China or Vietnam in 18 of 24 overseas migration cases.

Although southern China and Vietnam are often found to be possible sources, the Philippines were occasionally identified as the source in April and May 1998, under southerly wind conditions (Table 1), with the specific estimated source region being Luzon Island, which cultivates two rice crops a year. In the dry season, transplanting starts from late November to late December, and ends between December and January, depending on the region (Matsumura, personal communication). Harvesting ranges from March to May. In the wet season, transplanting ranges from June to July, and harvesting from October to November (Matsumura, personal communication). Therefore, the period from April to May is the maturing or harvesting stage, during which emigration from the source region into Taiwan can be expected. The source estimation in this study and the cropping pattern on Luzon Island support emigration from the Philippines to Taiwan. A previous study also showed that a possible source of immigration into eastern Taiwan recorded on 26 August 1978 was found to be Luzon Island (Otuka et al., 2005). Late August corresponds to one or two months after transplanting the second crop, which supports migration from the Philippines to Taiwan in that season. In addition to the rice growth stage being favorable for migration into Taiwan, the distance between the two islands is also supporting evidence. The distance from the northern limit of Luzon Island to the southern limit of Taiwan is about 360 km, which is relatively close compared with the typical migration distance between southern China and western Japan (more than 1,000 km). This short distance is additional evidence of overseas migration from the Philippines.

The characteristics of rice planthoppers in Taiwan, especially BPHs, are quite different from those of the tropical populations in southern Vietnam and the Philippines. For example, insecticide resistance was found against imidacloprid in BPH collected in 2006 in East Asia and Indochina, but not in the Philippines's population (Matsumura et al., 2008). In addition, a large increase in resistance to imidacloprid was shown in the population of southern Vietnam in 2007 (Matsumura, 2009). Virulence to resistant rice varieties in BPH is also different among populations in Taiwan, southern Vietnam and the Philippines (Matsumura, 2009). For instance, populations in southern Vietnam indicated high adult survival on the rice variety Babawee with a resistant gene *bph4* (Matsumura, 2009). These characteristics may affect the insect's reproduction rate when immigrants come from these tropical regions. In fact, southern Vietnam and the Philippines were estimated to be the source region in some cases (Table 2); therefore, careful monitoring of possible migrations from southern Vietnam or Luzon Island into Taiwan is needed for better pest management.

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