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Projecting Distribution of the Overwintering Population of *Sogatella furcifera* (Hemiptera: Delphacidae), in Yunnan, China With Analysis on Key Influencing Climatic Factors

Shao-Ji Hu,[1,*] Xiao-Fei Liu,[1,*] Da-Ying Fu,[2,*] Wei Huang,[3] Xue-Ying Wang,[1] Xiao-Jun Liu,[1] Jian-Ping Lü,[4] and Hui Ye[1,5]

[1]Laboratory of Biological Invasion and Ecosecurity, Yunnan University, Kunming 650091, China
[2]School of Life Sciences, Southwest Forest University, Kunming 650224, China
[3]Yunnan Climate Center, Kunming 650034, China
[4]Plant Protection and Quarantine Station of Yunnan Province, Kunming 650034, China
[5]Corresponding author, e-mail: yehui@ynu.edu.cn
*These authors contributed equally to this work.

ABSTRACT. *Sogatella furcifera* (Horváth) is the most threatening migratory rice pest in Yunnan, China. *S. furcifera* overwinters in low-altitude basins and valleys in southern Yunnan and migrates northward in spring and summer of the following year, causing serious damage during migration. The overwintering distribution, areas, and spatial pattern of *S. furcifera* are relevant to the migration and outbreak of this pest. Based on a 4-yr field survey (2010–2013), this study projected areas suitable for *S. furcifera* to overwinter using a species distribution model, and analyzed the key influencing climatic factors using principal component analysis (PCA) and ecological niche factor analysis (ENFA). Our field survey showed that the northern latitudinal- and upper elevation limits of overwintering *S. furcifera* was 25.4° N and 1,608 m in western Yunnan and 24.2° N and 1,563 m in eastern Yunnan. The species distribution model produced a fragmented distribution pattern, with most of which in western Yunnan and only a few in eastern Yunnan. The PCA and ENFA analyses showed that the mean temperature of the driest quarter and the precipitation of the coldest quarter significantly influenced the distribution of *S. furcifera* in winter. The results suggested that the complex topography, spatial differences in winter temperatures, and host availability altogether determined the distribution of overwintering *S. furcifera*. Compared with previous surveys, the northern latitudinal- and upper elevation limits of overwintering *S. furcifera* were higher, while the population became rarer in some suitable areas due to change of farmland utilization in winter and possibly climate change.

Key Words: species distribution model (SDM), bioclimatic factor, ecological niche factor analysis (ENFA), maximum entropy model (MaxEnt), rice pest

The white-backed planthopper, *Sogatella furcifera* (Horváth) (Hemiptera: Delphacidae), is among the most devastating pests on Asian cultivated rice, *Oryza sativa* L., in southern China and northern Indochina (Catindig et al. 2009, Cheng 2009). The continuous outbreak of *S. furcifera* in the last decade has caused immeasurable yield loss to the rice production of this region. Yunnan province in southwestern China is one of the most impacted areas of *S. furcifera* infestation. Since the major outbreak of *S. furcifera* in 2007 (Fu et al. 2009), the situation of planthopper infestation remained intensified and then escaladed in the last few years.

S. furcifera migrates from the south to the north annually from late March to August, eventually covering all rice-planting areas in Yunnan (Hu et al. 1988, Gui et al. 2008). Severe damage occurs to rice along the course of migration. Previous studies have shown that migration and high reproduction rate are the main causes of population eruption (Gui et al. 2008, Cheng 2009, Hu et al. 2014). The distribution, population density, and habitat of overwintering *S. furcifera* has a direct influence on the range and density of migratory populations in the coming year (Denno and Roderick 1990). Therefore, studying overwintering *S. furcifera* will help understand its migratory dynamics and population eruptions.

S. furcifera is able to overwinter in southern Yunnan in vacant paddies with ratooning rice (*Oryza sativa* L.) and other Poaceae grasses (i.e., *Leersia japonica* Honda being the most common species) (Yang et al. 1982; Liu et al. 1991; Tao and Sogawa 2000; Hu et al. 2012, 2015). However, recent studies of overwintering *S. furcifera* were unable to identify the current distribution range and areas. This may be in

part due to the significant change in winter farmland utilization in the region (YBS 1990, 2011). Hence, it is necessary to carry out a new survey for overwintering *S. furcifera* in Yunnan, to clarify its current spatial distribution, as well as to explain climatic factors that may affect these.

Distribution projections based on the occurrence data and bioclimate factors using various species distribution models (SDMs), for instance, CLIMEX (climate change experiment), ENFA (ecological niche factor analysis), GARP (genetic algorithm for rule-set prediction), and MaxEnt (maximum entropy), have been widely applied to many insects of agronomic interest, especially alien invasive species, to study their distribution patterns and predict their potential risks (Rafoss and Sæthre 2003, Sutherst and Maywald 2005, Peterson and Nakazawa 2008, Zeng et al. 2012, Liu et al. 2013). Among these analyses, ENFA and MaxEnt are the most frequently applied SDMs which project the suitable area of a species using the presence-only data without depending on the complicated bionomical parameters of the focal species (Hirzel et al. 2002, Elith and Graham 2009).

Based on the above-mentioned necessity to reevaluate the current distribution of overwintering *S. furcifera* in Yunnan and the recent advances in SDMs, this study was designed to project the suitable areas of overwintering *S. furcifera* in Yunnan based on the presence data obtained from a 4-yr field survey. It also analyzed the key influential climatic factors of overwintering *S. furcifera*. The results of this study could be useful for elucidating the distribution pattern of *S. furcifera* and key climatic factors influencing its distribution, to form a better understanding of the spatial and temporal dynamics of the population of

S. furcifera and to provide information for the formulation of an outbreak assessment for this rice pest.

Materials and Methods

Field Survey. The survey range was set approximately between 25° N and the southern border of Yunnan Province, based on previous studies on the overwintering rice planthoppers (Liu et al. 1991, Hu 2009) (Supp Table 1 and Supp Fig. 1 [online only]). Supplementary survey areas were also set in valleys and basins that occur north of the survey range to ensure the identification of the northern-most boundary. The survey range was then divided into a 50 by 50 km grid, and field sites were established within each grid based on the following two criteria: 1) at least one site was below 1,500 m elevation; and 2) one site was between 1,500 and 1,700 m above sea level (a.s.l.) in order to determine the upper-elevation distribution limit of overwintering *S. furcifera*. Previous studies have found that *S. furcifera* cannot survive the winter in areas above 1,700 m (Liu et al. 1991), therefore, no field sites were set above this altitude level. In total, 116 field sites were established in this study, and the geographical coordinates of each site was recorded using a Garmin eTrex Vista GPS handset (Version 3.2; Garmin Ltd., Taiwan).

Field surveys were carried out in January and February, 2010–2013. Habitat types 1, 2, 3, and 5, described by Hu et al. (2012), were selected to represent the winter habitats due to the large numbers of *S. furcifera* that were captured from these habitats in that study. Since the size of ratooning rice and other related Poaceae grasses are shorter in winter and the population density of *S. furcifera* is generally lower, instead of using a 33 by 45 cm white plate, a sweeping net (50 cm in diameter, 85 cm in depth, 90-mesh soft nylon; AQSIQ and SAC 2009) was used to sample for planthoppers in three 2 by 2 m areas within each habitat type within each study site. During sampling, each 2 by 2 m area was swept 20 times to minimize sampling bias. All captured planthoppers (including both adults and nymphs) were preserved in 95% ethanol, and identified in the laboratory using the descriptions by Ballou et al. (1987), Asche and Wilson (1990), and Chen et al. (2000).

Data Analysis. Presence-only data are commonly used in evaluating species suitability and potential distribution range (i.e., Pearson et al. 2007; Hengl et al. 2009; Liu et al. 2011, 2013), as it excludes absence data, which could be unreliable (Gu and Swihart 2004, Jiménez-Valverde et al. 2008, Lobo et al. 2010). Therefore, only field sites with the presence of *S. furcifera* were used as data points in subsequent analyses (Supp Table S1 [online only]; Fig. 1A). Decimal coordinates (with four decimal places) of each data points were arranged according to the

user manuals of Biomapper 4.0 (Hirzel et al. 2002) (www2.unil.ch/biomapper) and MaxEnt 3.3.3k (Phillips et al. 2004, 2006) (www.cs. princeton.edu/~schapire/maxent).

Data of ecogeographical variables (EGVs) were downloaded from WorldClim (www.worldclim.org). The bioclimatic (BioClim) dataset (averaged over 1950–2000) was used in the present research for its biological and ecological properties. The r29 dataset with 30 arc second resolution was obtained and then cropped by the political boundary of Yunnan Province in GlobalMapper 11.0 (www.globalmapper.com), both of the IDRISI (Eastman 1997) and the ASCII formats were used in accordance with Biomapper 4.0 and MaxEnt 3.3.3k, respectively. Host plant (*O. sativa*) and habitat are important environmental factors influencing the distribution of *S. furcifera*; however, this study could not include these parameters because the spatial data of rice distribution in Yunnan, especially the distribution of ratooning rice in winter, is not available to date.

In an attempt to analyze the distribution prevalence of overwintering *S. furcifera*, values of eight winter-related EGVs including, isothermality (Bio3), temperature seasonality (Bio4), minimum temperature of the coldest month (Bio6), mean temperature of the driest quarter (Bio9), mean temperature of the coldest quarter (Bio11), precipitation of the driest month (Bio14), precipitation of the driest quarter (Bio17), and precipitation of the coldest quarter (Bio19) in the overwintering region of *S. furcifera*, as well as the entire Yunnan Province were extracted using DIVA-GIS 5.7 (www.dive-gis.org) (Hijmans et al. 2012). Distribution frequencies were calculated in Biomapper 4.0. Then, key influencing factors were screened using both of principal component analysis (PCA) and ENFA function in Biomapper 4.0. The importance of factors was measured using the jackknife method in MaxEnt 3.3.3k with 1,000 iterations.

The PCA and the ENFA analyses calculated score matrices for all factors, among which the first *n* factors with a cumulative percentage of variance over 85% were taken as the most important, and the EGVs' importance were determined by the absolute values of scores obtained in the analyses (Pearson 1901, Hirzel et al. 2002, Abdi and Williams 2010). Compared with the PCA analysis, results of the ENFA analysis bear ecological meanings, where absolute scores represent the extent of distribution preference of the focal species in comparison to environmental backgrounds, and the signs (+ or −) flag the focal species' preference to extreme environmental backgrounds (Hirzel et al. 2002). This study applied both analyses for cross-validation, where 0.5 and 0.2 were taken as the boundary absolute scores in screening EGVs in the PCA and the ENFA analyses, respectively. However, the
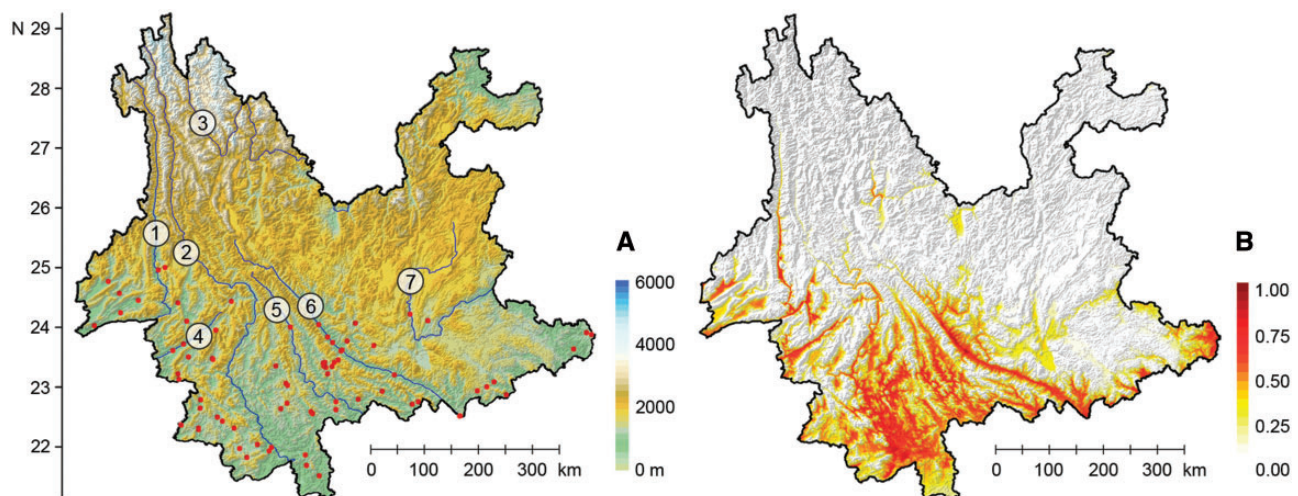

Fig. 1. Distribution of presence sites (red dots) in field survey with major rivers (from the west to the east: 1. Nujiang River, 2. Lancang River, 3. Jinsha River, 4. Nanding River, 5. Lixian River, 6. Yuanjiang River, and 7. Nanpan River) in Yunnan (A) and the suitability maps of overwintering *S. furcifera* produced by MaxEnt (B), color scales indicate altitudes and suitability levels, respectively.

ecological interpretations of the EGVs entirely depended on the ENFA analysis.

The selected EGVs were assigned to the MaxEnt analysis to project suitable areas based on the presence data points, among which 25% were extracted for random testing. The logistic output method was selected to estimate the distribution (or presence) probability of *S. furcifera* considering certain assumptions of species' prevalence and sampling effort (Elith et al. 2010). The resulting map was saved as ASCII format and then redrawn using Surfer 10.0 (Golden Software Inc., Golden, CO). Model robustness was evaluated using the receiver operation curve (ROC) and the area under the ROC curve (AUC), where an AUC value [AUC ∈ (0, 1)] that approaches 1.0 is usually considered acceptable and it should be rejected when approaching the random turquoise line of 0.5 (Fielding and Bell 1997).

Results

Overview of Presence Sites. The 4-yr field survey collected *S. furcifera* from 77 sites (presence sites) out of the total 116 field sites surveyed (Supp Table S1 [online only]). Presence of *S. furcifera* was inconsistent among sample years for 83.1% of the presence sites. Most of the presence sites (75.3%) were located on the western side of the Ailao Mountains, whereas the remaining sites were located on the eastern side. The northern limit of the 77 sites was at 25.4° N in western Yunnan (Wayao, Baoshan, Baoshan Prefecture), whereas the limit in the eastern portion was only 24.2° N (Panxi, Huaning, Yuxi Prefecture) (Fig. 1A). Altitudes of the 77 presence sites ranged from 100 to 1,608 m a.s.l., and 93.5% of the total presence sites were situated below 1,500 m a.s.l. (Supp Table S1 [online only]). The site in Hekou (Honghe Prefecture) had the lowest altitude and the site in Longba (Mojiang, Pu'er Prefecture) had the highest

Key Influencing Factors. Most of the frequency distributions of the eight overwintering area EGVs of *S. furcifera* showed different deviations from the normal distributions of the same EGVs for the entire Yunnan Province. Among which, the temperature-related EGVs (Bio6, Bio9, and Bio11) deviated toward the upper limits as expected, and the water-related EGVs (Bio14, Bio17, and Bio19) showed slight deviation toward the upper limits (Fig. 2). For EGVs like Bio3 and Bio4, the frequency distributions of the overwintering area showed deviation in the upper and lower limits, respectively (Fig. 2).

In both the PCA and ENFA analyses, Bio9 was selected as the most important temperature-related EGV (−0.914 in PCA; 0.506 in ENFA) whereas Bio19 was the most important water-related EGV (−0.814 in PCA; 0.229 in ENFA) (Table 1). The scores of all other EGVs were listed in Table 1. The jackknife analysis for importance produced similar results with the PCA and the ENFA analyses, demonstrating that Bio9 was the most important temperature-related EGV for estimating the distribution of *S. furcifera* in winter (1.047), and Bio19 was the most important water-related EGV (0.292) (Fig. 3A).

Suitable Overwintering Areas of *S. furcifera*. Eight EGVs selected by the PCA and ENFA analyses were utilized in the MaxEnt projection of the suitable overwintering areas for *S. furcifera*. ROC and AUC were generated (Fig. 3B and C), where the AUC value of training data was 0.907 and that of testing data was 0.922.

In the projection result, the northern limit of the suitable areas (suitability > 0.5, red colored) was 25.7° N in the west, situated at the middle portion of the Nujiang River Valley, whereas the northern limit was 23.9° N in the east, at the northeastern corner of Funing County (Wenshan Prefecture) (Fig. 1B). The projected northern limit in the west was slightly higher than that of the presence data points (Fig. 1A and B).

The suitable overwintering areas of *S. furcifera* showed similar distribution patterns with the presence data points, in that the suitable areas were aggregated to the west of Ailao Mountains, and most of the

Table 1. Score matrices of the eight EGVs important for overwintering *S. furcifera* in PCA and the ENFA

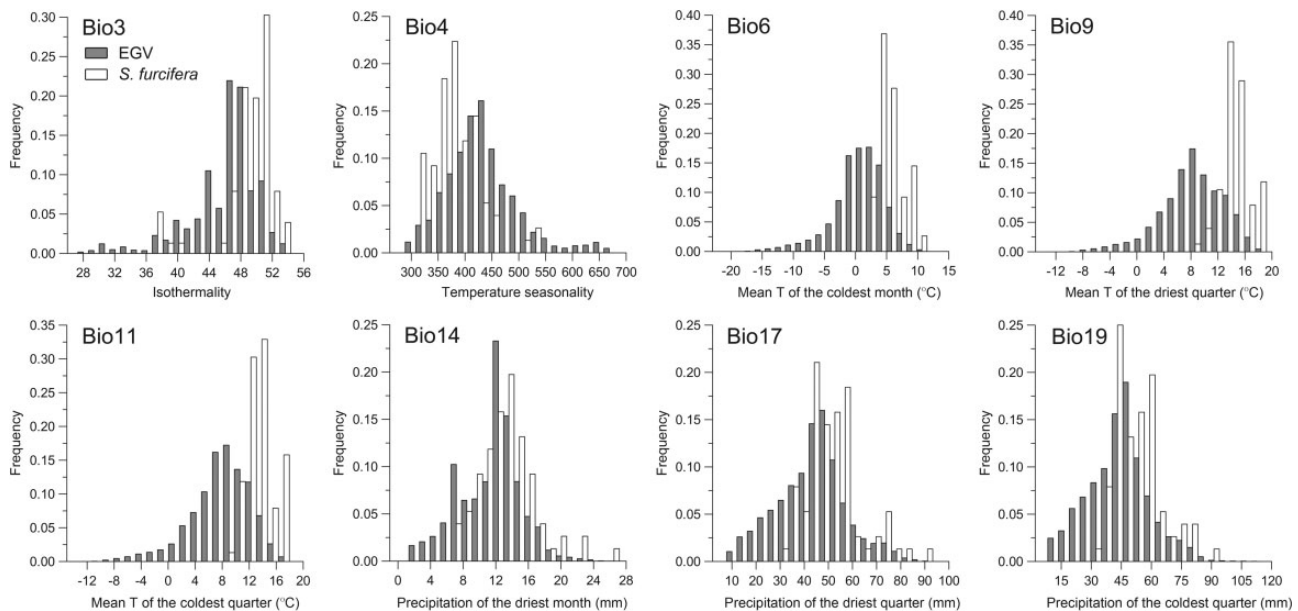| EGVs	PCA			ENFA			
	C1 (65%)	C2 (21%)	C3 (12%)	F1 (59%)	F2 (14%)	F3 (9%)	F4 (8%)
Bio3	−0.526	0.686	0.480	0.247	−0.366	−0.126	−0.288
Bio4	0.754	−0.525	−0.343	−0.303	−0.086	−0.410	−0.254
Bio6	−0.870	0.067	−0.479	0.462	0.149	0.339	−0.440
Bio9	−0.914	0.233	−0.318	0.506	−0.067	−0.239	0.248
Bio11	−0.909	0.218	−0.350	0.485	0.041	−0.166	0.113
Bio14	−0.772	−0.535	0.132	0.201	0.419	0.207	−0.072
Bio17	−0.799	−0.526	0.242	0.222	−0.719	0.309	0.611
Bio19	−0.814	−0.481	0.268	0.229	0.370	−0.691	−0.454

Fig. 2. Frequency distribution of the EGVs involved in this study, gray bars: distribution of entire Yunnan Province, and white bars: distribution of overwintering *S. furcifera*.
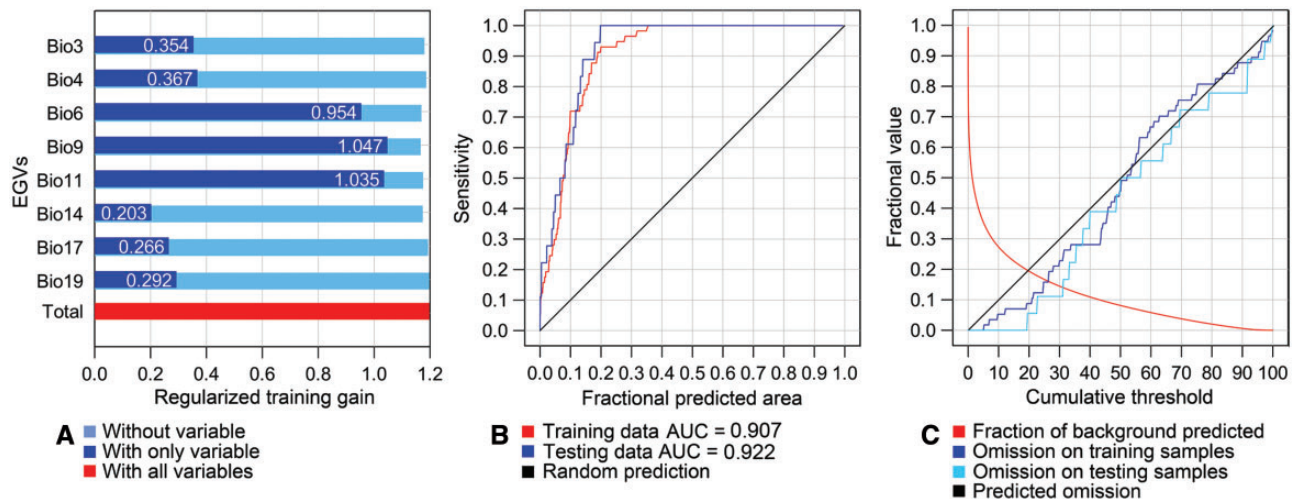
Fig. 3. Statistical charts of MaxEnt analysis, (A) the jackknife of the regularized training gain of the EGVs, (B) the ROC and AUC of prediction, and (C) the omission and predicted area, where the values indicate the training gain with only variables.

suitable areas were river valleys and low-altitudinal basins, i.e., the lower half of the Nujiang River valley and the Lancang River valley, most portions of the Yuanjiang River-, Lixian River-, and Nanding River valleys, and many basins scattered in Dehong, Licang, Pu'er, and Xishuangbanna prefectures in southwestern and southern Yunnan. However, the Nanpan River Valley was less suitable for *S. furcifera* in winter. It should be noted that though some river valleys (like the Jinsha River Valley and its connected branches) in northern Yunnan showed a low suitability rank (<0.5), no *S. furcifera* was ever collected during the 4-yr survey. Moreover, the suitability projection suggested that the overwintering areas of *S. furcifera* were extremely fragmented and scattered into low-altitude areas isolated by mountain ridges (Fig. 1B).

Discussion

The geographical distribution of *S. furcifera* is often regarded as one of the key factors which influence the spatial and temporal change of population density and the eruption potential each year. Therefore, previous studies have focused on these factors in an attempt to understand the winter distribution of *S. furcifera*. In Yunnan, three winter surveys on *S. furcifera*, carried out in 1979–1981, 1982, and 2000 (Yang et al. 1982, Liu et al. 1991, Tao and Sogawa 2000), found that *S. furcifera* mostly overwintered in the low altitudinal river valleys and basins that lie to the south of 24.2–25.1° N and below 1,300–1,500 m a.s.l. The surveys also found that the latitudinal- and elevation limits of the distribution in the area west of Ailao Mountains were higher than those to the east of the Ailao Mountains (Yang et al. 1982, Liu et al. 1991, Tao and Sogawa 2000). Our survey showed that the northern limit of *S. furcifera* in winter was 25.4° N (Wayao, Baoshan) and the upper limit was 1,608 m a.s.l. (Longba, Mojiang) in the area west of Ailao Mountains, while the limits were 24.2° N (Panxi, Huaning) and 1,563 m a.s.l. (Beize, Yuanjiang) in the area east of the Ailao Mountains (Fig. 1A; Supp Table S1 [online only]). Both of the northern and upper limits of overwintering *S. furcifera* in this study were higher than that reported by previous studies.

Winter temperature is the factor determining the northern and upper limits of overwintering *S. furcifera*. Lu et al. (2012) reported a northward shift of the limit in the overwintering brown planthopper, *Nilaparvata lugens* (Stål) (Hemiptera: Delphacidae), in China due to climate change. Similar cases were widely reported in other arthropods like *Dendroctonus ponderosae* (Coleoptera: Scolytinae), dragonflies (Odonata), *Operophtera brumata* (Lepidoptera: Geometridae), as well as *Loxosceles reclusa* (Araneae: Siraiidae) (Carroll et al. 2004, Hickling et al. 2005, Hagen et al. 2007, Saupe et al. 2011). Global climate change in the recent decades had influenced regional climate

significantly. For example, the winter temperature in Yunnan has increased rapidly since 1987, and the winters since 2000 have been warmer than the past (winter temperature increment 0.24–0.26°C per decade) (Duan and Tao 2012, Cheng et al. 2014), resulting in northern tropical and southern subtropical areas expanding significantly (Cheng et al. 2014). Based on this, authors of this study believe that the increase of northern and upper limits of overwintering *S. furcifera* in Yunnan could be attributed to climate warming driven by global climate change.

Within the geographical range of *S. furcifera*, overwintering populations were frequently recorded in the longitudinal range-gorge region (LRGR) located west of the Ailao Mountains, while far fewer were scattered on the altiplano located east of this mountain range forming a fragmented pattern restricted by river valleys and low-altitudinal basins (Fig. 1B). Factor analyses demonstrated that winter temperatures, like the mean temperature of the driest quarter (Bio9) and the mean temperature of the coldest quarter (Bio11), significantly influenced the distribution of *S. furcifera* in winter (Table 1 and Fig. 3A). Yunnan lies in the low-latitudinal plateau region of China (Qin et al. 1997, Xie and Liu 1998), with great mountains and deep river valleys that run parallel in the LRGR (He et al. 2005), forming many low-altitudinal basins and valleys which are warm and humid in winter (12–17°C of mean temperature in January) (Wang 2005), making them very suitable for *S. furcifera* to overwinter. In comparison, the eastern altiplano of Yunnan is much colder and drier in winter (6–14°C of mean temperature in January) (Wang 2005) due to lack of low-altitudinal basins and valleys and frequent exposure to cold currents, making this area much less suitable for *S. furcifera* to overwinter. This could partially explain why less *S. furcifera* populations were recorded in eastern Yunnan and the northern and upper limits were much lower in this area. Therefore, the large-scaled fragmented distribution pattern of overwintering *S. furcifera* is determined by the complex topography and distinct spatial distribution of winter temperature.

Host plant is another factor determining the distribution of *S. furcifera* in winter. The double-cropping rice areas in the low-altitudinal basins and valleys (<1,300 m) of the LRGR are warm and humid in winter, and the ratooning rice (*O. sativa*) and *L. japonica* could be commonly found in vacant or abandoned paddies after harvest (Chen et al. 1994, Zhu et al. 1999, Yu et al. 2009). The abundant ratooning rice and *L. japonica* provide sufficient food source for *S. furcifera* in winter. This was likely another reason why most *S. furcifera* populations were recorded from this area in winter. To the contrast, the single-cropping rice areas in the eastern altiplano as well as the medium-altitude hills (average 1,700–2,000 m) is colder and drier in winter, where ratooning

rice and *L. japonica* are scarcer and restricted to only a few river valleys (Chen et al. 1994, Zhu et al. 1999, Yu et al. 2009). The limited food source in this area further reduced the distribution of overwintering *S. furcifera*. Our field survey also failed to collect any *S. furcifera* in winter from areas with very suitable temperature but absence of host plant. Hekou and Duotie in the Red-River Valley of southern Yunnan were good examples of this scenario. Liu et al. (1991) recorded a good number of *S. furcifera* while our survey did not capture any due to lack of host plant because rice has been completely substituted with banana in most of the valley. Similarly, the Jinsha River (upstream of the Yangtze River) valley of northern Yunnan is warm in winter but extremely dry (Wang 2005, Cheng et al. 2014), where ratooning rice and *L. japonica* could not survive without irrigation. Despite the mid to low level of suitable areas in this valley (Fig. 1B), our 4-yr field survey did not find any hosts or collect any *S. furcifera*. Hence, host availability also determined the limited distribution in certain areas when temperature is suitable. The distribution of *S. furcifera* is strongly linked to host availability when climate is favorable. Therefore, reducing host availability by agricultural management in winter (i.e., plowing and replanting) is helpful in controlling the population density of overwintering *S. furcifera*.

This study did not include host plant in the factor analysis since such spatial data are still unavailable. Therefore the projection of suitable areas may bear a certain degree of bias. However, as suggested by many similar studies (Papeş and Gaubert 2007, Fløjgaard et al. 2009, Morueta-Holme et al. 2010, Pittman and Brown 2011, Reside et al. 2012, Yu et al. 2013), the SDM applied in this study is still useful because climate is the most important abiotic factor that determines and influences the distribution of organisms, especially for species where we have poor biological and distributional knowledge. Adding host plants and habitat data might improve the projection accuracy, and provide a more accurate prediction of the distribution of *S. furcifera* in Yunnan. Therefore, future endeavors are required to collect the spatial data regarding rice agroecosystems in Yunnan during different seasons, which could benefit the projection of *S. furcifera* as well as other rice pest. Moreover, based on the method applied herein, future studies using short-term weather data instead of long-term climate data (Reside et al. 2010) can be explored with *S. furcifera* to project more precise distributions under a rapidly changing climate.

Supplementary Data

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

Acknowledgments

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