

Identifying Immigrating *Sogatella furcifera* (Hemiptera: Delphacidae) Using Field Cages: A Case Study in the Yuanjiang (Red River) Valley of Yunnan, China

Shao-Ji Hu,^{1,2,8} Li-Min Dong,^{3,8} Wen-Xin Wang,⁴ Sui-Yun Chen,^{5,6} and Hui Ye^{3,7}

¹Institute of International Rivers and Eco-security, Yunnan University, Kunming, 650500, China, ²Yunnan Key Laboratory of International Rivers and Transboundary Eco-security, Yunnan University, Kunming, 650500, China, ³School of Agriculture, Yunnan University, Kunming, 650500, China, ⁴Yuanjiang Plant Protection and Quarantine Station, Yuanjiang, 653300, China, ⁵Biocontrol Engineering Research Centre of Crop Disease & Pest, Yunnan University, Kunming, 650500, China, ⁶Biocontrol Engineering Research Centre of Plant Disease & Pest, Yunnan University, Kunming, 650500, China, and ⁷Corresponding author, e-mail: yehui@ynu.edu.cn
⁸Joint first authors.

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Abstract

The white-backed planthopper, *Sogatella furcifera* (Horváth), is a devastating migratory rice pest in South China; lack of effective methods to identify immigrating populations is the main cause of difficulties in outbreak forecasting, active prevention, and control. The current study set up field cages (2 × 2 × 3 m each, US-80 standard nylon mesh) in both early- and mid-season paddies in Yuanjiang (Red River) Valley in Yunnan, China, in 2012 and 2014. The immigrating population was successfully separated from the local population of *S. furcifera* and identified using statistical comparisons. The findings showed that densities of macropterous adults outside the cages were all significantly higher than those inside the cages on both early- and mid-season rice in both years, whereas the densities of young nymphs and old nymphs showed no significant differences. This indicated that immigrations were occurring, the earliest of which occurred on early-season rice in early May and reached its peak in mid-late May before a rapid collapse in both years. In contrast, the immigration on mid-season rice showed a continuous decline or fluctuation throughout the entire period. Analyses demonstrated that the migration process of *S. furcifera* in the Yuanjiang Valley features continuous immigration from the adjacent southern parts of Yunnan, which may represent most migration events in Yunnan during the outbreak period of a year. The findings of this case study could benefit our understanding of planthopper migration and outbreaks in other parts of China, especially where the outbreak pattern is very different from Yunnan.

Key words: migratory rice pest, planthopper, population density, demographic structure, field cage

The white-backed planthopper, *Sogatella furcifera* (Horváth), is a serious pest on Asian cultivated rice, *Oryza sativa* L. in South China and North Indochina (Catindig et al. 2009; Cheng 2009, 2015). Migratory behavior, high fecundity, and exponential population growth are the main causes of disastrous yield loss as well as the difficulty in performing accurate forecast and effective prevention (Gui et al. 2008; Cheng 2009; Hu et al. 2014, 2017).

It is generally accepted that, in South China, the northward migration of *S. furcifera* is mainly driven by monsoon currents (monsoons from the Pacific and Indian oceans) with the following two forms: 1) long-range migration in East and South China where the terrain is flat with less hills (Zhai 2011, Zhao et al. 2014) and 2) short-range migration from the south to adjacent north in West China where the terrain is very complex, featuring high-altitude

mountain ranges and deep valleys (Hu 2013; Zhao et al. 2014; Wu et al. 2017, 2018).

Light trapping and field surveys are two methods applied in the routine monitoring of *S. furcifera* in China, as described in ‘National Standard of the People’s Republic of China (GB/T 15794-2009): Rules of Investigation and Forecast for the Rice Planthopper (*Nilaparvata lugens* Stål and *Sogatella furcifera* (Horváth))’ (AQSIQ and SAC 2009). Light trapping can detect large-scale and abrupt immigration, but would be interrupted by power failures or bad weather (e.g., strong wind and precipitation), as well as being unable to track demographic change as it only collects macropterous adults. Although ovary examination can partly identify outbreak sources in a few previously reported cases, it is on one hand too sophisticated for most rural plant protection administrations to apply, and on the other hand, it has only been reported from areas

without overwintering populations (Lu et al. 2011, Chen et al. 2012, Zheng et al. 2014a, Ma et al. 2017). Hence, developing a monitoring method to compensate the existing measures would be necessary in the monitoring and forecasting of *S. furcifera* in China.

Forecast and prevention methods for different outbreak sources and migration patterns should be differentiated in the light of active prevention and control strategy. When a local or overwintering population forms an early outbreak source, management of winter paddies, and ratooning rice should be prioritized, followed by regular monitoring and management measures. When the first and heaviest outbreak sources usually come from immigrants, regular monitoring and preimmigration management should be taken equally (Hu 2013; Hu et al. 2014, 2017). Hence, accurate identification of outbreak sources and migration patterns of *S. furcifera* is crucial to formulate highly efficient prevention and control strategies.

The current study aimed to explore a new feasible survey method to identify the source composition of a population of *S. furcifera* by setting up field cages to separate the population into two parts (inside and outside the cages). After separation, both populations continue on their own demographic courses, but only the population outside the field cages is able to receive immigrants when migration occurs. The key purpose is to distinguish immigrants from the mixed population composed of local and migratory populations, as well as to obtain the scale and time of migration. By setting up field cages, using periodic surveys, and statistical comparisons of population densities, the current study has identified the source composition of *S. furcifera*. The methods and findings of this case study would provide an example for effective monitoring and forecast of *S. furcifera*, as well as some clues for finally elucidating the migration pattern and outbreak mechanisms of *S. furcifera* in South China.

Materials and Methods

Field Site

The field site of the current study was a rice paddy near the tropical dry-hot Red-River Valley in Yuanjiang County, Yunnan, China

(23°38'N, 101°29'E, 449 m a.s.l.; Fig. 1); one of the areas with severe outbreaks of *S. furcifera* during the past decade in Yunnan. Early-season rice and mid-season rice of a local variety 'Yi Xiang II' was grown continuously in this paddy, which was left vacant in winter months from December to the following February. Several independent surveys have confirmed the existence of a local (overwintering) population on the ratooning rice in vacant paddies in winter, and those due to immigrants in early- and mid-season rice (Liu et al. 1991; Dou et al. 2012; Hu et al. 2015a,b). The experimental area was located at the center of this paddy, with a size of 200 m². No pesticides and herbicides were used throughout the experiment, whereas regular managements such as water and fertilizers were applied as usual.

Experimental Devices

The experimental device was a cubic cage, with a dimension of 2 × 2 × 3 m. The frame of the cage was made of bamboo and nylon rope, and the ceiling and four walls were covered with US-80 standard nylon mesh (mesh opening 180 μm). The cage walls not only prevented small nymphs of *S. furcifera* from entering or escaping but also avoided significant ambient temperature and humidity difference by allowing ventilation through cage walls and ceiling. A zipper door was fixed to a 2 × 2 m wall for the investigator to enter and exit.

Three of such cages were installed at 10-m intervals into the paddy soil with four underground stands (40 cm each) and were reinforced against wind using nylon ropes at four apices (Fig. 2A). Three equally sized (6 m² each) rectangular areas without cages were also set at 10 m intervals next to the cages as controls (Fig. 2B; Supp Fig. 1 [online only]).

The cages were set up 3 days before each starting date. Prior to installation of the cages, 10 plots in the paddy were randomly selected to survey the population density of *S. furcifera* to avoid installing the cages in sites with obvious spatial density bias. After installation, walls with zippers were rolled up to leave them wide open until the starting date. This 'open door' period allows the

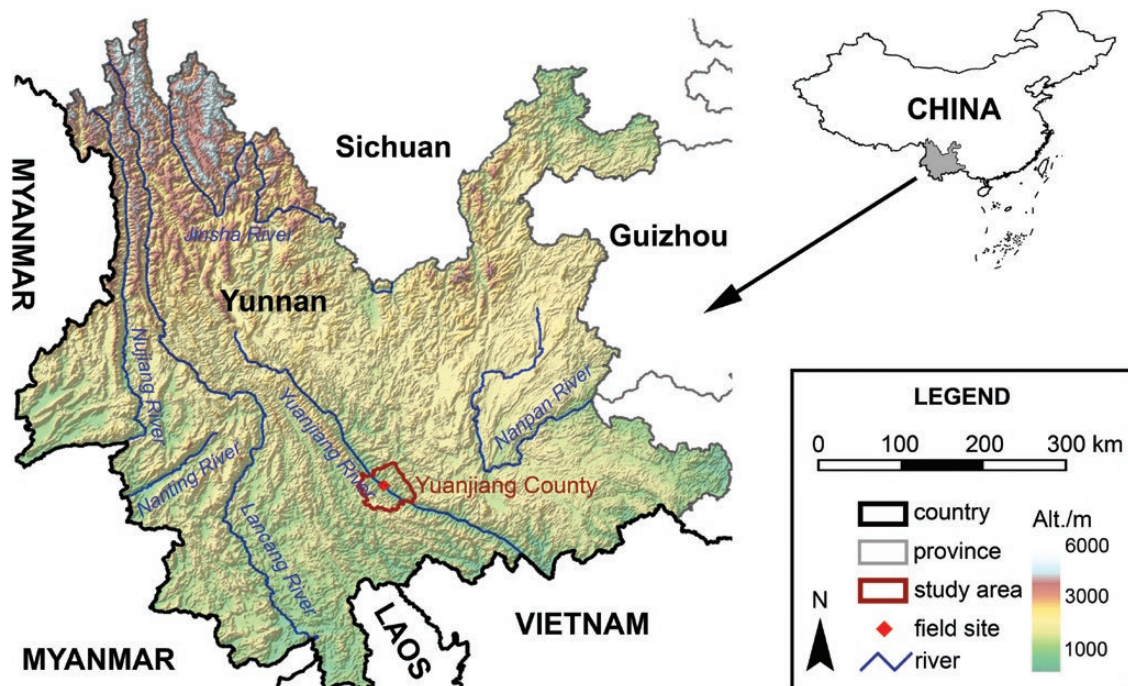


Fig. 1. Position of the field site and study area in Yunnan showing geographic topography and relevance with bordering countries and provinces

S. furcifera population as well as its natural enemies (e.g., predators and parasitoids) on both sides of each cage to interchange, in order to restore spatial density of *S. furcifera* and faunistic community due to artificial disturbances during the installation. The design and this installation protocol aimed to ensure the maximal environmental homogeneity inside and outside the cages.

Survey and Data Analysis

The field surveys were carried out in 2012 and 2014, respectively. Field survey on early-season rice in 2012 was started on 23 April 2012 and ended on 7 June 2012, the survey on mid-season rice in 2012 was started on 25 June 2012 and ended on 20 August 2012. Field survey on early-season rice in 2014 was started on 24 April 2014 and ended on 8 June 2014, and the survey on mid-season rice in 2014 was started on 25 June 2014 and ended on 15 August 2014.

The survey was performed every 5–6 d at 10:00–11:00 Beijing Time (GMT +08:00). Ambient temperature and humidity were measured by an Anymeter JB913 Hygrothermograph (Guangzhou, China) on both sides of each cage to test environmental homogeneity. The survey technique for *S. furcifera* population followed the plate-beating method described in the ‘National Standard of the People’s Republic of China (GB/T 15794-2009) Rules of Investigation and Forecast for the Rice Planthopper (*Nilaparvata lugens* Stål and *Sogatella furcifera* (Horváth)’ (AQSIQ and SAC 2009). Five rice plants (tillers) were randomly selected from each cage (IN) and each control area (OUT)

and beaten 10 times to shake the planthoppers off into a white plate (33 × 45 cm). The number of younger nymphs (YN, instars I–III), the number of older nymphs (ON, instars IV–V), the number of macropterous adults (MA), and the number of brachypterous adults (BA) of *S. furcifera* were counted and recorded. All collected planthoppers were released back to the paddy after counting, and the plate was cleaned for the next collecting and counting.

Statistical differences of ambient temperature and humidity measured on both sides of each cage were tested by an analysis of variance (ANOVA; Fisher 1970) using SPSS 17.0 (SPSS Inc., Chicago, IL). The recorded number of two nymphal categories and two adult forms were calculated into average population density (individuals per 100 tillers, ind/htl) according to GB/T 15794-2009, and plotted using Grapher 8.0 (Golden Software Inc., Golden, CO). Since the MA is the only migrating adult form (Denno and Roderick 1990), the ratio of MA to total nymphs (YN + ON) ($R_{A/N}$) were calculated, and an ANOVA (Fisher 1970) using SPSS 17.0 was performed to analyze the statistical difference of the average population density between the *S. furcifera* populations in the cage and that in the control area.

Results

Environment Homogeneity Tests

The ambient temperature inside the cages differed from that outside the cages by 0 to 0.4°C in 2012 and 2014 for early-season rice, and

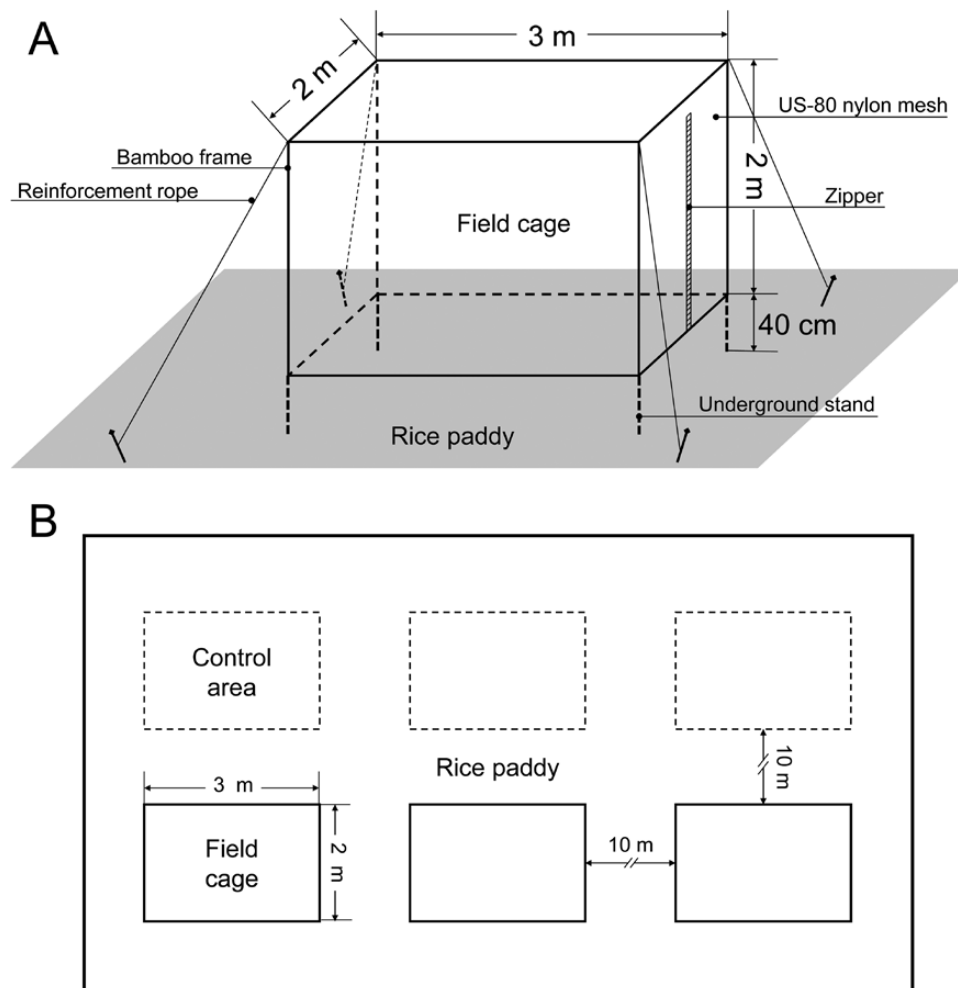


Fig. 2. (A) Structure of the experimental devices (field cages) and (B) installation and spatial configuration in the rice paddy

-0.3 to 0.7°C in 2012 and -0.4 to 0.5°C in 2014 for mid-season rice, respectively, but the result of ANOVA showed that this difference was not significant ($P > 0.1$ in all cases, Table 1). The humidity inside the cages is slightly higher than that outside the cages by an average of 0.8–2.3% in 2012 and 1.0–2.6% in 2014 for early-season rice ($P > 0.05$ in both cases, Table 1), and 0.9–1.8% in 2012 and 0.8–1.5% in 2014 for mid-season rice ($P < 0.01$ in both cases, Table 1), respectively.

Population Density and Demography in Early-Season Rice

The initial total density of IN and OUT were almost equivalent in both 2012 and 2014, and population growth was observed in both IN and OUT afterward. No BA were observed in both years. In 2012, total population density of IN reached the peak on 3 May 2012 (623.3 ind/htl), whereas that of OUT reached the peak on 8 May 2012 (760.0 ind/htl). In 2014, total population density of both groups reached the peak on 4 May 2014 (IN: 823.3 ind/htl; OUT: 1,116.7 ind/htl). After the peak period, total population density of both groups began to fall in general. During the entire experimental stage, total population density of OUT was higher than that of IN in both years (Fig. 3). The analysis showed a single continuous immigration event in each year, lasting for 20 d in 2012 and 30 d in 2014 (Fig. 3).

The initial percentage of YN, ON, and MA were almost equivalent in both 2012 and 2014 between IN and OUT. However, the percentage of macropterous adults in the control area (MA_{OUT}) grew much quicker than that inside the cage (MA_{IN}) when the population entered the growing stage. Especially after the peaking date, R_{AVN} of OUT multiplied compared to that of IN, e.g., after 13 May 2012 and after 14 May 2014, respectively (Tables 2 and 3).

In 2012, the density of young nymphs inside the cage (YN_{IN}) reached the peak on 3 May 2012 (390.0 ind/htl), 5 d later on 8 May 2012, the density of old nymphs inside the cage (ON_{IN}) reached the peak (173.3 ind/htl), and another 5 d later on 13 May 2012, the density of MA_{IN} reached the peak (276.7 ind/htl). The density of young nymphs in the control area (YN_{OUT}) and old nymphs in the control area (ON_{OUT}) reached the peak on the same day as that of IN (366.7 and 150.0 ind/htl, respectively), whereas MA_{OUT} reached the peak

10 d later on 18 May 2012 (576.7 ind/htl; Fig. 3). In 2014, YN_{IN} reached the peak on 4 May 2014 (436.7 ind/htl), whereas ON_{IN} and MA_{IN} both reached the peak 5 d later on 9 May 2014 (300.0 and 296.7 ind/htl, respectively). YN_{OUT} and ON_{OUT} both reached the peak on the same day as that of IN (460.0 and 296.7 ind/htl, respectively), whereas MA_{OUT} reached the peak on 14 May 2014 (566.7 ind/htl; Fig. 3).

Population Density and Demography in Mid-Season Rice

The initial total density of OUT was higher than that of IN in both 2012 and 2014. Similar to the early-season rice, no BA were observed in both years. In 2012, total population density fell continuously afterward in both groups, in general, whereas three small peaks were observed in OUT on 30 June 2012 (236.7 ind/htl), 10 July 2012 (173.3 ind/htl), and 30 July 2012 (170.0 ind/htl). In 2014, total population density showed a fluctuating pattern during the entire experimental stage with three small peaks observed in OUT on 10 July 2014 (20.0 ind/htl), 20 July 2014 (23.3 ind/htl), and 5 August 2014 (23.3 ind/htl). During the entire experimental stage, total population density of OUT was higher than that of IN in both years (Fig. 4). The analysis showed no obvious immigration peaking event in both years except for MA_{OUT} being significantly higher than MA_{IN} during most of the experimental period (Fig. 4).

The percentage of YN and ON in IN were mostly higher than that in OUT in 2012. However, the percentage of MA_{OUT} were obviously higher than MA_{IN} from 5 July 2012 to 10 August 2012. The R_{AVN} of OUT was higher than that of IN in 2012 except for on 30 June 2012 (Table 4). A similar pattern was observed in 2014 despite lower population density. The percentage of YN and ON in IN were either higher than that in OUT or almost equivalent, whereas the percentage of MA_{OUT} were obviously higher than MA_{IN} , as well as R_{AVN} (Table 5).

In 2012, the density of YN_{IN} reached the peak on 20 July 2012 (93.3 ind/htl), two peaks of ON_{IN} were observed on 25 June 2012 and 10 August 2012 (23.3 and 20.0 ind/htl, respectively), similarly, two peaks of MA_{IN} were observed on 25 June 2012 and 5 August 2012 (163.3 and 26.7 ind/htl, respectively). Outside the cages, the

Table 1. ANOVA for the difference of ambient temperature and humidity inside and outside the cages in 2012 and 2014, mean Δ indicates the differences of mean ambient temperature (°C) or humidity (RH%) between inside and outside the cages

Year	Rice stage	Variable	Source of variation	df	Mean square	Mean Δ	F	P
2012	Early-season	Temperature	Between groups	1	0.417	0.2°C	0.064	0.801
			Within groups	58	6.485	–	–	–
		Humidity	Between groups	1	36.193	1.6%	3.255	0.076
			Within groups	58	11.118	–	–	–
	Mid-season	Temperature	Between groups	1	0.551	0.2°C	0.094	0.759
			Within groups	70	5.836	–	–	–
	Humidity	Between groups	1	36.551	1.4%	9.156	0.003	
		Within groups	70	3.992	–	–	–	
2014	Early-season	Temperature	Between groups	1	0.504	0.2°C	0.093	0.761
			Within groups	58	5.02	–	–	–
		Humidity	Between groups	1	38.560	1.6%	1.349	0.250
			Within groups	58	11.118	–	–	–
	Mid-season	Temperature	Between groups	1	0.509	0.2°C	0.131	0.718
			Within groups	64	3.874	–	–	–
		Humidity	Between groups	1	22.342	1.2%	8.236	0.006
			Within groups	64	2.713	–	–	–

density of YN_{OUT} reached the peak on 25 July 2012 (83.3 ind/htl), two peaks of ON_{OUT} were observed on 25 June 2012 and 30 July 2012 (20.0 and 16.7 ind/htl, respectively), whereas MA_{OUT} reached the peak on 30 June 2012 (193.3 ind/htl; Fig. 4). In 2014, YN_{IN} reached the peak on 25 July 2014 (6.7 ind/htl), ON_{IN} reached the peak on 5 July 2014 and 30 July 2014 (both 3.3 ind/htl), and MA_{IN} reached the peak on 10 July 2014 and 30 July 2014 (both 6.7 ind/htl). YN_{OUT} and ON_{OUT} reached the peak on 20 July 2014 (both 6.7 ind/htl), and MA_{OUT} reached the peak on 5 August 2014 (16.7 ind/htl) (Fig. 4).

Statistical Comparison of Population Demography

The ANOVA showed that the density of MA_{OUT} was significantly higher than MA_{IN} in early-season rice stage, whereas the density difference of all nymphs between IN and OUT was not significant (Table 6). ANOVA for each survey also did not show a significant difference between MA_{OUT} and MA_{IN} in the beginning of the experiment but showed a significant difference after 28 April 2012 and 29 April 2014. Statistical analysis also detected no significant difference of all nymphs between IN and OUT (Supp Tables 1 and 2 [online only]).

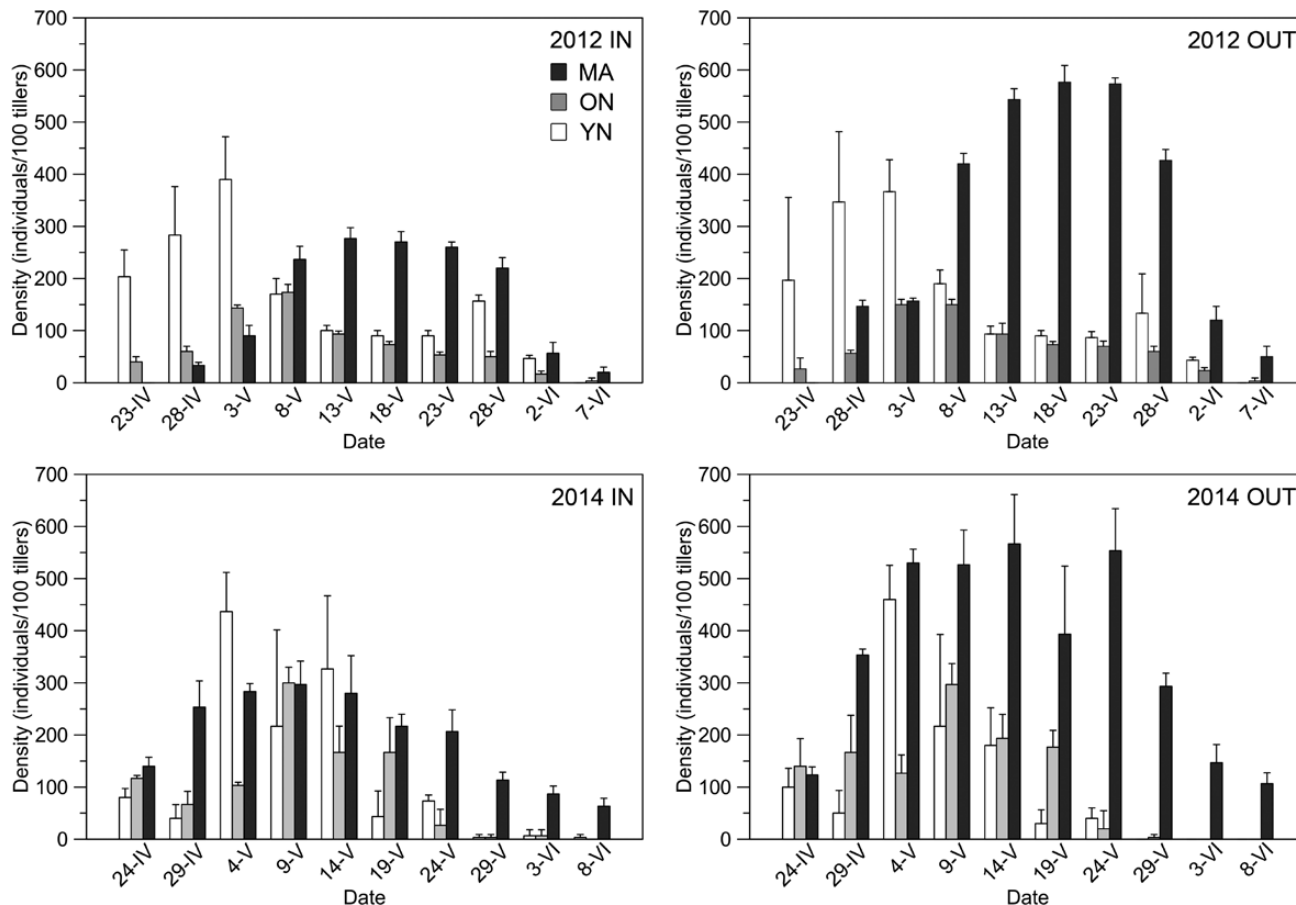


Fig. 3. Mean densities (with standard deviations) of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in early-season rice in 2012 and 2014, YN: young nymph (instars I–III), ON: older nymph (instars IV–V), and MA: macropterous adults

Table 2. Percentage of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in early-season rice in 2012

Date	IN				OUT			
	YN%	ON%	MA%	$R_{A/N}$	YN%	ON%	MA%	$R_{A/N}$
4.23	83.6	16.4	0.0	0.0	88.1	11.9	0.0	0.0
4.28	75.2	15.9	8.8	0.1	63.0	10.3	26.7	0.4
5.3	62.6	23.0	14.4	0.2	54.5	22.3	23.3	0.3
5.8	29.3	29.9	40.8	0.7	25.0	19.7	55.3	1.2
5.13	21.3	19.9	58.9	1.4	12.8	12.8	74.4	2.9
5.18	20.8	16.9	62.3	1.7	12.2	9.9	77.9	3.5
5.23	22.3	13.2	64.5	1.8	11.9	9.6	78.5	3.7
5.28	36.7	11.7	51.6	1.1	21.5	9.7	68.8	2.2
6.2	38.9	13.9	47.2	0.9	23.2	12.5	64.3	1.8
6.7	0.0	14.3	85.7	6.0	0.0	6.3	93.8	15.0

YN: young nymph (instars I–III), ON: older nymph (instars IV–V), $R_{A/N}$: ratio of adult to total nymphs (young nymphs + old nymphs).

Table 3. Percentage of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in early-season rice in 2014

Date 2014	IN				OUT			
	YN%	ON%	MA%	$R_{A/N}$	YN%	ON%	MA%	$R_{A/N}$
4.24	23.8	34.7	41.6	0.7	27.5	38.5	33.9	0.5
4.29	11.1	18.5	70.4	2.4	8.8	29.2	62.0	1.6
5.4	53.0	12.6	34.4	0.5	41.2	11.3	47.5	0.9
5.9	26.6	36.9	36.5	0.6	20.8	28.5	50.6	1.0
5.14	42.2	21.6	36.2	0.6	19.1	20.6	60.3	1.5
5.19	10.2	39.1	50.8	1.0	4.6	27.3	68.0	2.1
5.24	23.9	8.7	67.4	2.1	6.5	3.3	90.2	9.2
5.29	2.8	2.8	94.4	17.0	0.0	1.1	98.9	88.0
6.3	6.7	6.7	86.7	6.5	0.0	0.0	100.0	∞
6.8	5.0	0.0	95.0	19.0	0.0	0.0	100.0	∞

YN: young nymph (instars I–III), ON: older nymph (instars IV–V), $R_{A/N}$: ratio of adult to total nymphs (young nymphs + old nymphs).

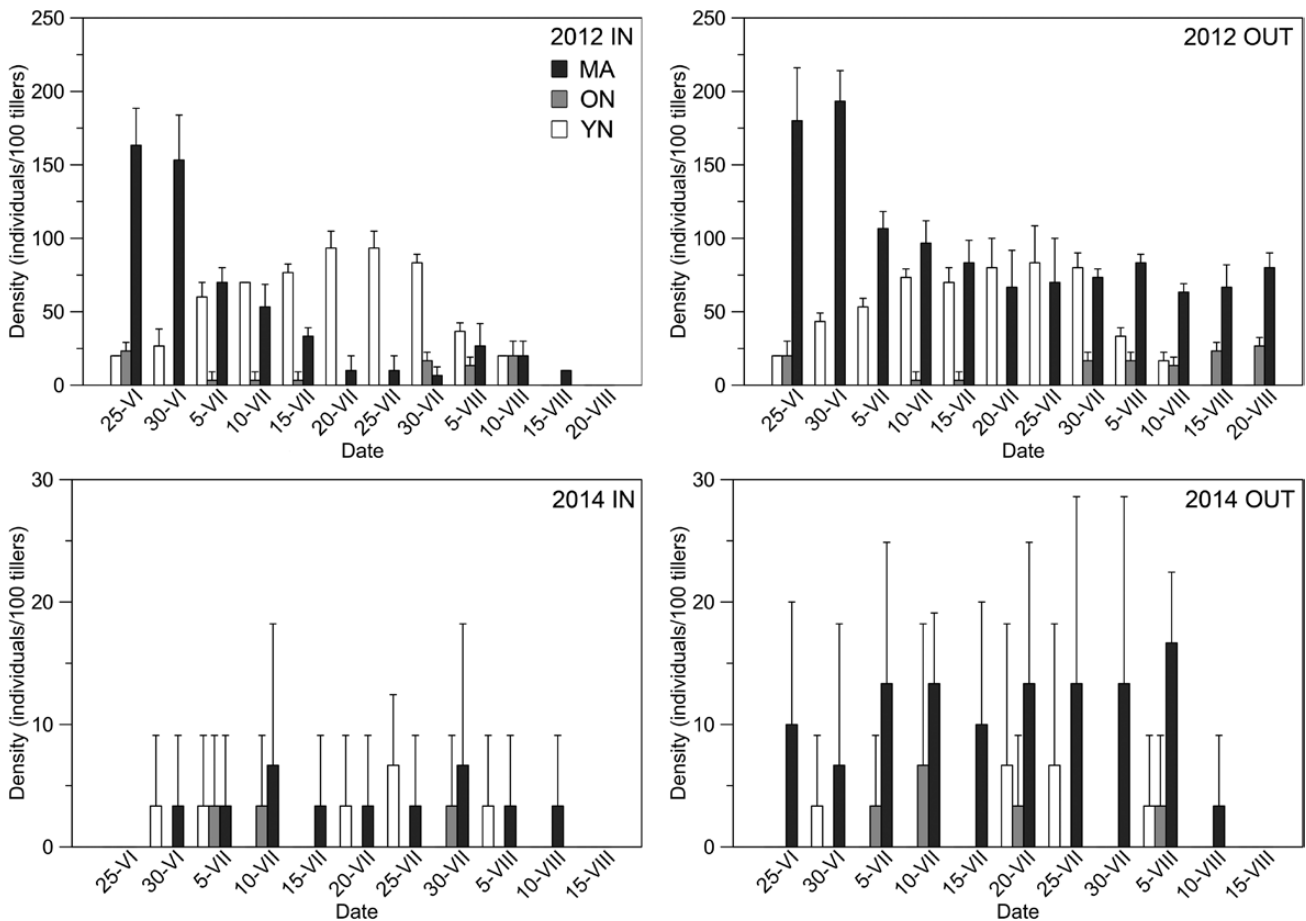


Fig. 4. Mean densities (with standard deviations) of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in mid-season rice in 2012 and 2014, YN: young nymph (instars I–III), ON: older nymph (instars IV–V), and MA: macropterous adults

In mid-season rice stage, the density of MA_{OUT} was still significantly higher than that of MA_{IN} , whereas the density difference of all nymphs was still not significant (Table 7). ANOVA of each survey showed certain difference between OUT and IN. In 2012, the density of MA_{OUT} was significantly higher than that of MA_{IN} except for the first two surveys on 25 June 2012 and 30 June 2012 (Supp Table 3 [online only]). In 2014, however, the density difference between MA_{OUT} and MA_{IN} was not significant except for that on 5 August 2014 (Supp Table 4 [online only]).

Discussion

Maximal environment homogeneity is crucial to ensure all subsequent analysis and interpretation when using field cages. Our ANOVA showed no significant difference for ambient temperature in all cases, but flagged significant difference for humidity in the mid-season rice stage for both years (Table 1). The authors believed that the humidity difference in this period was caused by frequent precipitation events in the wet season in Yunnan (Wang and Zhang

Table 4. Percentage of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in mid-season rice in 2012

Date 2012	IN				OUT			
	YN%	ON%	MA%	$R_{A/N}$	YN%	ON%	MA%	$R_{A/N}$
6.25	9.7	11.3	79.0	3.8	9.1	9.1	81.8	4.5
6.30	14.8	0.0	85.2	5.8	18.3	0.0	81.7	4.5
7.5	45.0	2.5	52.5	1.1	33.3	0.0	66.7	2.0
7.10	55.3	2.6	42.1	0.7	42.3	1.9	55.8	1.3
7.15	67.6	2.9	29.4	0.4	44.7	2.1	53.2	1.1
7.20	90.3	0.0	9.7	0.1	54.5	0.0	45.5	0.8
7.25	90.3	0.0	9.7	0.1	54.3	0.0	45.7	0.8
7.30	78.1	15.6	6.3	0.1	47.1	9.8	43.1	0.8
8.5	47.8	17.4	34.8	0.5	25.0	12.5	62.5	1.7
8.10	33.3	33.3	33.3	0.5	17.9	14.3	67.9	2.1
8.15	0.0	0.0	100.0	∞	0.0	25.9	74.1	2.9
8.20	—*	—	—	—	0.0	25.0	75.0	3.0

YN: young nymph (instars I–III), ON: older nymph (instars IV–V).

*Not calculated when all variables are zero.

Table 5. Percentage of *S. furcifera* stages in the cage (IN) and in the control area (OUT) in mid-season rice in 2014

Date 2014	IN				OUT			
	YN%	ON%	MA%	$R_{A/N}$	YN%	ON%	MA%	$R_{A/N}$
6.25	—*	—	—	—	0.0	0.0	1.0	∞
6.30	0.5	0.0	0.5	1.0	0.3	0.0	0.7	2.0
7.5	0.3	0.3	0.3	0.5	0.0	0.2	0.8	4.0
7.10	0.0	0.3	0.7	2.0	0.0	0.3	0.7	2.0
7.15	0.0	0.0	1.0	∞	0.0	0.0	1.0	∞
7.20	0.5	0.0	0.5	1.0	0.3	0.1	0.6	1.3
7.25	0.7	0.0	0.3	0.5	0.3	0.0	0.7	2.0
7.30	0.0	0.3	0.7	2.0	0.0	0.0	1.0	∞
8.5	0.5	0.0	0.5	1.0	0.1	0.1	0.7	2.5
8.10	0.0	0.0	1.0	∞	0.0	0.0	1.0	∞
8.15	—	—	—	—	—	—	—	—

YN: young nymph (instars I–III), ON: older nymph (instars IV–V).

*Not calculated when all variables are zero.

Table 6. ANOVA of population density of *S. furcifera* inside and outside the cages in early-season rice in 2012 and 2014

Year	Life stage	Source of variation	df	Mean square	F	P
2012	YN	Between groups	1	41.667	0.003	0.959
		Within groups	58	15,754.770	—	—
	ON	Between groups	1	0.000	0.000	1.000
		Within groups	58	2540.920	—	—
	MA	Between groups	1	360,375.000	11.721	0.001
		Within groups	58	30,745.575	—	—
2014	YN	Between groups	1	3526.667	0.145	0.705
		Within groups	58	24,337.356	—	—
	ON	Between groups	1	4166.667	0.415	0.522
		Within groups	58	10,049.540	—	—
	MA	Between groups	1	433,500.000	20.355	0.000
		Within groups	58	21,927.241	—	—

2002). However, despite statistical significance, the absolute difference was only between 0.8 and 1.8% (Table 1), and humidity variation at this scale does not influence the development and population growth of *S. furcifera* (Ye et al. 1992).

Apart from the precautionary points mentioned in connection with the design and installation of the field cages, which ensure maximal environmental homogeneity, the following points should also

be noted during the survey and data analysis. The MA is the only flying (migrating) form (Denno and Roderick 1990); therefore, significant density fluctuation of MA is widely adopted as an important criterion of migration activities or events (AQSIQ and SAC 2009). When using field cages to investigate planthopper migration, the density of MA is also the key statistical variable to detect immigration. However, the density of nymphs and their demographic

Table 7. ANOVA of population density of *S. furcifera* inside and outside the cages in mid-season rice in 2012 and 2014

Year	Life stage	Source of variation	df	Mean square	F	P
2012	YN	Between groups	1	88.889	0.080	0.778
		Within groups	70	1110.794	–	–
	ON	Between groups	1	200.000	1.928	0.169
		Within groups	70	103.730	–	–
	MA	Between groups	1	46,005.556	17.773	0.000
		Within groups	70	2588.492	–	–
2014	YN	Between groups	1	0.000	0.000	1.000
		Within groups	64	21.591	–	–
	ON	Between groups	1	6.061	0.432	0.513
		Within groups	64	14.015	–	–
	MA	Between groups	1	801.515	12.126	0.001
		Within groups	64	66.098	–	–

rhythms should also be measured and compared with ensure the statistical difference of MA is not caused by other factors, e.g., nonsynchronised population growth rates inside and outside the cage due to environmental heterogeneity, or overcrowding induced population change (Ikeshoji 1977, Kamioka and Iwasa 2017). When using this method on other planthoppers or populations in which brachypterous adults are more commonly encountered (e.g., *Nilaparvata lugens*), this form should not be neglected even though it is not the flying/migrating form.

The statistical comparison of both early-season rice and mid-season rice in 2012 and 2014 showed that the population density of OUT was significantly higher than that of IN, and MA contributed to the majority of such differences, whereas densities of the other two demographic components (YN and ON) were similar (Figs. 2 and 3; Tables 6 and 7). Since field cages separated *S. furcifera* populations of IN and OUT with maximal environmental homogeneity, such obvious and continuous high density of MA_{OUT} and its associated nonaccordance with the density of nymphs (more obvious in early-season rice than in mid-season rice) could only be logically explained by the immigration of *S. furcifera* into the study site via MA. The comparative analysis detected significant differences between MA_{OUT} and MA_{IN} in all experimental sets, whereas densities of the other two demographic components (YN and ON) were similar (Figs. 2 and 3; Tables 2–7). This can only be logically explained by the existence of immigrating *S. furcifera* in the form of MA in the study site.

Temporal demographic changes between early-season rice and mid-season rice are different regardless of being inside or outside the cages (Figs. 2 and 3). In the early-season rice of 2012 and 2014, compared with the gradual growth and decline of MA in IN populations, abrupt growth and decline were observed in OUT populations, indicating an immigration event near the rapid growth phase and possible emigration near the sudden decline (Fig. 3). However, such a tendency was not clear in mid-season rice of both years (Fig. 4). The authors believe that, apart from the lower population density (especially in 2014), such a difference was partly caused by the growing season of the mid-season rice in Yuanjiang, which lasts from mid-late June to late August. During this period, *S. furcifera* has almost passed its main migration and outbreak stage in this area (Liu et al. 1991, Dou et al. 2012), hence, little abrupt growth caused by immigration can be observed (Fig. 4). However, significant statistical differences can also be detected on MA in mid-season rice (Tables 4, 5, and 7), because migration activities during the entire early-season rice period already created a continuous and stable migratory flow of *S. furcifera* through the study site, making the density of MA_{OUT} still higher than MA_{IN}.

The current study showed that in central-southern Yunnan, represented by Yuanjiang, the outbreak of *S. furcifera* was mainly caused by continuous immigration initiated from late April to early-May, peaking in mid-late May (Fig. 3) and reducing later (Fig. 4). The authors believe that the continuous migration observed in the current study may well represent the short-range migration form of *S. furcifera* in Yunnan under normal circumstances, as reported by other research (Hu 2013; Zheng et al. 2014b; Li et al. 2017a,b; Wang et al. 2017; Wu et al. 2017). This migration pattern is remarkably different from some previously reported cases in a few localities in Yunnan and South to East China, which were characterized by a large abrupt immigration of macropterous adults in a very short period of time (e.g., overnight) and from a very distant source (Shen et al. 2011, 2016; Jiang et al. 2012; Wu et al. 2012; Zhao et al. 2014; Bi et al. 2017; Hu et al. 2017). Such migration events in South and East China are facilitated by flat terrain as mentioned previously; but in Yunnan, they are probably caused by occasional weather events or special terrain features (which may promote landings). Field cages could be used in association with other monitoring methods, e.g., light trapping, field surveys, and ovary examination, to finally clarify the migration process of *S. furcifera* in those localities.

Supplementary Data

Supplementary data are available at *Journal of Insect Science* online.

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