Migration analyses and predictions for migratory insect pests toward Japan

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ABSTRACT

The oriental fruit fly, *Bactrocera dorsalis* (Hendel), complex was eradicated in 1986 in Japan, and the state of eradication has been maintained until present. However, male adults of *B. dorsalis* complex were occasionally caught in the surveillance network in southwestern islands of Okinawa and Kagoshima Prefectures. Assuming if these catches were wind-borne migrations, possible source could be estimated with trajectory analysis. The results indicated one third of all the catches from 1986 to 2012 in Okinawa were found to be due to possible wind-borne migration. In 72 percent of those cases, Taiwan was estimated as possible source. In Taiwan, southeastern part was often estimated as source area. On the other hand, several catch cases occurred in 2015, 2017 and 2018 in Kagoshima Prefecture, northwestern part of Taiwan was estimated as source area. Southwesterly winds in the *Bai-u* rainy season were key factor for these estimated migrations. The migration prediction model for the white-backed planthopper, *Sogatella furcifera* (Horváth), was modified by both fining horizontal resolution and implementing assumed landing processes. The prediction was evaluated with net trap data at five sites in three years in Miyazaki Prefecture. The results indicated the prediction hitting ratio has been improved to be 83.8%, demonstrating that the simulation method is one possible approach to unknown landing process. The common cutworm, *Spodoptera litura*, is highly dispersible insect pest and attacks soybean leaves in summer in western Japan. Its dispersion was monitored with searchlight trap and entomological radar. At the same time, soybean leaf damages were investigated. The two-year survey results indicated that the catch peak of the searchlight trap preceded the leaf damage caused by *S. litura* larvae by 3-7 days, potentially suggesting that a short-term forecasting of soybean damage based on the monitoring with the searchlight trap might be feasible. To get firm conclusions, repetition of the survey for one more year will be necessary.

Keywords: migration, prediction, *Bactrocera dorsalis* complex, *Nilaparvata lugens*, *Sogatella furcifera, Laodelphax striatellus*, *Spodoptera litura*, entomological radar

INTRODUCTION

There are many migratory insects [4] or highly dispersible insects. Among them, our study targets are six agricultural insect pest species that immigrate from overseas into Japan: the oriental fruit fly, *Bactrocera dorsalis* complex, the brown planthopper, *Nilaparvata lugens* (Stål), the white-backed planthopper, *Sogatella furcifera*, the small brown planthopper, *Laodelphax striatellus* (Fallén), the common cutworm, *Spodoptera litura* and the oriental armyworm, *Mythimna separata* (Walker).

B. dorsalis complex has been eradicated in Japan in 1986 [10]. Although the state of eradication has been kept since then, male adults were occasionally trapped in the surveillance trap on Japanese southwestern islands every year [15, 22]. Wind-borne immigration source was estimated for these catches [21, 22], and the results are discussed in this paper.

Rice planthoppers are important migratory pests in rice production in Asia. Basically, the East Asian population of *N. lugens* and *S. furcifera* overwinter in the middle to northern Vietnam and Hainan Province of China, they emigrate to southern China in spring, multiply for a few generations there, and migrate northeastward again into Taiwan, Japan, Korea and northern mainland of China [20]. On the other hand, *L. striatellus* can overwinter in mid-latitude region and is thought to be indigenous. However, it was found that a population in eastern China occasionally disperse overseas to Korea and Japan [18, 20]. For these overseas movements toward Japan, prediction systems were developed for users in plant protection stations nationwide [16, 19]. Recently, migration prediction method for *N. lugens* and *S. furcifera* has been improved to present a prediction in a fine spatial resolution. The related research activities are summarized in this paper.

S. litura is also a migratory pest and it is suggested that *S. litura* immigrates from overseas into western Japan from May to mid-July when windy weather conditions occurred around Japan [24]. The species is highly dispersible and polyphagous insect pest that attacks a variety of crops, including vegetables, maize, soybean, flowers, and fruit trees. Of these, soybean seeded in mid-to-late July in western Japan usually

experiences attack by *S. litura* larvae from mid-August to September. To develop a method to forecast soybean leaf damage caused by the larvae, insect dispersion was monitored with a x-band entomological radar and a searchlight trap during the summer soybean season in 2016 and 2017 in western Japan. The results so far are introduced and discussed.

A migratory insect pest other than the above-mentioned ones, the oriental armyworm, *M. separata* is also an important migratory pest [(7)]. The insect immigrates often into northern Japan, or on rare occasions into other regions, mainly in late May to early June (Fig. 2) [(11)]. In the latter case, many larvae suddenly occurred in western Japan in late June 2017 [(25)]. This incident triggered an international research between Japan and China on migration of *M. separata*. This project is not presented in this paper but will be briefly introduced in my conference presentation.

(1) *B. dorsalis* complex

The accomplishment of the eradication of *B. dorsalis* complex in 1986 in Japan never eliminated the insect's problem. The reality has been the opposite. A few to tens of *B. dorsalis* complex has been caught in the surveillance traps every year in Okinawa Prefecture [(15)], and lately this insect has been occasionally captured on southern islands of Kagoshima Prefecture [(22)]. In general, possible arrival routes of the trapped insects are two: accidental importation of infested fruits, or wind-borne immigration from the source regions.

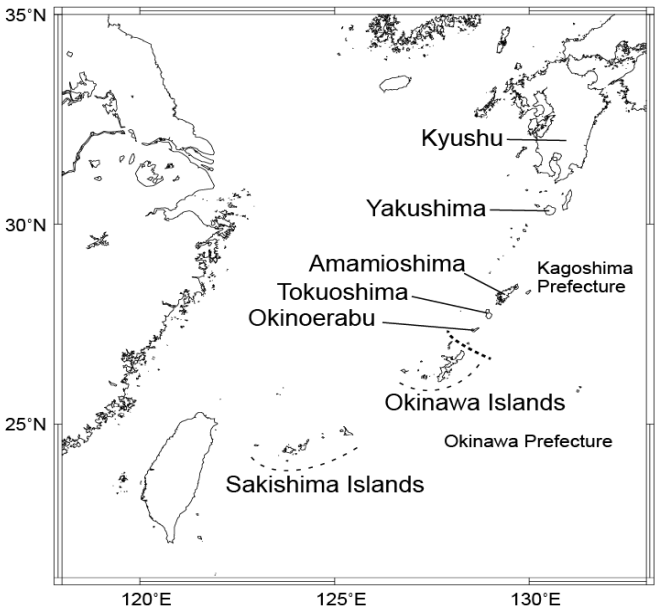


Fig. 1 Study area

Source estimation for Okinawa Prefecture

The latter route for catch cases from 1986 to 2012 in Okinawa was analyzed with trajectory analysis [21]. The surveillance data showed that more insects were trapped on southern Sakishima Islands than northern Okinawa Islands [21] (Fig. 1). Sakishima Islands are closer to Taiwan.

Possible source was estimated by investigating whether there was any air-current connecting between possible source areas and a trapped site before trapping. For that purpose, backward trajectories starting at 500 m above the ground over the trapped site in Okinawa Prefecture were calculated. Twenty-four trajectories for each day started at an interval of one hour, and their trajectory duration was set to be 24 h. Since the time interval of sample collection was mainly set to be 14 days, the analysis period for each catch was set to 14 days. Therefore, totally 336 trajectories for one trapped case were calculated.

The results indicated that in 66 percent, or two thirds, of all the trapped cases, the trajectories were found to reach over any of the possible sources: Taiwan, the Philippines or southern China [21], suggesting wind-borne immigration (Fig. 2). Taiwan was estimated as the source in 71.8 % of the wind-borne dispersion cases, following the Philippines (24.3 %) and southern China (3.9 %) [21]. A southeastern part of Taiwan, mainly Taitung area, was often estimated as the source area, because southwesterly winds often brew in the dispersion events. The peak period of the dispersion was found to occur in June, the *Bai-u* rainy season. Since Taiwan is very close to Sakishima Islands (Fig. 1), and the insect density in Taiwan increases in summer [13], where environmental and entomological conditions as the source seem to be sufficient. In other occasion, southerly winds occurred around a high-pressure system over the Pacific Ocean or at times of typhoon approach. In such cases, the Philippines was estimated as the source.

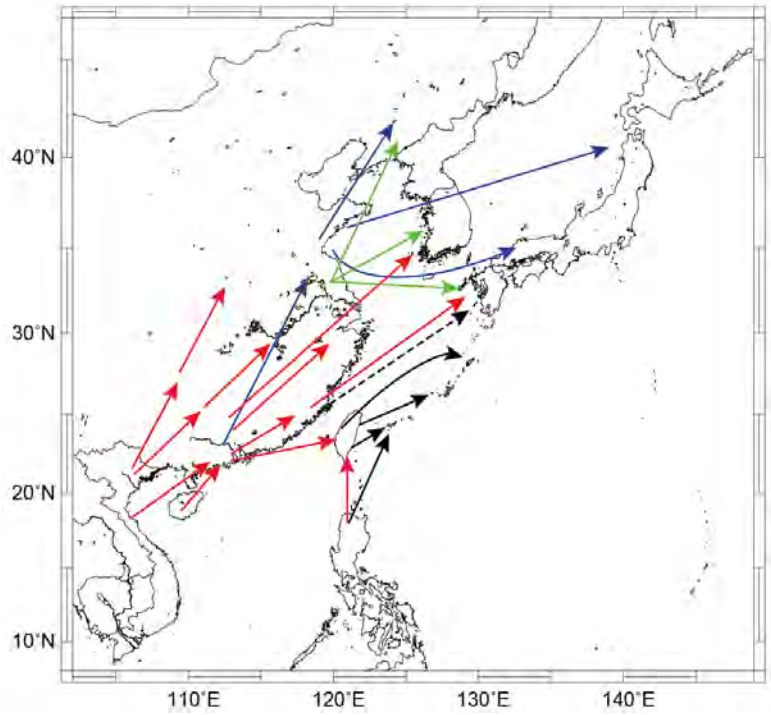


Fig. 2. Schematic of major migration routes of *S. dorsalis* complex (red), *S. furcifera* and *N. lugens* (red), *L. striatellus* (green), and *M. separata* (blue).

Source estimation for Kagoshima Prefecture

In 2015, many *B. dorsalis* complex were trapped and many infested fruits were found on Amamioshima, Yakushima and Tokunoshima Islands in Kagoshima Prefecture [(22)]. At the same time, several *B. dorsalis* males were also found on some islands of Okinawa. A trapped insect on Amamioshima Island was firstly found on June 30, and a trapped insect was found also on Kume Island in Okinawa on July 3 [(22)]. To find the source for these trapped cases, trajectory analysis was performed. The method was the same as described above for Okinawa. The results indicated that northwestern and eastern part of Taiwan were found to be the source for the Amamioshima and Kume Island, respectively. Inversely, forward trajectories from a northwestern point (Taoyuan: 24.90ºN, 121.22ºE) or a west-central point (Yuanlin: 23.96ºN, 120.59ºE) on Taiwan reached over Amamioshima Island for 5 days (June 25-29), or 3 days (June 25-27), respectively. This result suggested western parts of Taiwan were the source for early immigrants on Amamioshima Island in 2015 [(22)].

Moreover, *B. dorsalis* males are also trapped on several islands in Kagoshima Prefecture in 2017 and 2018 (Table 1, Fig. 1). The backward trajectory analysis for

these trapping cases indicated that the northwestern part of Taiwan was estimated as the source.

Table 1 Monitoring data and the trajectory analysis in 2017 and 2018 in Kagoshima Prefecture

Date of collection	Island name (Starting location for trajectories)	Number of trapped *B. dorsalis* males	Date and height for backward trajectories that reached Taiwan	Estimated source
June 21, 2017	Okinoerabu	1	June 12, 13	Northwestern
June 22, 2017	Okinoerabu	1	500m	Taiwan (NWT)
June 27, 2017	Okinoerabu	1		
July 5, 2017	Okinoerabu	2		
July 5, 2017	Tokunoshima	1	June 26, 27, 1000m	NWT
July 5, 2017	Yakushima	4	June 24	NWT
July 10, 2017	Yakushima	3	1000m	
August 1, 2017	Yakushima	1		
August 22, 2017	Yakushima	1	Augsut 9, 10, 11	NWT
August 24, 2017	Yakushima	2	500m	
August 28, 2017	Yakushima	1		
June 5, 2018	Okinoerabu	1	May 27,500m	NWT
June 5, 2018	Tokunoshima	2	May 27	NWT
June 14, 2018	Tokunoshima	1	500m	
June 7, 2018	Amamioshima	1	May 27	NWT
June 14, 2018	Amamioshima	1	500m	

Discussion

The southwestern islands of Japan are distributed long from the southwest to the northeast. There are mainly southwesterly winds in the rainy season. Therefore, it is suggested that the source areas in Taiwan for dispersions to Okinawa and Kagoshima are different (Fig. 2). So far, it is estimated that *B. dorsalis* complex arrived on Yakushima Island (Table 1), which is a farther point in Kagoshima Prefecture from Taiwan (Fig. 1). It is unknown whether the species could arrive in the mainland of Kyushu, or not. However, if the insect could arrive in Kyushu, the possible source area would be Fujian Province, like the migration case of rice planthoppers, whose source was estimated to be Fujian Province [(17)], because Kyushu Island is located in the north of the southwestern islands, southern China is located in the southwestern direction (southwesterly wind direction) from Kyushu. It might be possible that climate change

could affect the distribution and density of *B. dorsalis* complex in southern China. Therefore, it is important to survey the *B. dorsalis* complex in all western Japan.

(2) Rice planthoppers

There are two types of predictions for rice planthoppers in Japanese real-time prediction systems: one for tropical species, *S. furcifera* and *N. lugens*, the other for *L. striatellus*. This is mainly because take-off areas and migration seasons are different between the two groups. *S. furcifera* and *N. lugens* migrating towards Japan mainly take off in southern China in late June to early July, the *Bai-u* rainy season (Fig. 2) [16,20]. These planthoppers emigrate from fields of the early rice crop harvested in July there. In contrast, *L. striatellus* migrates from eastern China, mainly Jiangsu Province, to Korea, northeastern China or occasionally Japan, from late May to early June (Fig. 2) [18, 20]. *L. striatellus* emigrates from wheat fields during harvesting season [23].

However, there are many common features that are listed as follows: the basic prediction model is the same; the horizontal resolution is 33 km; modelled planthoppers take off in the source regions and fly up for some time to make use of upper air-currents; take-off occurs every day during prediction period; fly at the same velocity as winds, taking vertical diffusion into account; relative aerial density of the planthoppers below 100 m above the ground over Japan are used to know the arrival of the insect; modelled planthoppers never land on the surface, so that the prediction of immigration amount is not feasible; email notification is available when prediction is positive for prefectures previously registered by a user; and the database of past predictions is available [16,19]. Using these systems, the insects' arrival time and area is known in real time. The prediction information as well as the monitoring data of light and net traps or the density survey in rice fields are used by prefectural plant protection offices to determine the dates of major immigrations. Based on the immigration dates, the plant protection offices predict the insect's growth stage and release information on insect's density in fields and the right time for chemical control.

Although the current prediction system works well, there are some rooms for improvement to fulfill the users' requests. One was the horizontal resolution of the prediction. It is set at 33 km now that is not enough to distinguish local difference of the immigration within a prefecture of about 100-km size. A prediction in a fine mesh was desired. Another area that the users demanded for improvement was on the prediction of immigration density, or the arriving insect number. The current systems

present an arrival area only. Therefore, this study was set to improve the horizontal resolution of the model calculation and to implement the landing processes to approach the prediction of density

Materials and methods

1. Survey area and species

Since the number of trapped planthoppers is larger in western Japan, Miyazaki Prefecture on Kyushu Island was selected as the survey area. Five net traps with a 1-m ring and tow net mounted at 10 m above the ground were newly set up at five different points; they located in Nobeoka (northern), Miyazaki and Kunitomi (middle), Miyakonojo (southern), and Ebino (southwestern) in the prefecture. The traps were operated from June to July each for the following three years, 2015, 2016, and 2017. Samples were collected at around 09:00 hours local time every morning. *S. furcifera* was selected as a study target, because its trapped number was much larger than that of *N. lugens*.

2. Modification of the migration model

The horizontal resolution of the model was changed to 9 km. The value was determined considering both the distance between local regions in a prefecture (about a few 10-km scale), and calculation cost that increases rapidly as the resolution becomes finer.

No direct observation of rice planthopper's landing process has been reported. Therefore, two types of assumed landing processes were implemented based on two facts. The one fact is that immigration density decreases as migration distance from the source increases (e.g. Fig.3 of Lu et al. [12]), or that the trap catch number is larger in western part of Japan than that in eastern part (Fig.5 of Kisimoto [8], Fig. 8 of Nasu [14]). The other fact is that landing is associated with rain belts of front, suggesting rain falls make planthoppers land [6,9,12,26].

A landing process that planthoppers land at a temporally constant rate, dry landing process, was implemented as follows:

$dC = -\alpha C dt;\ \alpha = const.$ ie. $C = exp(-\alpha t)$

where C, dC, t and dt are aerial density of planthopper, change of aerial density, time, and time step of calculation, respectively. These means that the aerial density will exponentially decrease with flight duration. The value of the constant factor is unknown

and was assumed to be 0.001 with a time step of 40 sec. Fig. 2 indicates how aerial density decreases as flight duration increases. This process was turned on at 15 hours after each take off, when planthoppers flying toward Japan on the East China Sea.

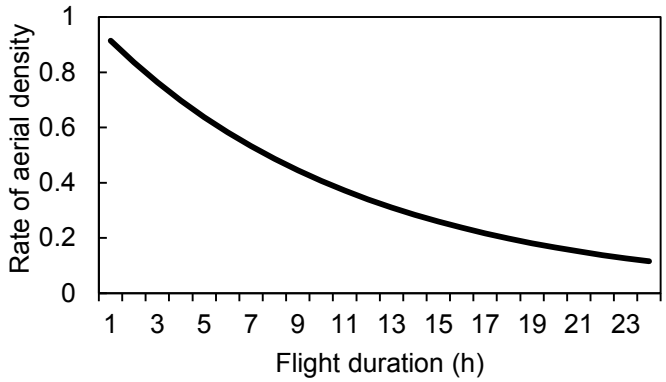


Fig. 2 Decrease of aerial density in dry landing process

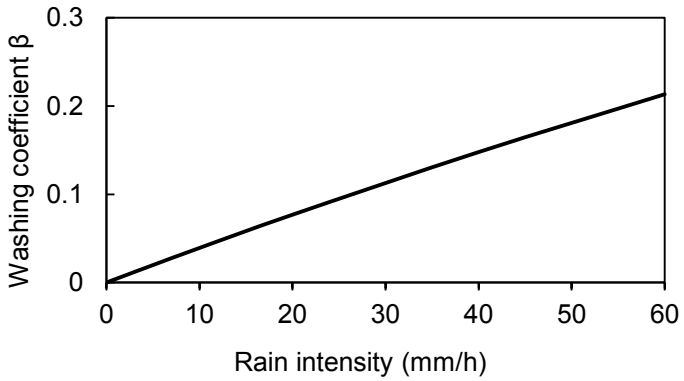


Fig. 3 Washing coefficient depending on rain intensity

When it rains, planthoppers are assumed to land depending on rain intensity. Since there is no direct observation of such a wet landing process, change of aerial density by rain fall was assumed referring to wet deposition process in meteorology as follows:

$dC = -\beta C dt;\ \beta = 1-exp(-aRdt)$

where β, a, and R are washing coefficient (s^{-1}), constant factor (0.0001), rain intensity (mm/s), respectively. The washing coefficient β changes with rain intensity as shown in Fig. 3.

The constant factors, α and a were determined by trial and error, or repeating prediction simulations with changes of values.

A square takeoff area, 3º in latitude by 2.5º in longitude, was set on Fujian Province that is a main possible source for planthoppers immigrating into western Japan. Takeoff time was set at dusk, 19:00 hours Chinese local time.

In evaluation of the new prediction, relative density of *S. furcifera* that landed on the ground in Japan was calculated, and immigration at a monitoring site was determined when relative density was larger than a threshold. Prediction data were compared with daily net trap monitoring data at 5 sites in Miyazaki Prefecture from 2015 to 2017. When no insect was captured, no immigration was regarded to have occurred, and when more than one was captured, immigration was regarded to have occurred.

Results

The monitoring data for three years indicated that there was difference in the number of caught *S. furcifera* within the prefecture; the numbers in southern and southwestern areas were larger than those in eastern and northern areas. The prediction evaluation result indicated that hitting ratio averaged in three years at the five sites was found to be 83.8 % (Table 2). For comparison, evaluation of a prediction model of 9-km resolution without the landing processes was also performed. The result showed the hitting ratio of 77.1 %.

Table 2 Evaluation of the new prediction method in Miyazaki Prefecture

Year	Hitting ratio (%)					
	Ebino	Miyakonojo	Kunitomi	Miyazaki	Nobeoka	Average
2015	85.0	77.5	80.0	70.0	87.5	80.0
2016	82.9	77.5	80.0	77.5	70.0	77.6
2017	96.5	87.9	94.8	93.1	96.5	93.8
Average	88.1	81.0	84.9	80.2	84.7	83.8

Summary

The results showed the prediction accuracy of the high-resolution model was improved with the landing processes. The hitting ratio was over 80 % that is good enough for actual use in a next step. However, the evaluation was performed only in one prefecture in this study. Therefore, an evaluation in other prefectures is desired as well. Nevertheless, it is rather difficult to perform such an evaluation with dense net trap monitoring in a wide area, due to its high evaluation cost. Therefore, it is practical that a prototype migration prediction system with the new model is operated, while the user's feedback is collected for future improvements.

Our knowledge on the landing process of rice planthoppers is very limited. Direct observation with an entomological radar, for example, is impossible because the insects arrive mostly when it rains and radar observation is prevented from rain drops. However, this study presented a different approach to the landing process, an approach with simulation. At least, the results suggested that some landing processes affected the number of immigrants. The fine horizontal resolution should have affected the predicted number of immigrants, because topography in the model became finer when the horizontal resolution was changed, and simulated winds over the mountains could also be changed. The contribution of each of the three factors (rain, distance, and resolution) to the number of migrants is not clear at this moment. Further study is necessary.

(3) *Spodoptera litura*

S. litura is a polyphagous insect pest that attacks a variety of crops. Of these, soybean seeded in mid-to-late July in western Japan usually experiences attack by larvae from mid-August to September. Usually, Japanese farmers perform chemical control based on the severity of actual damage in their soybean fields. However, the number of fields managed by a farmer or an agricultural company is growing recently, it is getting harder to observe every field frequently. The damage could get worse if an initial occurrence was missed. Therefore, this study aims to develop a method to forecast soybean damage. If such forecasting could be realized, chemical control could be effectively timed to target the larvae in its early stages. In this study, therefore, dispersion of the common cutworm is investigated by using entomological radar and a searchlight trap to find the correlation with the soybean damage.

Materials and methods

1. Survey area

The area located in the Saga Plains, Saga Prefecture in western Japan, where rice and soybean are cultivated in summer, was used. The monitoring of the insect occurrence and soybean damage attacked by larvae of *S. litura* was conducted in 2016 and 2017. An entomological radar and a searchlight trap were located at the same place (33.3055°N, 130.3299°E). The soybean field used in 2016 was located about 300-m west of the monitoring site, and that used in 2017 was about 550-m north of the site.

2. Survey of soybean leaf damage

The number of soybean leaves damaged by *S. litura* was counted by checking all the leaves of 1,000 soybean plants in an experimental field to see if there were small white food mark dots on green leaves and newly hatched green 1st-instar larvae on the back of the leaf. The survey was conducted every Monday, Wednesday and Friday from early August to early October.

3. Vertically-emitting visible light trap

The searchlight trap was used to collect flying insects in the night sky. It consisted of a 1,000-watt metal halide lamp vertically emitting a strong narrow visible-light beam in the dark sky, with a large metal funnel set above an insect collection box. It was turned on at 19:00 hours local time and off at 24:00 hours. Samples were collected in the next morning. The species and sex of *S. litura* were later identified based on the morphology of genitalia.

4. Monitoring with entomological radar

A type of vertical-looking radar [2,3] was used to retrieve flight direction, height, speed, body alignment, body size, and shape parameters of individual insects passing over the radar continuously. These flight parameters were retrieved from radar signals with a method by Harman and Drake [5]. Unfortunately, because noise was on a rotary encoder signal, flight direction and body alignment could not be estimated in 2016. Therefore, surface wind direction at a weather station about 10-km southwest of the monitoring site was referenced for that year.

The radar receives various echoes from different species of insects and other animals in the air. To select only *S. litura*-type targets among all the observed echoes, body size and shape parameters of radar cross sections were used. The data were previously measured with live male samples in the laboratory. The measurement method was similar to that in Aldhous [1]. The radar cross section has a form of the equation: $a_0 + a_2*\cos 2ø + a_4*\cos 4ø$ (cm^2), where ø is an angle between the body axis and the polarization of microwave. The conditions found to select *S. litura*-like targets were as follows:

$$0.4 \leq a_0 \leq 1.0 \ (cm^2);\ 1 \leq a_2/a_0 \leq 1.35;\ 0.2 \leq a_2/a_0 \leq 0.5$$

Results

Several catch peaks of *S. litura* including female adults were found in late August and late September in the searchlight trap in 2016. Large catch peaks occurred on 20

Aug and 20-23 Sep 2016. The flight parameters of these *S. litura*-like targets were estimated by the radar. Although no flight direction data were available this year due to the noise on the radar signal, surface wind direction at the weather station closest to the site was northerly during outstanding peaks on 20 Aug and 20-23 Sep. There are other peaks on 26, 30 Aug, and 26 Sep. Wind directions on 30 Aug were southwesterly, and on the other peak days was northerly. The average flight height on the northerly days was 700–800 m. Meanwhile, the average flight speed ranged from 7.6–13.6 m/s.

The results of the 2016 survey also showed that soybean leaf damage appeared some days after corresponding catch by the searchlight trap. The time difference between the catch peaks and the corresponding peaks of the number of newly damaged leaves was found to be 3 to 5 days.

The catch numbers in 2017 were smaller than those in the previous year. The number of newly damaged leaves was also lower than that in 2016. Therefore, pairing of the two peaks was rather difficult for this year. The time difference between the two peaks seemed to be 3–7 days. Among six catch peaks on 27, 29 Aug, 12, 22, 29 Sep, and 3 Oct, only three on 12, 29 Sep and 3 Oct 2017 had many *S. litura*-like targets in the radar observation. It was estimated that the targets moved toward the south or southeast. The estimated flight heights were 700–800 m, which was similar to the previous year. The average of flight speed ranged from 6.3–12.3 m/s.

Discussion

The study showed that the catch peak of the searchlight trap preceded the leaf damage caused by *S. litura* larvae by 3–7 days. The egg period of the insect is reported to be four days at air temperatures of 25 °C. Therefore, this result indicated that the catch of the searchlight trap potentially indicated the insect's arrival in the survey area. Thus, the study suggests that a short-term forecasting of soybean damage based on the monitoring results with the searchlight trap might be feasible. However, since the numbers of the 2017 survey were too small for firm conclusions, repetition of the survey for one more year will be necessary.

The flight height estimated by the radar was high and close to the height of the mountains located to the north of the monitoring site. The closest distance between the site and the mountains was only 3 km. This suggests that the insects dispersed from the

mountains, or that they came flying over the mountains from somewhere beyond. It is necessary to identify the insect source.

Large target numbers in the northerly winds in late September and October in the two-year study should indicate the likely returning migrations toward the south in autumn. The numbers must include not only echoes from *S. litura*, but also other insect species with similar body size and shape to *S. litura*, because the radar technique is unable to discriminate them. Therefore, the combination of entomological radar and the searchlight trap is necessary to investigate the dispersion of a specific insect target.

SUMMARY

Japan is located to the east of China, which is a big source of migratory insects in mid-latitudes of the north sphere of the rotating Earth, and from there the basic direction of air-currents is southwesterly or westerly. In addition, a distance from the source area to Japan ranges between a few hundreds to one thousand km, which migratory insects can easily fly over. In other words, Japan seems to be an ideal destiny for the migratory insects to land. Taiwan seems to be under a similar environmental condition, too. Therefore, sharing the knowledge and technologies shown in this study should benefit the researchers and growers of both countries. In fact, scientists from NARO and TARI are conducting an international joint research on monitoring and management of *B. dorsalis* complex since 2016. In the research, the Japanese scientists always thank the kind and effective supports provided by Taiwanese scientists. The author hopes that our collaborations continue to not only improve plant protection research, but to expand to other agricultural researches for even deeper understanding in the future.

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