ORIGINAL RESEARCH PAPER

Prediction of overseas migration of the small brown planthopper, *Laodelphax striatellus* (Hemiptera: Delphacidae) in East Asia

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Abstract A method has been developed for predicting the overseas migration of *Laodelphax striatellus* (Fallén) from eastern China to Japan and Korea. The method consists of two techniques: estimation of the emigration period in the source region and simulation of migration. The emigration period was estimated by calculating the effective accumulated temperature for the insect by use of real-time daily surface temperatures at the source. During the emigration period, migration simulations were performed twice a day, at every dusk and dawn. The prediction method was evaluated, by cross-validation using migrations in the 4 years from 2008 to 2011. The results showed that the emigration periods included the mass migrations, and that the method successfully predicted those migrations.

Introduction

The small brown planthopper *Laodelphax striatellus* (Fallén), a vector of *Rice stripe virus* and *Rice black streaked dwarf virus*, is one of the major insect pests of rice. Because it is able to overwinter in temperate regions including Japan, Korea, and China, most *L. striatellus* have long been believed not to be a migratory insect pest, although small numbers of *L. striatellus* migrants have been caught over the sea (Noda 1986). Therefore, rice stripe disease in rice fields was believed to be caused mainly by local *L. striatellus* populations. Mass overseas migration of *L. striatellus* and a subsequent outbreak of rice stripe disease were reported to have occurred in western Japan in 2008, and Jiangsu province in China was identified as a possible source (Otuka et al. 2010). After this migration, another mass immigration occurred in western Korea in 2009 (Kim 2009; Kim et al. 2009; Otuka 2009). Large numbers of immigrants were captured in net traps along the western coastline of the Korean peninsula, and the immigrants subsequently caused a severe outbreak of rice stripe disease in paddy fields there (Kim 2009; Kim et al. 2009). A possible source of these immigrations was estimated to be Jiangsu province (Otuka 2009).

Since 2004 a severe outbreak of *L. striatellus* and rice stripe disease has spread throughout Jiangsu province. Viruliferous *L. striatellus* in the province peaked at 30 % in 2005 and decreased to 12 % in 2009 (Zhu 2006, 2009). This was higher than the value of approximately 5 % for Kyushu district, Japan (Matsumura and Otuka 2009).

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It has, thus, become important to predict the migration of *L. striatellus* to enable prediction of the pest's arrival time and areas of invasion.

A migration-prediction technique has been applied to migration of two other tropical species of rice planthoppers—the brown planthopper, *Nilaparvata lugens* (Stål), and the white-backed planthopper, *Sogatella furcifera* (Horváth)—and has achieved a prediction accuracy of 78 % (Otuka et al. 2005a). In the prediction of migration of these species, it is assumed that they take off in southern China every dusk and dawn, mainly during the *Bai-u* rainy season from late June to early July, and their overseas migration is predicted to occur when southwesterly winds blow over the East China Sea. Overseas migrations of *L. striatellus* have so far been confined to within very short periods of time, from late May to early June, as shown below. This period of emigration corresponds environmentally to the time of the wheat harvest and entomologically to the emergence of the first generation macropterous adults of *L. striatellus* (Zhu 2009, Sogawa 2005). Therefore, prediction of migration on the basis of the previously developed simulation technique was expected to be improved if the emigration period was accurately estimated and the prediction was performed during that period only.

This study, therefore, proposes a method for prediction of migration involving a combination of the prediction of the emigration period of *L. striatellus* in the source region and simulation of migration. The former prediction is conducted by calculating the effective accumulated temperature (EAT) for the insect. The simulation model for tropical rice planthoppers, with a few modifications, is used for the migration simulation. The prediction accuracy was evaluated by comparing the prediction with insect catches in the destination areas. Meteorological conditions which cause the overseas migrations and possible domestic migrations within China are discussed.

Materials and methods

This section describes monitoring methods in three countries and outlines how to predict an overseas migration. The method of prediction consists of two steps: prediction of the timing of emergence of the first generation of the overwintering population in a source region, and simulation of migration. The section also describes a method for evaluation of a prediction.

Trap monitoring in China, Korea, and Japan

To monitor the occurrence of *L. striatellus*, net traps were located in three different countries: Taean, Korea (36.76°N,

126.34°E; open square in Fig. 1), Sinan, Korea (34.82°N, 126.10°E; open triangle), Isahaya, Japan (32.84°N, 130.03°E; open circle), and Tongzhou, China (32.11°N, 121.08°E; solid triangle). Monitoring in Korea and China was started in 2009 and 2010, respectively. At each site, a tow net trap 1.5 m in depth with a 1-m ring was mounted at the top of a pole 10 m above the ground. Insects caught in each trap were collected every morning and counted by extension officers, except that insects in the net trap at Taean in 2009 were collected every week until June 3 and those in the same trap in 2011 were collected every 12 h at 0900 and 2100 hours local time on May 31 and afterward. Insects in the net trap at Sinan in 2009 were not collected on Saturdays and Sundays.

Backward trajectory analysis

To determine whether a catch in the net traps in Korea and Japan was a result of immigration from overseas, backward trajectory analysis was conducted (Otuka et al. 2005b). The analysis traces an air parcel backwardly to find a possible migration source. The method has previously been applied to net trap catches obtained on 5 June 2008 in Isahaya and 1–3 June 2009 in Taean and Sinan, and those catches were found to be a result of immigration from overseas (Otuka et al. 2010; Otuka 2009). The same analysis was applied to monitoring data in Korea and Japan in 2010 and 2011. The results were used for evaluation of the prediction.
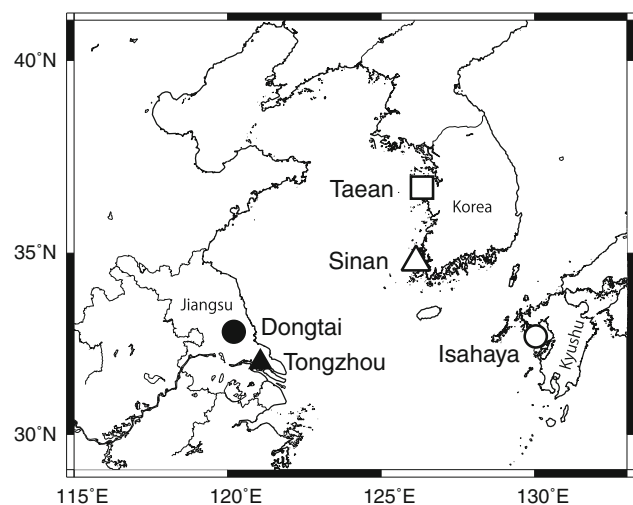

Fig. 1 Location of net traps in China, Korea, and Japan. The *solid triangle* indicates the location of the net trap at Tongzhou, Jiangsu province for emigration monitoring. The *open square*, *triangle*, and *circle* indicate net traps for immigration monitoring at Taean and Sinan, Korea, and Isahaya, Japan, respectively. The *solid circle* indicates the location of a weather station in Dongtai

Migration source in this study

A whole region of Jiangsu province was assumed to be a source area of *L. striatellus* overseas migration (the location of the province is given in Fig. 1). This assumption was based on the following:

– First, the province was estimated to be the possible source of migration into western Japan in 2008 (Otuka et al. 2010).
– Second, *L. striatellus* has been widespread throughout the whole of Jiangsu province since 2004 and its density in wheat fields in the spring has been very high (Zhu 2006, 2009). The area of occurrence of rice stripe disease in Jiangsu province accounted for 70 % of the total in China in 2003 (Zhou 2009).

An overview of predicting the timing of emergence and emigration

The timing of emergence and that of emigration are both of interest. Emigration occurs within a few days after emergence (Zhang et al. 2011). To predict the timing of emigration of *L. striatellus* from a source region, first, the EAT value at emergence of the first generation of the overwintering population must be determined in advance; this calculation is repeated for several previous years so that several EAT values for the emergence are obtained (Fig. 2a). Second, these EAT values are averaged to obtain a previously determined threshold. The threshold is used for prediction of the date of emergence for the current prediction year (Fig. 2b).

In the prediction, the actual daily increase of the EAT value is calculated at one site in the source region, and presumed daily increases are added to the current EAT value until the sum goes beyond the previously determined threshold (Fig. 2c). By use of this process, the date of emergence is determined.

In addition, uncertainties in the EAT calculation must be considered, first because Jiangsu province is a large region and there may be deviations in the timing of emergence within the province as a result of different local temperatures. Another factor that introduces uncertainty into the calculation is the variation of the insect's age when it emigrates. During the emigration season in early June in 2009 and 2010 in Shandong province, the age of *L. striatellus* samples collected in a light trap had been estimated to be 1 to 3 days after emergence, on the basis of the development of their ovaries (Zhang et al. 2011). Therefore, emigration should be considered to occur within a period of time that includes the emergence date estimated above (Fig. 2d). The migration simulations are performed during the emigration period. The length of the period was set to 9 days, for reasons explained in the section "The emigration period for
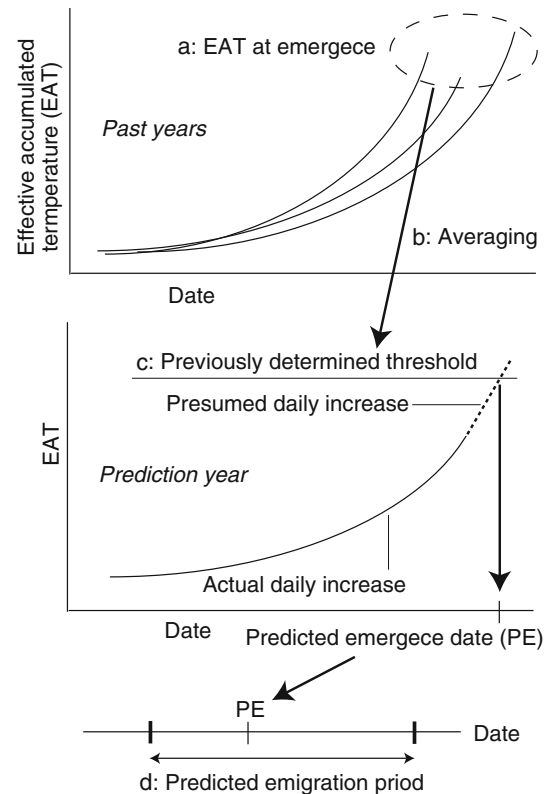

Fig. 2 Schematic diagram of prediction of the emigration period. The emergence date is predicted by calculating the effective accumulated temperature (EAT), and its threshold value is determined in advance by averaging the EAT values at emergence from past years. The emigration period is determined by using the predicted emergence date (PE), taking into account both the yearly variation of EAT in the source region and the age of the emigrating insects (cf. section "The emigration period for prediction")

prediction" in "Results" below. The details of the EAT calculation are presented in the next section.

Effective accumulated temperature at emergence

To estimate the EAT value at emergence, accurate emergence and/or emigration dates must be known (Fig. 2a). The emergence and emigration dates in the source area were determined directly on the basis of the maximum catch peak in the net trap located in southern Jiangsu in 2010, or indirectly via both immigration monitoring using net traps in Korea and Japan and the estimated migration duration over the sea in 2008, 2009, and 2011. The indirect determination was performed as follows:

(Emigration date in Jiangsu) = (immigration date captured by the traps in Korea or Japan) − (migration duration of 1 day)

(Emergence date in Jiangsu) = (emigration date in Jiangsu) − (pre-emigration period of 2 days)

where the duration of migration was determined by the analysis of the 2008 migration (Otuka et al. 2010), and found to be 1 day. The pre-emigration period was determined by reference to Zhang et al. (2011), in which it was reported that *L. striatellus* adults 1–3 days old were caught in a light trap during an emigration period.

The daily increase in EAT for the Jiangsu population from 2008 to 2011 was calculated by use of the daily maximum and minimum surface temperatures at a station in Dongtai city (32.85°N, 120.28°E; solid circle in Fig. 1), Jiangsu province. The station was selected because it is located almost at the center of the province. The data were obtained from a database of the National Oceanic and Atmospheric Administration, USA (WMO Resolution 40-NOAA), and the triangle method was used to calculate EAT (Sakagami and Korenaga 1981) with a developmental zero temperature of 11 °C, a developmental maximum temperature of 29 °C, and a developmental arrest temperature of 40 °C. The first two values were determined by reference to Noda (1989). The last value was used so that the developmental arrest would not be taken into account, because the developmental arrest temperature is not known and the daily maximum temperature in early June in the source region is usually not very high. The EAT value at each growth stage is listed in Table 1, and a value of 374.3 degree days for one generation was used. The calculation was started on 1 January each year and terminated on the estimated emergence date of the first generation of the overwintering population (estimated above). The first day of the year was used because no growth was expected during the winter and, therefore, it is an appropriate starting point.

Prediction of migration, and its evaluation

The emergence date was determined as a date when the EAT of *L. striatellus* exceeds a previously determined

Table 1 The effective accumulated temperature (EAT) to each growth stage of the small brown planthopper, *Laodelphax striatellus*

Stage	EAT (degree days)
One generation	374.3
Pre-oviposition	54.3
Hatching	110.0
2nd instar	150.5
3rd instar	183.1
4th instar	218.6
5th instar	258.3
Emerging	320.0

The EAT value for pre-oviposition is from Noda (1989) and the others for the later stages are from Hachiya (1997)

threshold (Fig. 2), and this date consequently determined the emigration period for the purpose of predicting the migration. During the emigration period, migration simulation was performed to calculate the movement of *L. striatellus*. The prediction results were evaluated by comparison with monitoring data. Because the number of overseas migrations of *L. striatellus* that had occurred by the time this paper was prepared was small, only three migrations in 4 years (see "Results"), cross-validation had to be performed to evaluate the validity of the whole prediction method, including prediction of emigration period and prediction of migration.

In the cross-validation, first, a 4-year temperature data set from 2008 to 2011 was divided into a training set containing data for 3 years and a validation set containing data for 1 year. For example, three EAT values for 2008, 2009, and 2010 accumulated from January 1 to the estimated emergence date of the first generation were initially determined with a training data set. The three values were then averaged, and the average, as a threshold, was used to predict the emergence date in 2011.

A predicted EAT value for each day was calculated both with real-time daily temperatures until the present day and with an assumed daily EAT value of 11 degree days beyond that day.

Likewise, three other combinations of the training set, (2009, 10, 11), (2008, 10, 11), and (2008, 09, 11), were produced, and the averaged EAT values were calculated and used to predict the emergence dates for 2008, 2009, and 2010, respectively.

Model for prediction of migration

The migration simulation model was based on a model for the brown planthopper, *Nilaparvata lugens* (Fig. 3; Otuka et al. 2005a). However, three modifications were made for *L. striatellus*. First, a take-off square, only, had been used previously; in this work a polygonal take-off area was used, so that a take-off area with a complicated shape such as that of Jiangsu province could be used. Second, the take-off time used to be set manually at dusk or dawn (Otuka et al. 2005a); this was modified to be automatically calculated on the basis of the sun's orbit (Nagasawa 1999), thus enabling accurate setting of take-off times in a wide take-off area with a complex shape.

Last, the temperature ceiling was modified (Fig. 3). The temperature ceiling is a level across which simulated planthoppers do not enter a higher atmospheric region with lower air temperatures. For *N. lugens*, the temperature ceiling was set to 16.5 °C, at which half of *N. lugens* stopped beating their wings in a tethered flight experiment under laboratory conditions (Ohkubo 1973). For *L. striatellus*, the ceiling was set to 13 °C, at which the new
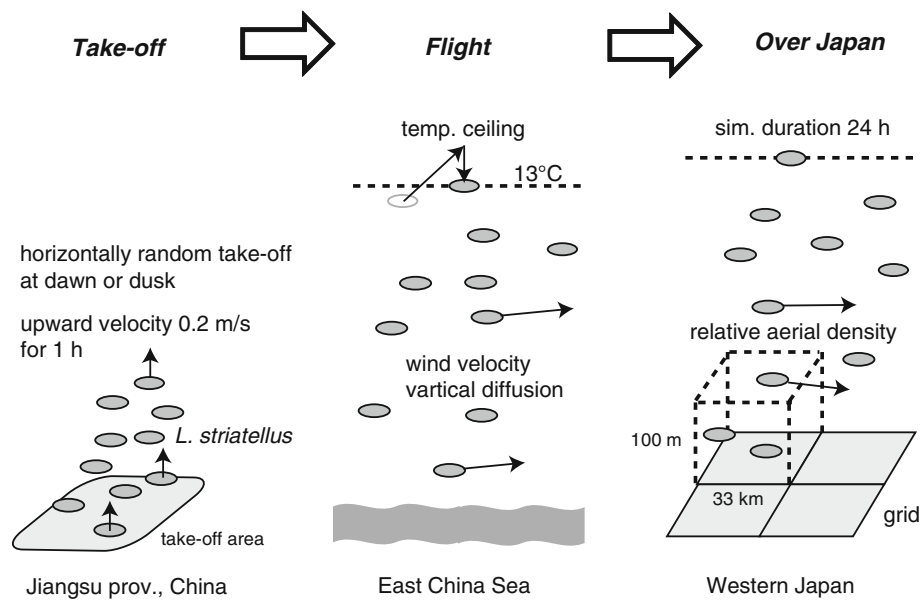
Fig. 3 Schematic diagram of the method of simulation. A *dark ellipse* represents an insect. At take-off (*left*), small brown planthoppers take off from the slanted belt area where the sun sets or rises. The insects move upwards for 1 h after take-off. During the flight (*center*), they move at the same velocity as winds, taking vertical diffusion into account. They do not enter upper levels higher, or regions cooler, than a ceiling level with a temperature of 13 °C. Arriving over Japan (*right*), the number of insects is counted in each calculation grid cell to produce the relative areal density, whose non zero areas at the lowest level (ground surface to 100 m), which are called migration clouds, are mapped. Figures drawn by use of this method are shown in Fig. 6

migration simulation model well reproduced the 2008 overseas migration in a preliminary examination.

Because no landing process of the insects is considered in the model because of lack of knowledge, all simulated planthoppers can fly until the simulation stops. A predicted duration of 24 h was therefore used to avoid overestimated mal-predictions.

Prediction of migration is made up two steps: weather prediction and prediction of migration. Weather was predicted by use of a numerical weather-prediction model, MM5 (NCAR 2003), with both global gridded weather data, i.e. GSM data of the Japan Meteorological Agency (JMA 2007), and sea surface temperature data, i.e. RTG_SST of the US National Oceanic and Atmospheric Administration (Thiebaux et al. 2001). Predicted wind and air temperature data were used by the modified migration simulation model that predicted the relative aerial density of the insect. Non-zero regions of the relative aerial density are called "migration clouds".

Results

Monitoring data

The catches of *L. striatellus* in the net traps in Japan, Korea, and China are shown in Fig. 4.

The catch at Isahaya resulting from immigration from overseas is that made on June 5 2008 (Fig. 4a; Otuka et al. 2010). Small catches from May 29 to June 1 were a result of emigration from the local wheat fields, which were being harvested (Otuka et al. 2010).

In 2009, there was no catch at Isahaya. A large catch, however, was made on June 1 at Sinan, Korea (Fig. 4b). Because this trap was not operational on Saturdays and Sundays, the possible immigration date ranges from May 30 to June 1. The net trap located at Taean was operated weekly, and had a large catch of 963 insects on June 3. Backward trajectory analysis suggested that the catch at Sinan was a result of immigration from Jiangsu province (Otuka 2009).

In 2010, no obvious catch was observed in Korea or Japan from late May to early June. Backward trajectory analysis showed that easterly winds blew over Korea and western Japan during early June (data not shown), suggesting that no immigration from overseas occurred in Korea and Japan. There is a catch peak of 972 on June 10 at Tongzhou (Fig. 4c) which indicates a large emigration.

In 2011, the first catch occurred at Taean, Korea during the night of May 31 (from 2100 hours on May 31 to 0900 hours on June 1) (Fig. 4d), and a subsequent catch occurred in the next 12 h and lingered for an additional 12 h. Later than that, interestingly, outstanding catches were observed only during the day time. No insect was caught during the night. As for 2008 and 2009, backward trajectory
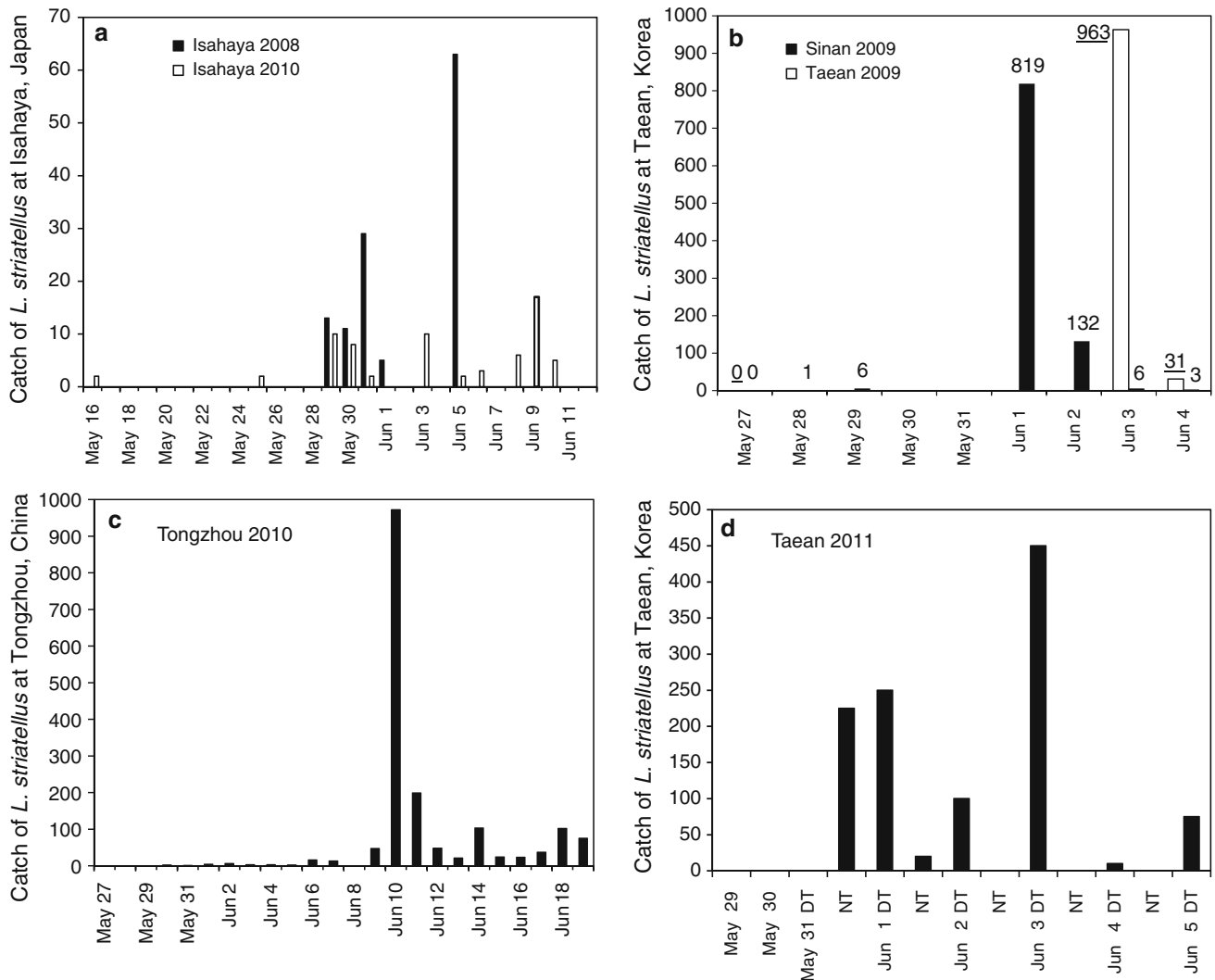
Fig. 4 Net trap monitoring in China, Korea and Japan. The abbreviations *DT* and *NT* stand for monitoring period in the daytime (0100–1300 hours UTC) and nighttime (1300–0100 hours UTC), respectively. The Japanese data were obtained from the database service of the Japan Plant Protection Association (JPP-NET 2012)

analysis suggested that the catches made during the night on May 31 and during the daytime on June 1 were a result of immigration from Jiangsu province (data not shown). The terminal points of the backward trajectories of 24-h travel duration for the catches made in the daytime on June 2 and 3 were distributed over the sea. It is suggested those catches were not a result of immigration from overseas.

EAT values from 2008 to 2011

The EAT values from January 1 to the emergence date each year are shown in Table 2. The emigration peak in 2010 was directly observed in daily catches in the net trap in Tongzhou, China. The emergence dates in 2008, 2009, and 2011 were estimated from immigration dates in Japan and Korea, which were monitored by use of the net traps there.

As an example, trends of the EAT value in 2008, 2009, and 2010 are shown in Fig. 5b. The EAT values did not increase much during January and February, and started to grow similarly in March in each of the 3 years, but they then diverged, because of subsequent different temperature trends in the spring. The EAT prediction for May 30 2011 is shown in Fig. 5a. The latest value was that on May 28 (2 days before May 30) because of the time lag of the data distribution. The EAT threshold, an average of the EATs in 2008, 2009, and 2010 in Table 2, was set at 453.7 degree days, which was exceeded by the predicted EAT on June 2.

The emigration period for prediction

Table 2 indicates the variations in the EAT value at emergence (variations of −39.1 to +35.9 degree days from

Table 2 Effective accumulated temperature for *L. striatellus* from January 1 to emergence date

Year	Effective accumulated temperature	Emergence date	Emigration date in the source	Immigration date in Japan or Korea
2008	476.2	June 2	June 4	June 5 in western Japan
2009	445.4	May 29	May 31	June 1 in western Korea
2010	438.4	June 8	June 10	(No immigration occurred.)
2011	401.2	May 28	May 30	May 31 in western Korea
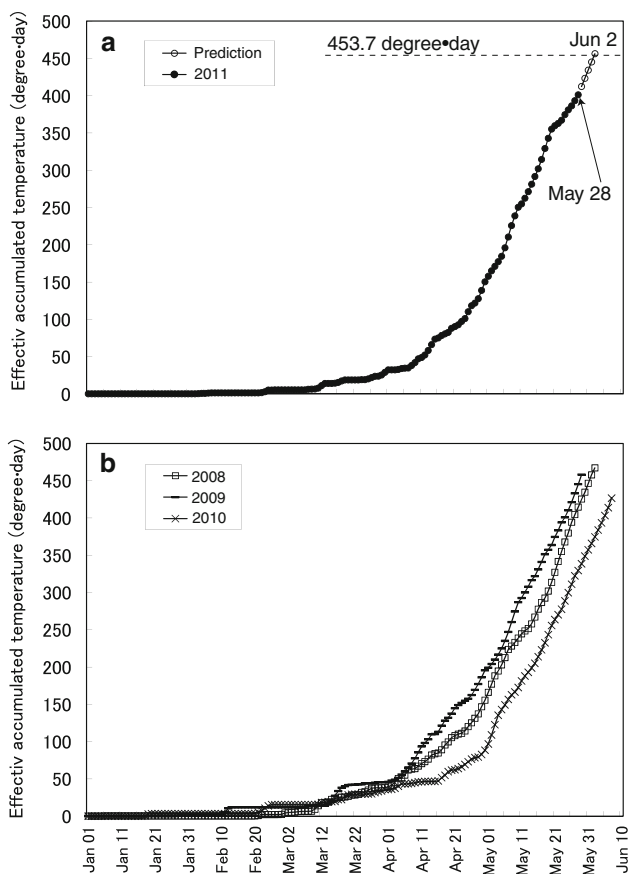
Fig. 5 Effective accumulated temperature (EAT) for the Chinese *L. striatellus* population. **a** shows the prediction of EAT in 2011. The predicted value exceeded the threshold of 453.7 degree days on June 2, which was estimated on May 30. **b** shows the trend of EAT values in 2008, 2009, and 2010. The calculation was terminated on the estimated emigration date in each year

the average). These values corresponded to −3.6 to +3.3 days if a daily increase of 11 degree days was used. Because of this error, a time of 3 days was used for pre-emergence in the emigration period. A time of 5 days was selected for post-emergence in the emigration period

because *L. striatellus* adults 1–3 day(s) old after emergence have been observed to emigrate from Shandong province, China (Zhang et al. 2011), and the 3 days of error in the emergence prediction plus 2 days for the pre-emigration make up a total of 5 days. In total, the emigration period for prediction of migration was set at 9 days (3 days + 1 day of emergence date + 5 days).

Prediction of migration, and its evaluation

For example, an EAT threshold for emergence prediction in 2011 was found to be 453.3 degree days (Table 3). By use of this value, on 30 May 2011 the emergence date was predicted to be June 2 (Fig. 5a). The predicted migration started on May 30 (=June 2—3 days) and continued until June 7 (Table 3). Examples of predicted migration clouds are shown in Fig. 6. Among a total of 18 predictions in 2011, three that started from Jiangsu province on May 30 and 31 were to arrive over western Korea on May 31 and June 1 (Fig. 6g–i), corresponding to catches during the night on May 31 and during the day on June 1 (Fig. 4d). The prediction of migrations to Korea were therefore successful. A prediction of migration to Japan on 6 June 2011 was incorrect, because no corresponding catch was observed in southern Kagoshima (JPP-NET 2012).

The predicted area and the evaluation of the predictions for 4 years in the cross-validation are summarized in Table 3 and Fig. 6. It is apparent that the emigration period of 9 days included all overseas migrations in 2008, 2009, and 2011. Though there was no overseas migration in 2010, the emigration peak on June 10 in China was included in the emigration period. In some predictions, migration clouds moved to North Korea (N. Korea in Table 3), where no monitoring data were available and the result was unknown. Outside the emigration periods, it is believed that no overseas migration occurred in the 4 years studied. The overall hit ratio for predictions (= the number of successful predictions/the total number of predictions) excluding the unknown cases was found to be 0.93 (29/31) (Table 3).

In addition, to compare the emergence dates in Table 2 that were assumed to be the true values, with the dates predicted on Day 0 in Table 3, the error of the emergence prediction was found to be within −3 to +5 days of the emergence dates.

Discussion

This paper presents a method for prediction of migration of *L. striatellus* consisting of the prediction of the emigration period and migration simulation during that period. The emigration period was predicted by use of the EAT, which

Table 3 Cross-validation of the prediction of overseas migrations

Year	EAT threshold (degree days)	Prediction date								
		Day −3	Day −2	Day −1	Day 0[a]	Day +1	Day +2	Day +3	Day +4	Day +5
		Predicted immigration area: prediction result[b]								
2008	428.3	May 27	May 28	May 29	May 30	May 31	Jun 01	Jun 02	Jun 03	Jun 04
		Korea: u	NM: S	NM: S	NM: S	N. Korea: u	NM: S	NM: S	NM: S	Japan: S
		Japan: ×								
2009	438.6	May 26	May 27	May 28	May 29	May 30	May 31	Jun 01	Jun 02	Jun 03
		NM: S	NM: S	NM: S	NM: S	Korea: u	Korea: S	N. Korea: u	NM: S	NM: S
2010	440.9	Jun 06	Jun 07	Jun 08	Jun 09	Jun 10	Jun 11	Jun 12	Jun 13	Jun 14
		NM: S	NM: S	NM: S	NM: S	NM: S	NM: S	NM: S	NM: S	NM: S
2011	453.3	May 30	May 31	Jun 01	Jun 02	Jun 03	Jun 04	Jun 05	Jun 06	Jun 07
		Korea: S	Korea: S	NM: S	N. Korea: u	NM: S	NM: S	NM: S	Japan: ×	N. Korea: u
		N. Korea: u								

[a] Day 0 of the prediction date corresponds to predicted emergence on Day −3

[b] A prediction is successful (S) when a predicted immigration area (Fig. 6) and a catch of immigration there (Fig. 4) matched each other, or when no predicted migration (NM) and no catch occurred concurrently in Korea or Japan. Otherwise, the prediction is wrong (×). Letter *u* represents unknown result because of the lack of monitoring data in Korea or North Korea (N. Korea)

was calculation from developmental data for Japanese *L. striatellus* populations and surface temperatures observed at the Chinese weather station in the center of Jiangsu province. The method of prediction was evaluated by the cross-validation method and net trap data in the immigration countries. The results showed that the overseas migrations in 2008, 2009 and 2011 were included in the emigration periods and were successfully predicted as simulated migration clouds, indicating that the proposed method is effective. Prediction of migration for future years will be performed with an EAT threshold of 440.3 degree days, an average of the four EAT values in Table 2.

The reason why the EAT value in Table 2 has decreased year by year is not clear. There may be regional differences in the insect's development in the source because Jiangsu province is a very large area, yet the temperature data for the prediction came from one weather station only in the central province. Division of the source into smaller regions might, therefore, improve prediction of the emigration period and overseas migration; this should be further investigated.

Another topic related to the EAT is the growth stage of the *L. striatellus* Jiangsu population on the first day of the year. Because emigrating insects in early June are those of the first generation of the overwintering population, the growth stage can be inversely estimated by subtracting an EAT value of 374.3 degree days for one generation (Table 1) (Noda 1989; Hachiya 1997). Both the remaining values, ranging from 101.9 to 26.8 degree days, and EAT values at various stages in Table 1 suggest that the hibernating stage on January 1 was the 3rd to 5th instar. Because

the 4th instar has previously been reported as a main diapause stage (Kisimoto 1958), the estimated 5th nymph in 2011 is more advanced than that. The emigration date in 2011 was also earlier in the emigration period than in other years (Table 2). In the previous study, southern Japanese *L. striatellus* populations emerged over shorter periods than a northern one under laboratory conditions (Noda 1992). This suggests there might be a similar difference in the diapause characteristics of the Chinese populations. It is important to examine emigration timing and area in the source area in relation to the insect's diapause.

Interestingly, catches from June 2 to 5 in 2011 at Taean occurred only during the daytime (Fig. 4d). Although the catch on June 3 was the largest in Fig. 4d, there was no prediction of migration from Jiangsu to Taean. Additionally, the backward trajectory analysis found no other Chinese regions as a source (data not shown). These daytime catches might, therefore, be a result of a local population, or of relocation activities of immigrants that arrived from China by June 1. However the origin of the catches is still unknown.

The weather conditions necessary to bring *L. striatellus* into Japan in early June were investigated in a previous study (Syobu et al. 2011). It was found that cold vortexes were the driving force for the overseas migrations. The frequency of this phenomenon, however, has been estimated to be low, occurring only twice in the most recent 10 years (2000–2009). On the other hand, in Korea, the frequency of overseas migrations may be larger than in Japan, currently occurring at least twice in 4 years (2008–2011). The outbreak of the disease also occurred in the western coastal regions of the Korean Peninsula in
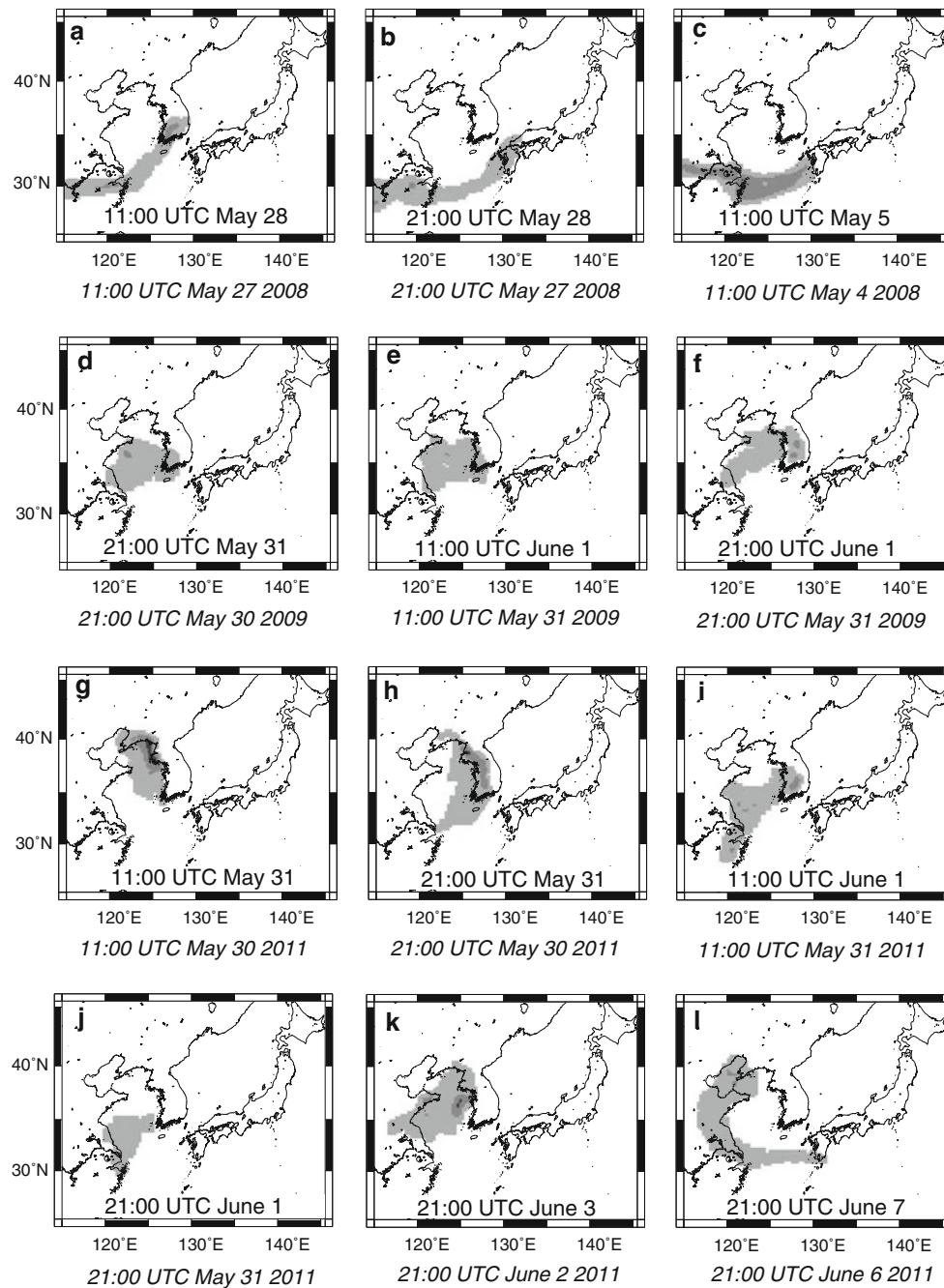
Fig. 6 Examples of prediction of migration. Migration clouds (*dark areas*) after 24 h (at the *upper time*) from each take-off time (*lower italic time*) are shown. Areas on the land covered with migration clouds are the predicted immigration areas

2001, 2007, and 2008 although their causes have not yet been analyzed (Kim 2009). This possible difference in frequency between the destinations may be due to differences in their direction and distance from the source. Korea is closer to Jiangsu province than western Japan, and southwesterly winds are typical when a low pressure system occurs in the northern hemisphere. A study similar to that by Syobu et al. (2011) is preferred to determine the frequency of overseas migrations in Korean cases.

The prediction technique for *L. striatellus* migrations developed in this study is mainly for overseas migrations from China to Korea or Japan. The same method may be applicable to analysis and prediction of domestic migrations in China. In fact, for example, migration clouds in 2010 moved to the north or northwest from Jiangsu province, suggesting that domestic migrations occurred. It has also been reported that the outbreak of rice strip diseases has spread to adjacent provinces, such as Zhejiang, Anhui,

Shandong, and Hubei (Wei et al. 2009; Wang et al. 2008). Analysis of domestic migrations is a topic for a future study.

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