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Density, Demography, and Influential Environmental Factors on Overwintering Populations of *Sogatella furcifera* (Hemiptera: Delphacidae) in Southern Yunnan, China

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ABSTRACT. *Sogatella furcifera* (Horváth) (Hemiptera: Delphacidae) is the most serious pest on rice in southwestern China. Yunnan province is within this region and is a major overwintering area for *S. furcifera* in China. This field study was carried out over 4 yr (2010–2013) and focused on *S. furcifera* distribution, population density, and demography, as well as the relationship between various environmental factors and the distribution and density of overwintering *S. furcifera* in Yunnan. Our study demonstrated that overwintering populations of *S. furcifera* mainly occurred in valleys and lowlands below 25.02°N and 1,680 m above sea level (a.s.l.), where ratooning rice was present. The overwintering range of *S. furcifera* has expanded in Yunnan compared with 20 yr ago, and regional climate change is believed to be the main contributing cause for this expansion. Environmental factor analysis showed that the mean air temperature of the coldest quarter and precipitation of the coldest quarter were two key factors that were strongly linked to the overwintering distribution and density of *S. furcifera* in Yunnan. Wintertime temperature was the principal influencing factor to determine the distribution and density of *S. furcifera*, while the effect of precipitation was indirect in that it influenced the insect's distribution via its host. This study documented the major overwintering areas of *S. furcifera* in Yunnan, which can be used to predict outbreak potential in the following spring. Hence, key climatic factors, overwintering distribution, and density of *S. furcifera* should be used when forecasting outbreaks in spring.

Key Words: rice pest, population density, distribution pattern, Yunnan

The rice planthoppers (Hemiptera: Delphacidae), including *Nilaparvata lugens* (Stål), *Laodelphax striatellus* (Fallén), and *Sogatella furcifera* (Horváth), are the most important pests on rice in Asia (Dyck and Thomas 1979, Catindig et al. 2009, Cheng 2009). The dominant species and damage levels caused by these rice planthoppers vary throughout Asia (CAB 1980, 1984, Reissig et al. 1986, Catindig et al. 2009), with *S. furcifera* being the most common species in southwestern China, and in Yunnan it has caused high economic losses during the past decade (Fu et al. 2009). For example, during the major outbreak in Yunnan in 2007, it was estimated that 26,700 ha of rice paddies were severely damaged with a loss of 190,000 metric tons of grain (Gui et al. 2008). The escalating impact of *S. furcifera* has become a threat to regional agroecosecurity of Yunnan.

The white-backed planthopper *S. furcifera* is a migratory insect that cannot survive cold winter temperatures. In China, *S. furcifera* is usually able to overwinter in areas below 25°N latitude, i.e., portions of southern Yunnan, southwestern Guangxi, and Hainan, where winter temperatures are less severe (Hu et al., 1988). The overwintering populations of *S. furcifera* migrate northward when temperature rise in spring (Hu et al., 1988). During the course of migration, large populations of *S. furcifera* feed in rice paddies and cause severe damage to the crop. A recent study also pointed out that overwintering *S. furcifera* in tropical Yunnan could be a source of a serious rice virus, the southern rice black-streaked dwarf virus (SRBSDV) (Guo et al. 2013). It is generally accepted that overwintering populations of *S. furcifera* are the source for the migrating populations that appear in the subsequent year, and the size and distribution of the overwintering population is related to the magnitude of the outbreak and damage the following spring. Hence, understanding the density and distribution of the overwintering population is key to predicting the outbreak potential of *S. furcifera*.

Yunnan Province is located in the low-latitude plateau region of southwestern China, which is characterized by complex terrain and climate (Wang and Zhang 2002). The southern part of Yunnan connects to Indochina, where winters are warm and humid with ratooning rice commonly distributed (Chen et al. 1994), and it is this area that is believed to be the major overwintering place of *S. furcifera* in southwestern China (Hu et al. 1988). Two broad surveys were carried out on overwintering populations of *S. furcifera* in this area over 20 years ago, which provided early information on the distribution and density of overwintering *S. furcifera* in Yunnan, and also provided some clues to our current understanding of the outbreak dynamics of *S. furcifera* (Yang et al. 1982, Liu et al. 1991). However, during the past 20 years the regional climate (Duan and Tao, 2012), rice varieties (Li, 2008, Yu et al. 2009), and planting systems (Hou 1996, Zhang et al. 2000, Xin and Li 2009) have changed significantly in southwestern China, which likely have influenced the distribution and density of overwintering *S. furcifera* populations. Therefore, historical survey data is not well suited to assess the current status of overwintering *S. furcifera* in Yunnan and its outbreak potential in the coming year.

The present research was based on 4 yr of large-scale field surveys using geographic information system (GIS) and biological climatic factor analysis in an attempt to study 1) population density of overwintering *S. furcifera* in Yunnan; 2) demographic composition under different environments, and 3) key environmental factors that may influence the distribution and population density of overwintering *S. furcifera*. This research will improve our understanding of overwintering ecology of *S. furcifera* in Yunnan, which will provide fundamental data to further analyze outbreak dynamics of *S. furcifera* and help formulate pest management strategies for early-season rice plantations in Yunnan.

Materials and Methods

Field Surveys. The survey area was based on the description given by Hu et al. (2012), which broadly covered the area between the southern border of Yunnan (21°N at the southernmost) up to 25°N latitude within Yunnan. The survey area was divided into a 50 by 50 km grid, and field sites were established in each cell based on the following criteria: 1) at least one site was established at an elevation below 1,500 m above sea level (a.s.l.) which is the generally believed suitable overwintering upper limit for *S. furcifera*, and 2) supplementary sites were established between 1,500–1,700 m a.s.l. when winter rice agroecosystems were available in order to determine the true upper limit of the distribution of overwintering *S. furcifera*. As it has been shown in previous studies that *S. furcifera* cannot survive winter conditions in areas above 1,700 m a.s.l. (Liu et al. 1991); therefore, no field sites were established above this altitude. In total, 105 field sites were established in this study (Fig. 1A). The geographical coordinates of each site were recorded using a Garmin eTrex Vista GPS handset (Version 3.2; Garmin Ltd., Taiwan).

Field surveys were carried out in January and February in 2010–2013, with each field site being surveyed once each month. Since *S. furcifera* may consume other Poaceae plants in winter for food beside its primary host, *Oryza sativa* L., ignoring other Poaceae plants may cause sampling bias, therefore four types of habitats closely related to rice agroecosystems defined in Hu et al. (2012) were assigned to each site. Based on observations at the time of survey, the four types of habitats are paddies with actively growing rice (habitat type 1), paddies with ratooning rice (habitat type 2), abandoned paddies with dense grass (habitat type 3), and field drainages with dense grass (habitat type 5). During the surveys, for each habitat type at a given field site, three 4 m² areas were randomly selected to collect planthoppers.

Since the rice plants in winter are shorter (<20 cm measured from soil to the leaf tip) and much more scattered than those in summer, direct counting of planthoppers using a rectangular plate often fails to sample. Therefore, this research adopted the sweep-netting 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). During the survey, each sample area was swept 20 times with an insect net (50 cm in diameter, 85 cm in depth), and all captured planthoppers (including adults and nymphs) were preserved in 95% ethanol.

All *S. furcifera* samples were identified in laboratory under a Nikon SMZ1500 stereoscope (Nikon, Tokyo, Japan) according to the descriptions given in Ballou et al. (1987), Asche and Wilson (1990), and Chen

et al. (2000) and counted according to the following categories. The nymphs were categorized into young nymphs (YN, instars I–III) and older nymphs (ON, instars IV and V) according to 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 *S. furcifera* Horváth)” (AQSIQ and SAC, 2009). As the ratio of branchypterous adults in the survey range is extremely low and only occasionally encountered during the 4-yr survey, this research only included macropterous adults (MA). The population density per 100 m² of *S. furcifera* at each site was calculated from the surveyed data.

Data Analysis. To analyze the pattern of *S. furcifera* population density with respect to longitude and latitude of each sampling site, the corresponding data were loaded into Surfer 10.0 (Golden Software Inc., Golden, CO) and contour maps were generated and coupled with the topography of Yunnan using Kriging methods (Yang et al. 2004).

To further analyze the relationship between various insect parameters and latitude and elevation, density and ratios of YNs, ONs, and MAs were calculated for each site and illustrated as bar charts with localities and latitudes on the X axis and population density on the Y axis using Grapher 8.0 (Golden Software Inc., Golden, CO), also, a contour map of the ratio of nymphs (including YN and ON) was generated and coupled with the topography of Yunnan using Kriging methods.

Long-term climate data were obtained for each of the 105 sites from BioClim (averaged over 1950–2000) (www.worldclim.org) and used to generate ecogeographical variables (EGVs). The r29 dataset from BioClim, which includes data for all of Yunnan as well as part of southern China and Indochina (with 30 arc second resolution), was obtained and then cropped by the political boundary of Yunnan Province in GlobalMapper 11.0 (www.globalmapper.com). We extracted the following data for each sampling site using DIVA-GIS 7.5 (www.diva-gis.org) (Hijmans et al. 2012) and stored in an Excel spreadsheet: site altitude (*Alt*), and eight winter-related EGVs for the period 1950–2000, including isothermality (*I*, Bio3), temperature seasonality (*T*_{season}, Bio4), minimum air temperature of coldest month (*T*_{minCM}, Bio6), mean air temperature of driest quarter (*T*_{meanDQ}, Bio9), mean air temperature of coldest quarter (*T*_{meanCQ}, Bio11), precipitation of the coldest month (*P*_{CM}, Bio14), precipitation of driest quarter (*P*_{DQ}, Bio17), and precipitation of coldest quarter (*P*_{CQ}, Bio19). The denotations in parentheses are the variable names uses in this research and the EGV names designated by BioClim.

The distribution of *S. furcifera* population density data was first tested for normality using a histogram with normality curve in SPSS 13.0 (SPSS Inc., Chicago, IL), given that skewed data can affect the resulting regression models.

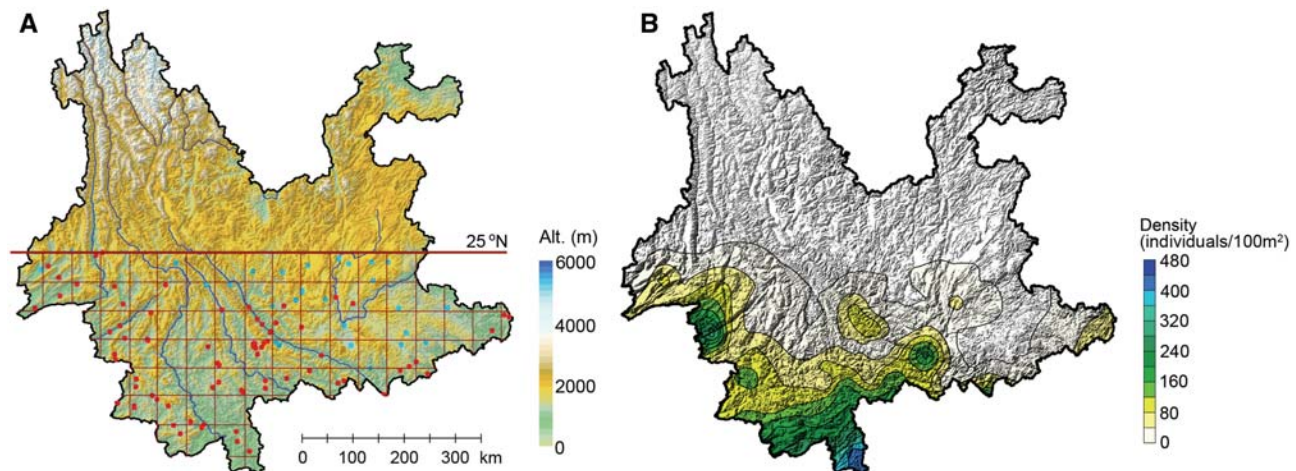


Fig. 1. (A) Distribution map of Yunnan showing the location of the 105 sampled field sites with grids below 25°N, where the red dots represent *S. furcifera*-positive sites, the blue dots represent *S. furcifera*-negative sites, and the blue lines indicate major rivers in Yunnan. (B) A contour map of the overwintering *S. furcifera* density distribution based on the 4 yr of field sampling (2010–2013).

We let D represent the population density in all analyses that were performed using SPSS 13.0. We first performed a Pearson zero-order correlation to determine the correlation between D and the nine EGVs and to detect for possible autocorrelation between the variables, which were used to check for multicollinearity in linear stepwise regression (using the forward-entering method) and to explore the relationship between D and each EGV, when using either the linear regression formula (in $y = bx + C$ form) or the standardized regression formula (in $y' = \beta x$ form). The relative importance of each entered variable was evaluated by a Pearson one-order partial correlation. During the stepwise regression, the 3- σ criterion was adopted by casewise diagnosis for possible outlier in the dataset (Smirnov and Dunin-Barkovskii 1969).

Results

Population Density and Demography. *S. furcifera* was collected from 76 of 105 field sites, with 75.0% of the positive field sites being distributed in western Yunnan, compared with only 25.0% in eastern Yunnan (Fig. 1A).

Population density of the overwintering *S. furcifera* ranged from less than 10 individuals per 100 m² in the northern sites to over 400 individuals per 100 m² in the extreme southern sites. Overwintering densities showed a declining gradient from south to north, with three major independent density centers in southern Yunnan from the west to east, including the Nanding River Valley (density: 330 individuals per 100 m²), southern Xishuangbanna (density: 290–430 individuals per 100 m²), and the Red River Valley (density: 240 individuals per 100 m²) (Fig. 1B; Supp Table 1 [online only]).

YNs were found at 53 of the 76 sites (69.7%) in the demographic analysis, while ON were also found at 42 sites (55.3%) (Fig. 2). The detailed demographic composition of each site was listed in Supp Table 1 [online only]. Demographic analysis showed a clear tendency

for declining ratio of nymphs from south to north, but the data then showed a differentiated demographic composition related to altitude (Figs. 2 and 3). For instance, Guoqing and Nandaohu are situated at roughly the same latitude (22.64°N and 22.66°N, respectively) but different altitudes, densities of all stages of *S. furcifera* at Guoqing (1,248 m) were greater than those at Nandaohu (1,307 m). Also, densities of all *S. furcifera* life stages were greater at Nansha than those at Zhongdong, Guoqing, Nandaohu, and Ning'er, despite Nansha being located at a higher latitude (23.22°N), but a much lower elevation (444 m) (Fig. 2). The data also showed that the ratio of nymphs at field sites in western Yunnan was relatively greater than that in east Yunnan (Fig. 3).

Environmental Factors in Relation to Overwintering Populations.

The histogram of *S. furcifera* population density showed a certain degree of deviation from normal, given that nearly half of the data points were clustered near zero (Fig. 4). The possible causes of this deviation will be discussed later.

The Pearson zero-order correlation analysis for the all-data model showed that the population density of overwintering *S. furcifera* was significantly correlated with all nine EGVs, among which significant negative correlations were found for *Alt* ($r = -0.564$, $P < 0.001$) and T_{season} ($r = -0.550$, $P < 0.001$), while the remaining EGVs were all positively correlated with population density (Supp Table 2 [online only]). The analysis also detected significant autocorrelations between different EGVs, i.e., between *Alt* and the three temperature variables, T_{minCM} , T_{meanDQ} , and T_{meanCQ} ; within the three temperature variables; between the two precipitation variables, P_{CM} and P_{DQ} ; between I_t and T_{season} , T_{meanDQ} , T_{meanCQ} , P_{CM} , and P_{CQ} ; and between T_{season} and T_{meanDQ} , T_{meanCQ} , P_{CM} , P_{DQ} , and P_{CQ} (Supp Table 2 [online only]).

In the stepwise regression, T_{meanCQ} and P_{CQ} contributed significantly to the analysis, with the resulting standardized linear

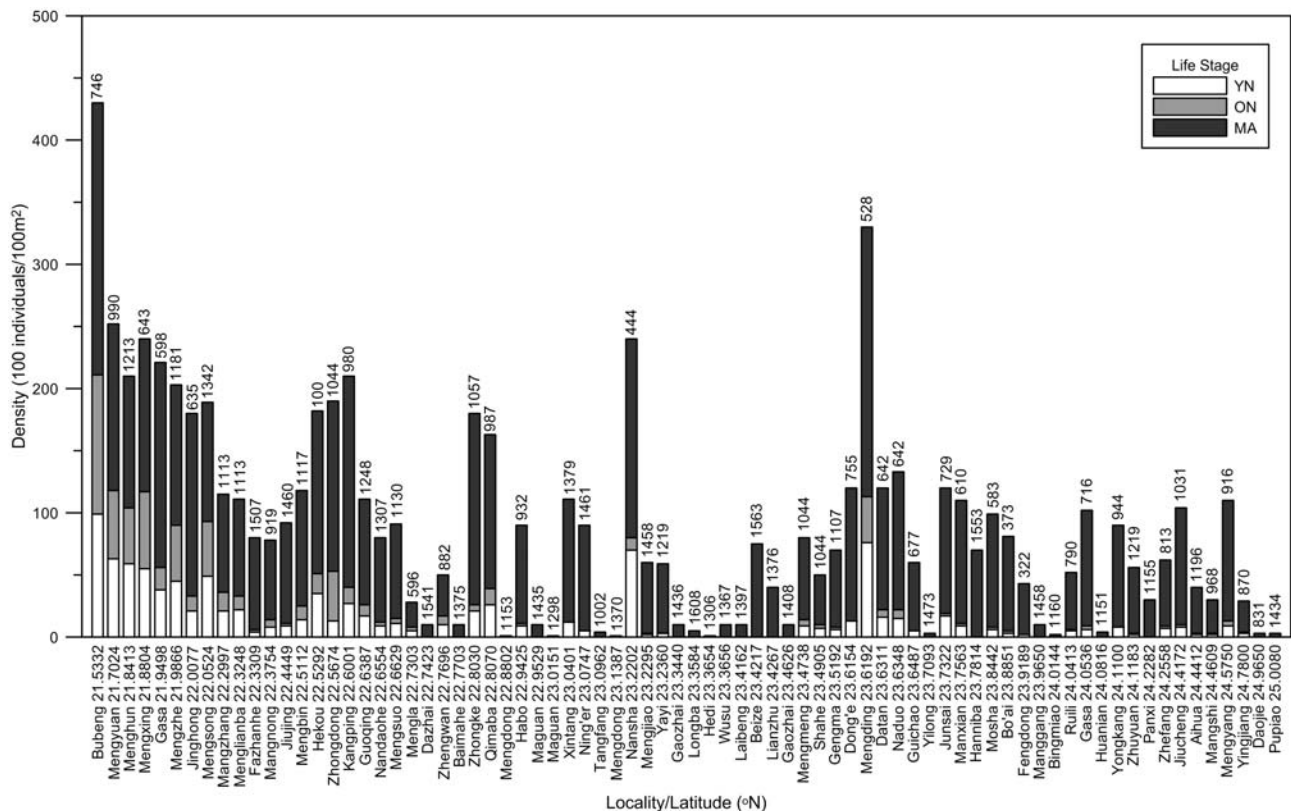


Fig. 2. Demography of overwintering *S. furcifera* populations at 76 planthopper-positive sites in southern Yunnan in January and February during 2010–2013, where YN = young nymphs, ON = older nymphs, and MA = macropterous adults.

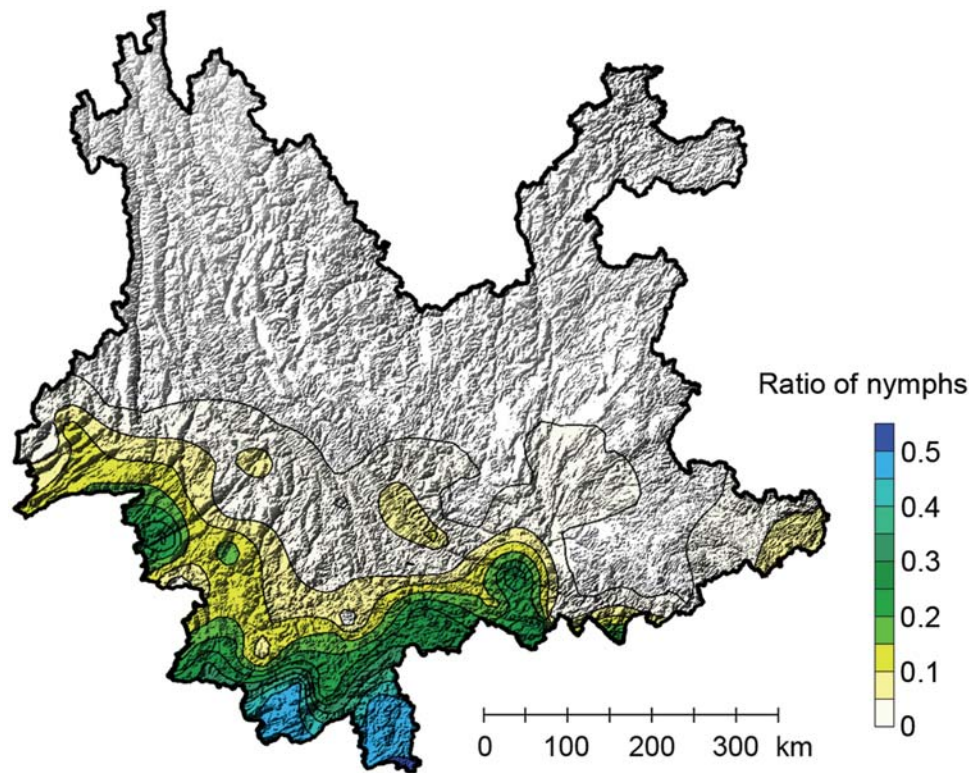


Fig. 3. A contour map of the ratio of nymphs (including young nymph and older nymphs) in southern Yunnan in January and February during 2010–2013.

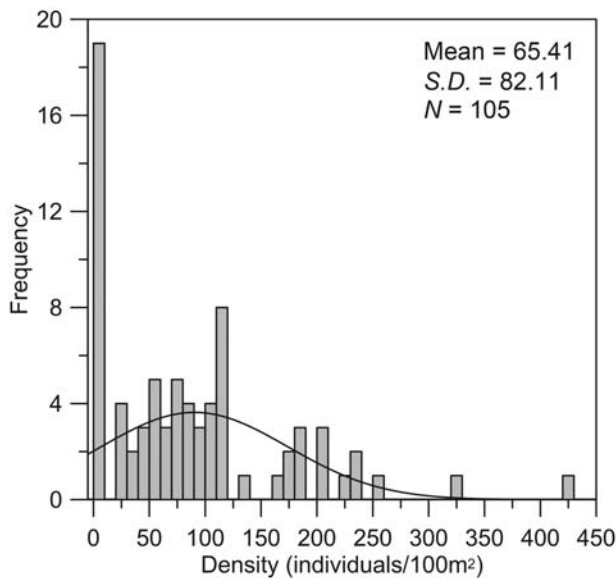


Fig. 4. Histogram of the overwintering *S. furcifera* population density at the 105 field sites in this study with the overall population mean and SD are given for all 105 sites combined.

regression formula between population density and the climatic factors being:

$$D = 21.092T_{\text{meanCQ}} + 2.561P_{\text{CQ}} - 364.87;$$

$$D' = 0.633T_{\text{meanCQ}} + 0.342P_{\text{CQ}}$$

where D represents the regression formula in $y = bx + C$ form, D' represents the formula in $y' = \beta x$ form.

Table 1. Results of model-fit of stepwise regression

Entered variable	SE	b	β	r'	t	P	VIF
T_{meanCQ}	2.225	21.092	0.633	0.648	9.478	0.000	1.005
P_{CQ}	0.500	2.561	0.342	0.452	5.121	0.000	1.005
C	39.675	-364.870	—	—	—	0.000	—

SE, standard error for all variables; C , constant; b , regression coefficient; β , standardized regression coefficient; r' , partial correlation coefficient; t , t -test value and VIF, variance inflation factor.

Stepwise regression analysis showed a 0.01 level of significance for all coefficients and constants for both models (Table 1). The analyses yielded a regression correlation $R = 0.740$ and an adjusted $R^2 = 0.539$ ($F = 61.695$, $P < 0.001$), and the maximum absolute value of the regression standardized residual was 4.034 (> 3 ; $D = 430.0$, predicted value = 205.0, residual = 225.0; $D = 330.0$, predicted value = 108.9, residual = 221.1), indicating the presence of outlier in the dataset.

The Pearson one-order partial correlation found significant positive correlations between both of T_{meanCQ} and P_{CQ} with the overwintering population density of *S. furcifera*, and the partial correlation coefficients (r') suggesting that the mean air temperature of the coldest quarter (T_{meanCQ}) had a more influential effect than did precipitation of the coldest month (P_{CQ}) (Table 1).

Discussion

Population Density and Demography. Yunnan is one of the major overwintering areas for *S. furcifera* in mainland China (Hu et al., 1988). Yang et al. (1982) and Liu et al. (1991) both carried out large-scale surveys regarding the distribution and population density of overwintering *S. furcifera* in Yunnan. Liu et al. (1991) concluded that *S. furcifera* mainly occurred in the valleys and lowlands of southern Yunnan during winter, or more exactly in areas below 25.1°N and 1,480 m a.s.l. Data from this study showed that the overall distribution pattern of

overwintering *S. furcifera* in southern Yunnan has not changed much; however, we found *S. furcifera* overwintering up to 1,680 m a.s.l. (Fig. 1A, Supp Table 1 [online only]), demonstrating that the upper edge of overwintering *S. furcifera* has moved approximately 200 m upward in elevation in the past two decades. This study also demonstrated that the population density of overwintering *S. furcifera* declined with increasing latitude and altitude (Fig. 1B), which is a pattern that was also found in the earlier studies.

Wintertime temperature is regarded as the most important factor influencing the distribution and population density of overwintering *S. furcifera*. In Yunnan, during the past two decades, the average winter temperature for the entire province has increased at a rate of 0.24–0.33°C per decade, and the diurnal temperature range decreased (Liu et al. 2010, Fan et al. 2011, Duan and Tao 2012), which resulted in the northward expansion of the tropical and southern subtropical zones in Asia (Duan and Tao 2012). The data showed that the increase of average winter temperatures and spatial changes of climate zones is able to partially explain the northward and upward shift in the distribution of overwintering *S. furcifera*.

Shift in planting systems is also an important reason for declining densities of overwintering *S. furcifera* in recent years in some areas of Yunnan. For instance in the Honghe Prefecture alone, banana plantations were highly promoted since 2006 (Zhao 2009). By the end of 2011, at least 30,000 ha of banana were planted in this area, with nearly 13,000 ha was shifted from rice paddies (J. P. Lü, personal communication). Such shift has dramatically compressed the available habitat for overwintering *S. furcifera* compared to two decades ago (Liu et al. 1991). Another example is from the lowlands in southern and southwestern Yunnan where the paddy fields are more commonly reutilized in winter for other crops compared to 20 yr ago, which results in less habitat for ratooning rice and winter paddies (Xin and Li 2009).

Based on the occurrence and reproductive characteristics of *S. furcifera*, Liu et al. (1991) divided the overwintering area of *S. furcifera* in Yunnan into three zones, namely the “year-round reproductive area, YRA” (21–22°N or <800 m, mean air temperature in January between 13 and 16°C), the “usual overwintering area, UOA” (22–24°N or 800–1,300 m, mean air temperature in January between 10 and 13°C), and the “occasional overwintering area, OOA” (24–25°N or 1,200–1,500 m, mean air temperature in January between 8 and 10°C). This study found MA and nymphs in both of the YRA and the UOA, and the proportion of nymphs in the YRA is greater than that in the UOA (Fig. 2). Occurrence and ratio of nymphs in winter reflect the status of population growth in a particular area. The density and distribution pattern of nymphs in the present study matched the three overwintering zones defined by Liu et al. (1991), indicating that the spatial distribution of overwintering *S. furcifera* has not changed much in the past two decades. In the YRA and UOA, the mean daily temperature in winter is 10–18°C, which exceeds the average development threshold of *S. furcifera* (9.13°C; Tang et al. 2009); hence, *S. furcifera* is able to develop continuously. However in the OOA, the mean air temperature in winter is only 8–10°C, which is just above the overwintering threshold for survival of *S. furcifera* (8.82°C; Liu et al. 1991), but likely not warm enough to promote population growth. The partition between these overwintering areas and their strong temperature differences support the contention that temperature is a key factor in the occurrence and distribution pattern of *S. furcifera* in winter.

Denno and Rodrick (1990) pointed out that planthoppers that occur in more than one climatic zone are able to overwinter by diapausing. However, true diapause in *S. furcifera* has not been described yet. Our field survey could not verify whether *S. furcifera* was able to diapause in the OOA area, therefore, questions concerning the ability to diapause in *S. furcifera* still need to be answered by future research. In addition, during our field surveys, we collected planthopper eggs from ratooning rice at various localities but failed to identify whether they were eggs of *S. furcifera*. Therefore, it is logical to assume that the lack of data on

eggs may have caused the deviation from normality in our dataset, and the actual population density of *S. furcifera* in winter could have been greater if we could have accounted for eggs.

Key Influencing Factors. This study analyzed three temperature factors in winter, i.e., the minimum air temperature of the coldest month ($T_{\min\text{CM}}$), the mean air temperature of the driest quarter (T_{meanDQ}), and the mean air temperature of the coldest quarter (T_{meanCQ}). Our analyses showed important influences made by all three temperature factors (Supp Table 2 [online only]), but the relative importance of each factor differed. Among these three factors, T_{meanCQ} was the key influential factor (Table 1), which most clearly reflects the severity of winter and thus has a strong regulatory influence on the distribution and population density of *S. furcifera* in winter. By contrast, the factor $T_{\min\text{CM}}$ appears to reflect more of a short-term extreme low temperature event, rather than the long-term average represented by T_{meanCQ} . The third factor, T_{meanDQ} , represents the temperature in the dry season, which lasts from November to April in Yunnan (Chen 2001), and may easily exceed 20°C in the study area in March and April. Therefore, the restrictive effect of this factor on the distribution and density of overwintering *S. furcifera* was quite likely limited given that it already exceeds the thermal requirement of *S. furcifera*.

Precipitation is another important factor that appears to influence the density of *S. furcifera* in winter. Our analysis found different levels of influence for the three wintertime precipitation factors analyzed (Supp Table 2 [online only]), among which the precipitation of the coldest quarter (P_{CQ}) was flagged as a key factor (Table 1). Since paddies with ratooning rice is the major overwintering habitat for *S. furcifera* in our survey area (Hu et al. 2012), it is logical that water availability, in the form of precipitation, would strongly determine the distribution and quality of ratooning rice (Chen et al. 1994). Hence, winter precipitation is thus strongly linked to the distribution and quality of ratooning rice, which subsequently influences the density of *S. furcifera*. This relationship also helps explain why the factor representing the drought in winter was also flagged as the key factor influencing the distribution of *S. furcifera*.

Implication for Pest Management. This study demonstrated that overwintering populations in Yunnan often occur in areas below 25°N, and can maintain population growth throughout winter at elevations below 1,500 m. In such areas in Yunnan, there are often two or three rice crops harvested yearly (Wang and Zhou 1992; Zhu 2000). The first rice crop (early season) is planted in mid-February, when ambient temperatures rise quickly in spring. As the rice crop grows, the overwintering *S. furcifera* can develop and multiply quickly, often reaching pest levels in spring (Li et al. 2013). Hence, multiple pest management tactics can be adopted to reduce overwintering *S. furcifera* numbers, such as elimination of ratooning rice by immediate plowing after harvest, reutilization of vacant paddies with a different crop in winter, as well as monitoring *S. furcifera* populations.

Utilizing the key climatic factors identified in this study will aid managers in the design of future surveys for overwintering *S. furcifera* populations. Winter temperature and precipitation are two important factors influencing the distribution, density, and demography of overwintering *S. furcifera*. This study demonstrated that the effect of temperature was greater than that of precipitation (Table 1; Supp Table 2 [online only]). Therefore, mean air temperatures from December to February should be analyzed first to determine whether the thermal requirements of *S. furcifera* are met, and then precipitation of the area could be taken into consideration. When both temperature and precipitation are suitable for successful overwintering of *S. furcifera*, field surveys could be carried out to assess the actual distribution and density of overwintering *S. furcifera*. By using this sequential analysis-and-survey approach, human and financial resources could be used more efficiently. However, to develop a mathematical model between the population density of overwintering *S. furcifera* and the magnitude of subsequent spring outbreak, further biological studies on the population growth of *S. furcifera* are required.

Supplementary Data

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

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