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A migration analysis for rice planthoppers, *Sogatella furcifera* (Horváth) and *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae), emigrating from northern Vietnam from April to May

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Abstract
Rice planthoppers are long-distance migratory insects. The East Asian population is believed to migrate from northern Vietnam to southern China in the spring. To understand its major migration paths, a migration analysis was conducted with catch data by a single light trap located in the Red River delta in northern Vietnam. The catch data showed large peaks in late April to early May, each of which was used as a starting point of a simulation. Destination regions of simulated migrations were found to be distributed over southern Chinese provinces: Guangxi, southern Hunan, Jiangxi, northern Guangdong and northwestern Fujian. The region formed a diagonal belt stretching in the northeast direction. According to Chinese data, many planthoppers were caught in light traps along the diagonal belt region, supporting the simulation results. The planthoppers that arrive on rice plants of the early crop can multiply by one or two generations before their next emigration.

Key words: *Nilaparvata lugens*; *Sogatella furcifera*; long-distance migration; East Asian population; migration simulation

INTRODUCTION

The brown planthopper, *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae), and the white-backed planthopper, *Sogatella furcifera* (Horváth), are major insect pests of rice in Asia. Especially, heavy outbreaks of *N. lugens* have occurred in East Asian countries since 2005, with hopper burns appearing in many paddy fields and damaging rice production (Otuka et al., 2007). The rice planthoppers are long-distance migratory insects. Based on temporal changes of biotype, it is believed that the East Asian population is comprised of the rice planthoppers that overwinter mainly in northern Vietnam and emigrate to China and other East Asian countries (Sogawa, 1992, 1993).

Planthoppers are thought to arrive in Japan in the *Bai-u* rainy season, in June and July, by two steps of migration (Sogawa, 1993). In the first step of migration from April to June, planthoppers are believed to migrate from northern Vietnam to southern China, where they multiply for a few generations (Sogawa, 1993). In late June to early July, when strong south-westerly winds develop over the East China Sea, they are believed to migrate from southern China to Japan (the second step of migration) (Kisimoto, 1976).

Because important characteristics of the species for pest management such as biotype and insecticide susceptibility are dependent on the rice variety and insecticide used at the source, estimation of the source is essential. Based on this understanding, several previous studies have estimated possible migration sources for the second step using two- or three-dimensional backward trajectory analysis (Rosenberg and Magor, 1983; Sogawa, 1995; Otuka et al., 2005a, b). Those studies used trap data to determine both the arrival date and site of immi-

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gration, from which backward trajectories started; the distribution of the terminal points of the trajectories indicated the possible source regions to be southern China and Taiwan. However, since trap data in China was difficult for foreign scientists to access before the outbreak of *N. lugens* in 2005, the available information on occurrence in the source regions has been limited. Without the trap data, no backward trajectory analysis was able to be conducted, and knowledge about the first step of migration was limited, despite its importance to Japanese agriculture. Conversely, when trap data in northern Vietnam became available, forward migration simulations (Furuno et al., 2005; Otuka et al., 2006) could be conducted and indicate destination regions from there, presenting new ecological knowledge on the first step of migration.

The objective of this study was to estimate the destination regions of the first step of migration by migration simulation using light trap data in northern Vietnam. The destination regions of simulated planthoppers were expected to indicate the locations of possible sources for the second step of migration bound for Japan, Korea and northern paddy regions in China. Additionally, in the evaluation, the simulation result was compared with recent new information on actual planthopper catches in southern China obtained from Chinese plant protection organizations and their web sites on the Internet. This information became available beginning in 2006, after the outbreak of *N. lugens* in 2005.

MATERIALS AND METHODS

Catch of rice planthoppers in a light trap in northern Vietnam. In Vietnam, which lies north to south for a long distance along the eastern Indochina Peninsula, populations in the northern part, or Red River delta, and the southern part, or Mekong delta, are thought to be ecologically isolated without known genetic interaction, and with only the northern population thought to comprise the East Asian population (Sogawa, 1992, 1993). There are two crop seasons in the northern delta: a winter-spring crop and a summer crop. Planthoppers overwinter, multiplying on the winter-spring crop, for which rice is transplanted in January to early March and harvested in June (Sogawa, 1993; Suzuki and Wada, 1994; Otuka et al., 2007). To monitor insect pests, there is a light trap for planthoppers in Hai Phong, located on the eastern part of the Red River delta (20.78°N, 106.65°E; solid triangle in Fig. 4). It was the only trap available for monitoring the occurrence of planthoppers in northern Vietnam. The trap consisted of an 18-W fluorescent lamp and a water pan 1 m in diameter. Paddy fields extended to the east of the trap; the farmer's house stood in the west. Insects caught by the trap in 2005 to 2007 were collected daily in the morning from March to May. The catch numbers of *S. furcifera* and *N. lugens* were recorded by plant protection officers.

Simulation method. A migration simulation model developed by Otuka et al. (2006) was utilized to estimate the destination regions in the first step of migration. In the model, as many as 34,000 planthoppers took off from the trap site at dusk, 11 UTC (Coordinated Universal Time), on dates of major catch peaks that were larger than 50 per day. The three-dimensional positions of migrating planthoppers were calculated using meteorological data simulated by a weather prediction model; the planthoppers were assumed to move mainly by wind vectors in the time step, taking vertical diffusion into account (Otuka et al., 2006). The planthoppers in flight were also assumed to be kept from entering upper air at temperatures less than 16.5°C (Ohkubo, 1973). The simulation duration was 36 h, and all the planthoppers kept flying during the simulation without landing on the Earth's surface. The relative aerial density of the insects was calculated hourly, based upon their number in a simulation grid cell stretching 33 km square horizontally and 100 m high vertically above the ground. An area of non-zero value of the relative aerial density was used. The relative aerial density drawn on a map, which looks like a cloud, is referred to as a migration cloud hereafter. The destination regions were estimated with superposition of multiple distributions of migration clouds at 24 or 36 h after takeoff. The flight durations (24 and 36 h) were chosen because the flight duration of the second step of migration from southern China to Japan in the *Bai-u* rainy season has been estimated to be in the range 24–36 h (Otuka et al., 2006). In other words, typical long-distance migration of rice planthoppers in East Asia is believed to be a phenomenon on such a time scale.

Catch of rice planthoppers in light traps in

southern China. Various plant protection organizations in southern China released catch data for rice planthoppers several times during the rice cultivation season in 2006 and/or 2007 on the Internet (No catch data released in 2005 were found and no data from Hunan, Anhui or Hainan were available on the Web; see Fig. 4 for province map). These included the Guangxi Plant Protection General Station (PPGS) in Guangxi Zhuang Autonomous Region, Guangdong PPGS in Guangdong province, Jiangxi Plant Protection and Quarantine Station (PPQS) in Jiangxi province, Guizhou PPQS in Guizhou province, Fujian PPQS in Fujian province, Hubei PPGS in Hubei province and Zhejiang Plant Protection and Quarantine Bureau (PPQB) in Zhejiang province. The information included the daily catch numbers from light traps, or the total catch number during the period when clear migration peaks appeared. The catch numbers included both *S. furcifera* and *N. lugens* (Fujian PPQS, 2007; Guangdong PPGS, 2007; Guangxi PPGS, 2007; Guizhou PPQS, 2007; Hubei PPGS, 2007; Jiangxi PPQS, 2007; Zhejiang PPQB, 2007). According to the occurrence information in Guangxi released in 2006, the total catch number of rice planthoppers from 1 March to 20 April (5,976 in 2005; 15,016 in 2006) was one order of magnitude smaller than that during first ten days in May (96,876 in 2005; 116,328 in 2006) (Guangxi PPGS, 2007). This implied that major migrations did not occur in March. Therefore, the catch data in April and May were used for evaluation of the migration simulation.

RESULTS

Catch data at Hai Phong and migration simulations

There were large catch peaks of *N. lugens* and *S. furcifera* at Hai Phong in late April to May in 2005 to 2007 (Fig. 1). Only peaks larger than 50 per day regardless of the species were used for migration simulations. Nineteen peaks were selected in 2005, and 19 and 13 peaks in 2006 and 2007, respectively. It was considered that these peaks were due to newly emerged long-winged planthoppers of the local population based on surveys in paddy fields conducted by the authors in April 2007 (unpublished data). Figure 1 indicates that the largest catch peak in each year appeared from late April to early May. Peaks of *N. lugens* have a tendency to be larger than those of *S. furcifera* in May at the ripening stage of the winter-spring crop.

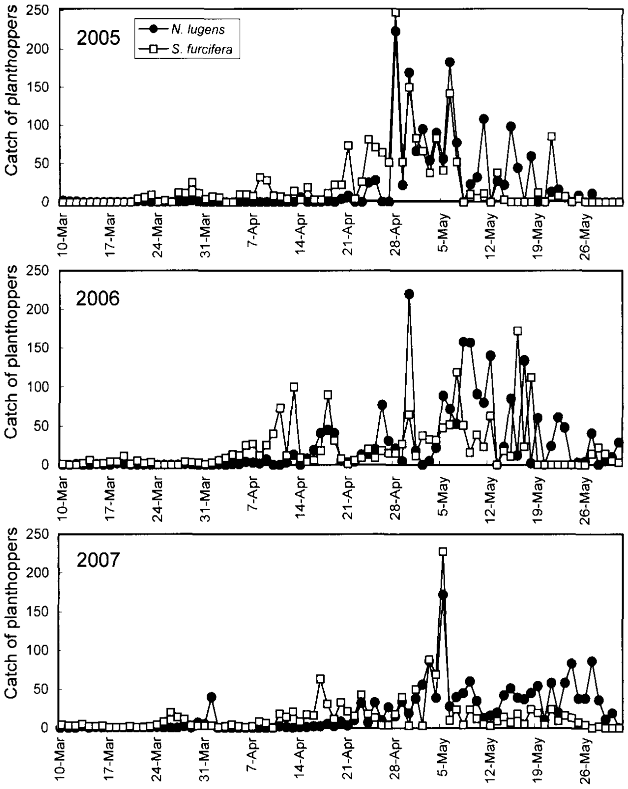

Fig. 1. Catch of rice planthoppers, *Nilaparvata lugens* and *Sogatella furcifera*, in a light trap at Hai Phong, Vietnam in 2005 to 2007. Location of Hai Phong is shown as a solid triangle in Fig. 4.

Two typical examples of the movement of a migration cloud are shown in Fig. 2. Figure 2a shows a migration cloud that started at Hai Phong at 11 UTC on 28 April 2005, when the largest catch peak appeared in Fig. 1. The migration cloud moved northeast, blown by a southwesterly air current. At 24 h after take-off, at 11 UTC on April 29, it was located mainly over Jiangxi province. Figure 2b shows a migration cloud that started at Hai Phong at 11 UTC on 6 May 2006. At 6 UTC on 7 May the cloud passed over Shaoping, Guangxi and at 19 UTC reached Wanan in Jiangxi province. Catch peaks were recorded on 7 May at both sites: 8,832 at Shaoping and 512 at Wanan (Guangxi PPGS, 2007; Jiangxi PPQS, 2007).

Destination regions for the first step of migration were estimated as shown in Fig. 3. The destination region at 24 h after take-off in 2005 was located northeast of Hai Phong and over a region covering Guangxi, southern Hunan, Jiangxi, the northern part of Guangdong and the northwestern Fujian

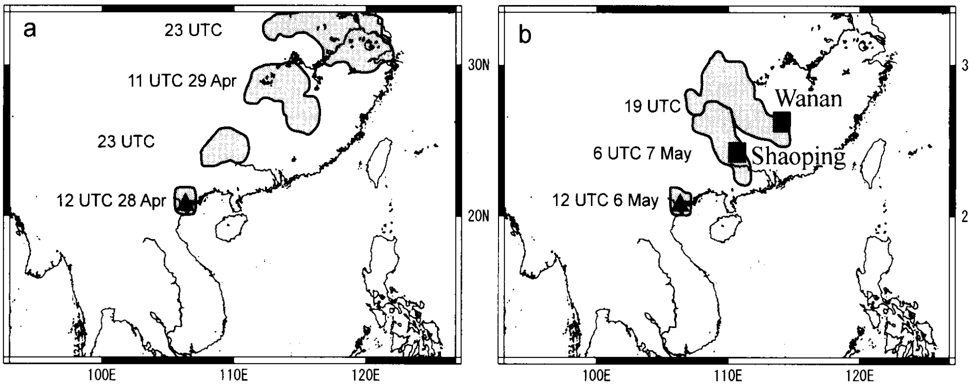

Fig. 2. Examples of the movement of migration clouds. Migration clouds, or areas of non-zero aerial density of migrating planthoppers, were calculated by a simulation model (Otuka et al., 2006). a: This cloud started at 11 UTC (dusk) on 28 April 2005, when a large catch was recorded with a light trap at Hai Phong. b: This cloud started at 11 UTC on 6 May 2006. Solid squares show the location of Shaoping and Wanan, solid triangle Hai Phong.

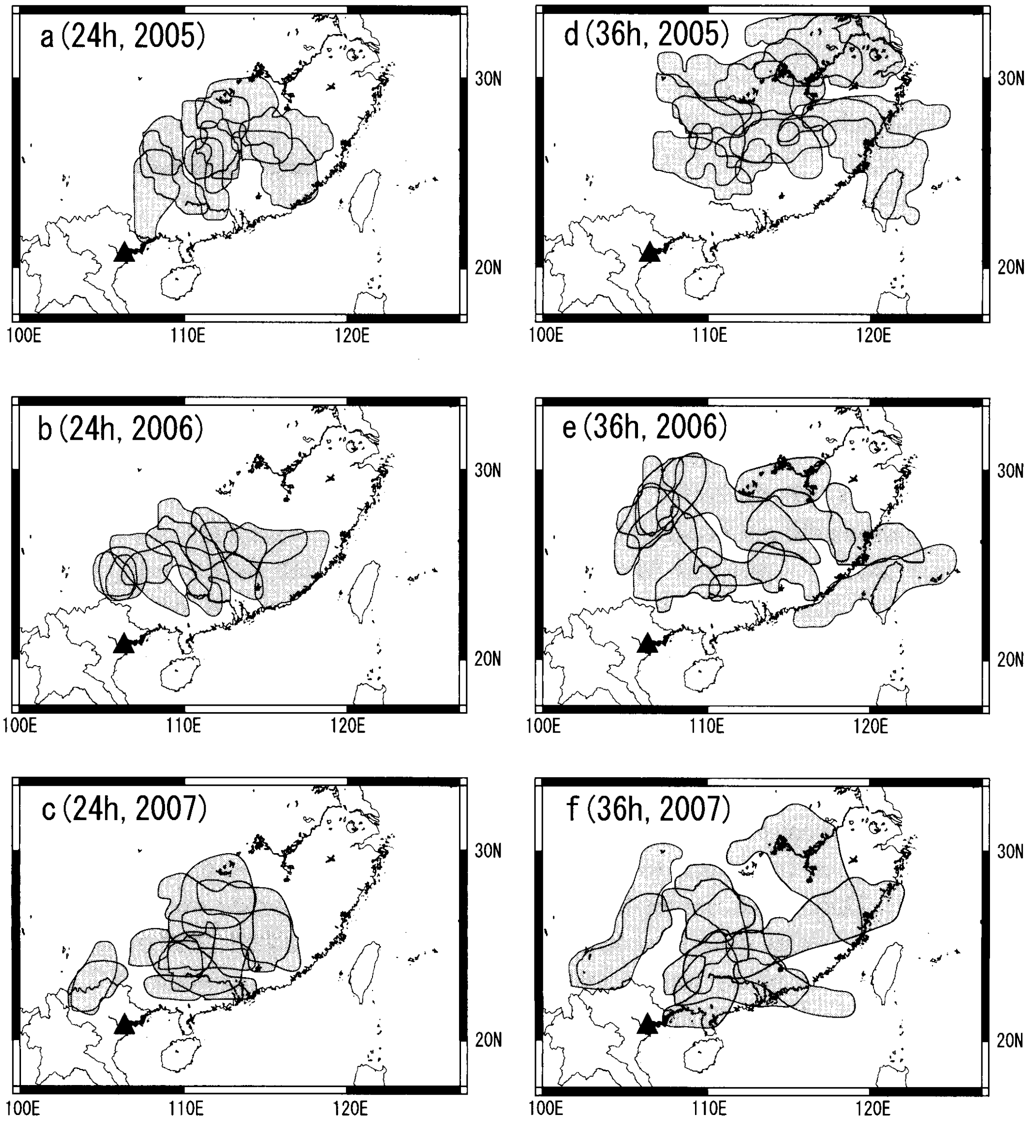

Fig. 3. Superposition of migration clouds at 24 and 36 h after take-off at Hai Phong in late April to May in 2005 to 2007. Each migration cloud was calculated to take off at dusk on a date when a distinct catch larger than 50 insects per day was recorded at Hai Phong (Fig. 1). Figures in the row from top to bottom (a and d, b and e, and c and f) are the 2005, 2006 and 2007 cases, respectively. Figures in the column from left to right (a, b and c, and e, f and g) are superpositions at 24 and 36 h after take-off, respectively.

province (Figs. 3a and 4). The region moved farther to the northeast at 36 h, with some migration clouds over the lower reach of the Yangtze River (Fig. 3d). The destination region at 24 h in 2006 was located over a region stretching west to east, which was lower in latitude than that in 2005, but still most were located northeast of Hai Phong (Fig. 3b). The clouds broke apart into three at 36 h after take-off and moved in three different directions: to the east, north and northeast (Fig. 3e). The clouds that moved to the northeast had a similar migration pattern to that in 2005. The destination region at 24 h in 2007 was similar to the 2005 case, except for two migration clouds which moved to the northwest (Fig. 3c). At 36 h some migration clouds moved to the northeast, but many stayed because of weak winds during those 12 h (Fig. 3f). The destination regions at 24 h over three years (Fig. 3a to c) showed that they formed a diagonal belt region stretching from northern Vietnam to Guangxi, southern Hunan, northern Guangdong, Jiangxi and northwestern Fujian provinces (the diagonal belt region between two arrows in Fig. 4).

Catch data in southern China

Clear catch peaks that appeared in April and May 2006 to 2007 in the seven provinces are shown in Table 1 (Fujian PPQS, 2007; Guangdong PPGS, 2007; Guangxi PPGS, 2007; Guizhou PPQS, 2007; Hubei PPGS, 2007; Jiangxi PPQS, 2007; Zhejiang PPQB, 2007). Each trap site was ordered, as in the 'Site ID' column, by the average daily catch number (insects/day), or the value of total catch in a period divided by the number of days in the period (Table 1). The locations of the Chinese traps are shown as solid circles in Fig. 4. The radius of the solid circle reflects the size of the average daily catch.

Table 1 shows that migration peaks occurred in late April to early May or in late May. Table 1 also shows that many peaks are synchronized with each other. For example, catch peaks at Yongfu (3) and Wanan (12) appeared simultaneously on 11 April, 2006. During the period of 6 to 10 May 2006, several sites in Guangxi, Guangdong and Jiangxi province had immigrations. Similar simultaneity can be seen for 2007. Furthermore, the period of these peaks approximately coincided with the catch peaks at Hai Phong (Fig. 1). Table 1 and Fig. 4 indicate that the sites in Guangxi had a larger catch than other sites. Guangxi is close to northern Vietnam. The two solid arrows in Fig. 4 show the diagonal belt region in Fig. 3. The sites in Guangxi, Guangdong, Jiangxi and Fujian except for sites 5, 18 and 25 were under the simulated destination regions in Fig. 3b and c. The sites 1, 9 and 10 in Guangxi were covered by migration clouds on the way to the destination regions at 24 h. Therefore, most of the trap sites in these provinces corresponded well to the destination regions estimated in Fig. 3b and c, supporting the identification of the diagonal belt region as the migration path. The sites in Guizhou had immigrations when southerly winds blew, according to the wind data used in the migration simulation. Sites 13 and 21 in Hubei province had immigrations in late April 2007 (Hubei PPGS, 2007), but no catch numbers were reported on the web. The sites in Zhejiang province had the first immigration of the 2007 season in late May, and there was no catch in late April to early May (Zhejiang PPQB, 2007).

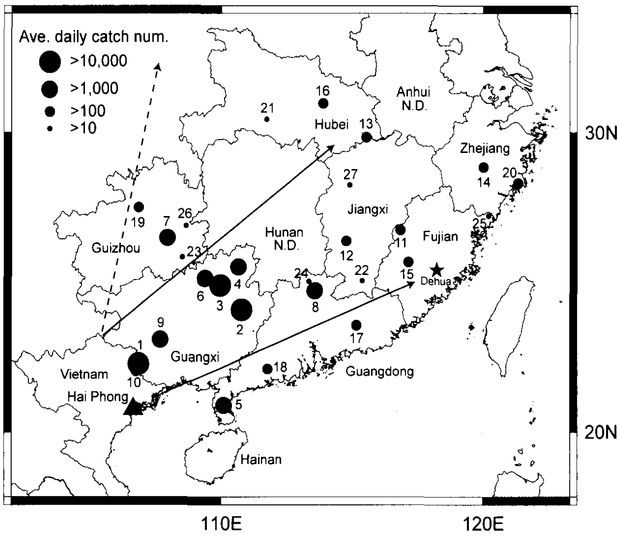

Fig. 4. Location of light traps of interest in Vietnam and southern China. Solid circles and the solid triangle indicate trap sites in China and Vietnam, respectively. No data from Hainan, Hunan and Anhui were available on the Internet (N.D.). Chinese traps had a marked catch in April and May in 2006 and 2007 as shown in Table 1. The radius of the solid circle is one of four sizes depending on the average daily catch number (ADCN) (insects/day), calculated by dividing the total catch number in a period by the number of days in the period (Table 1). The maximum ADCN was used for the sites with several ADCNs. Site IDs in Table 1 show the numbers. The two arrows indicate the path of the first step of the migration derived from Fig. 3a–c. The dashed arrow indicates the northward direction of migration to Guizhou province.

Table 1. Total catch numbers of *S. furcifera* and *N. lugens* in light traps located in southern China during periods in April and May in 2006 and 2007

Period	Total catch number	Province	Site	Site ID	Period	Total catch number	Province	Site	Site ID
11 Apr 2006	4,032	Guangxi	Yongfu	3	22 Apr 2007	24,288	Guangxi	Shaoping	2
6–10 May 2006	20,864	Guangxi	Shaoping	2	22 Apr 2007	10,240	Guangxi	Yongfu	3
6–8 May 2006	CP*	Guangxi	Xingan	4	22–25 Apr 2007	HH*	Guangxi	Longzhou	1
21–25 May 2006	32,200	Guangxi	Longzhou	1	3–5 May 2007	31,100	Guangxi	Longzhou	1
21–25 May 2006	4,689	Guangxi	Pingxiang	10	19–20 May 2007	85,000	Guangxi	Longzhou	1
21–25 May 2006	5,114	Guangxi	Longan	9	22–25 May 2007	38,021	Guangxi	Xingan	4
6 May 2006	6,858	Guangdong	Leizhou	5	22–25 May 2007	30,921	Guangxi	Shaoping	2
1–10 May 2006	1,641	Guangdong	Qujiangqu	8	22–25 May 2007	26,079	Guangxi	Rongan	6
21–30 May 2006	642	Guangdong	Leizhou	5	21–25 Apr 2007	337	Guangdong	Zijin	17
21–30 May 2006	21,658	Guangdong	Qujiangqu	8	21–25 Apr 2007	340	Guangdong	Lechang	24
11 Apr 2006	320	Jiangxi	Wanan	12	27 Apr–8 May 2007	2,358	Guangdong	Yangchun	18
25 Apr 2006	296	Jiangxi	Wanan	12	6–10 May 2007	1,402	Guangdong	Zijin	17
25 Apr 2006	28	Jiangxi	Shanggao	27	1–10 May 2007	7,293	Guangdong	Leizhou	5
30 Apr 2006	416	Jiangxi	Wanan	12	21–26 Apr 2007	13,506	Guizhou	Kaili	7
30 Apr 2006	7	Jiangxi	Shanggao	27	21–26 Apr 2007	451	Guizhou	Rongjian	23
7 May 2006	512	Jiangxi	Wanan	12	21–26 Apr 2007	239	Guizhou	Sansui	26
7 May 2006	82	Jiangxi	Anyuan	22	1–3 May 2007	458	Guizhou	Zunyi	19
7 May 2006	5	Jiangxi	Shanggao	27	26–29 Apr 2007	2,618	Fujian	Jianning	11
6–10 May 2006	1,408	Jiangxi	Wanan	12	26–29 Apr 2007	1,424	Fujian	Yongan	15
6–10 May 2006	349	Jiangxi	Anyuan	22	4 May 2007	52	Fujian	Fuding	25
19–28 May 2006	5,076	Jiangxi	Wanan	12	8–11 May 2007	1,775	Fujian	Jianning	11
					17–21 May 2007	281	Hubei	Xiaogan	16
					27–29 May 2007	1,211	Hubei	Wuxue	13
					22–26 May 2007	440	Hubei	Zhijiang	21
					24 May 2007	150	Zhejiang	Wenling	20
					27 May 2007	378	Zhejiang	Yongkang	14

* CP: clear peak, HH: historically high. In both the cases, no catch number was reported. Location of the site is shown in Fig. 4. Site ID was ordered by the average daily catch number, or the value of total catch number in a period divided by the number of days in the period.

Data were cited from following Internet sites: Fujian Plant Protection and Quarantine Station (PPQS) (2007), Guangdong Plant Protection General Station (PPGS) (2007), Guangxi PPGS (2007), Guizhou PPQS (2007), Hubei PPGS (2007), Jiangxi PPQS (2007) and Zhejiang Plant Protection and Quarantine Bureau (2007).

DISCUSSION

This study demonstrated that the destination regions of rice planthoppers migrating from northern Vietnam over the three years formed a diagonal belt region, which is referred to as the first-step migration path of populations eventually reaching Japan. The path stretches from northern Vietnam to Guangxi, northern Guangdong, southern Hunan, Jiangxi and northwestern Fujian provinces. Since rice planthoppers are very small in size, it is thought that they are carried by winds and land somewhere on the ground along the path. Therefore, the region along the path is expected to have had many immigrants. In fact, information on planthopper occurrence provided by the provinces in southern China supported that such migrations had indeed occurred. Additionally, according to Guangdong PPGS and Fujian PPQS, the northern part of Guangdong province and the northwestern part of Fujian province had larger numbers of immigrants in this season than the other parts (Matsumura et al., 2006). The fact also supports the location of the first-step migration path over the northern parts of the provinces.

The Chinese trap data showed that Guizhou province had some immigrations in late April to early May (Table 1). It was estimated that southerly winds assisted rice planthoppers to arrive in Guizhou from northern Vietnam. These migrations were located outside the first-step migration path. If migrations to Guizhou are the part of major migrations in the spring, the first-step migration path has to be modified. However, the fact that the southerly winds are not as predominant as southwesterly winds in that season (Fig. 3) implies migrations to Guizhou are peripheral. But, for lack of sufficient light trap information, it is still unknown whether these migrations are minor or not. More detailed occurrence information in this province is necessary to know a clear picture there.

The comparison of simulation and trap results indicated that the destination regions not at 36 h but at 24 h corresponded well to the catch peaks in southern China. The catch information in southern China also indicated that the number of immigrants under the first-step migration path was inversely correlated to the distance from northern Vietnam (Table 1). Importantly, the present simulation model did not take the landing of planthoppers into account due to lack of knowledge about the landing process (Otuka et al., 2006). This means that none of the planthoppers in the model were assumed to land on the ground, probably causing overestimation of the size of migration clouds later in the simulation time. These facts may imply that the migration clouds at 36 h are less important than those at 24 h to estimate the destination regions of the first step of migration.

In the areas of southern China along the first-step migration path, rice plants of the early crop are transplanted from late March to late April (Matsumura et al., 2006), after which planthoppers can invade the rice plants. Since the early crop is harvested in the middle of July, the planthoppers that invade by the beginning of May or earlier can multiply by one or two generations on the early crop.

Generally, for *S. furcifera* the occurrence peak of the first generation after an invasion is larger than those of later generations, or they mainly emigrate after the multiplication of one generation (Kuno, 1968). Therefore, emigrations of *S. furcifera* from the invaded areas of the first step of migration may occur in early June in this case. In fact, as many as 54,272 planthoppers were caught by a light trap on 6 June 2006 at Dehua (solid star in Fig. 4) in Fujian province due to the southwesterly winds, and 84% of them were *S. furcifera* (Fujian PPQS, 2007). Their source was estimated to be Guangxi and Guangdong province (data not shown). On the contrary, *N. lugens* has a tendency to stay on a rice plant hill and multiply for a few generations (Kuno, 1968). After the first step of migration, *N. lugens* can spend two generations, about two months, on the early crop in southern China. In fact, trap catches of *N. lugens* in southern Jiangxi in 2006 formed peaks from 7 to 13 July (Jiangxi PPQS, 2007). For example, 38,912 *N. lugens* and 2,048 *S. furcifera* were caught by a light trap on 11 July 2006 at Wanan (12 in Fig. 4) (Jiangxi PPQS, 2007), and 95% were *N. lugens*. These facts imply that the density distributions of *S. furcifera* and *N. lugens* in southern China in early July, which is a prime time for migrations into Japan, might differ. If this is true, source location of the two species that migrate to Japan could be different. However, since available occurrence data in China are currently not sufficient to test this hypothesis, further study is required.

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