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Analysis on the migration of first-generation *Mythimna separata* (Walker) in China in 2013

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Abstract

Mythimna separata (Walker) is an important pest which can cause serious damages to cereal crops. In the past two decades, several heavy outbreaks have taken place in northern China. In order to develop a fine-scale method of forecasting outbreaks, population data were collected in northern China using searchlight traps and ground light traps. A background weather pattern analysis and trajectory analysis were performed *via* the Weather Research and Forecast (WRF) and FLEXPART models. Our results showed that heavy migration of first-generation *M. separata* appeared in northern China in 2013. In Yanqing District, Beijing, the cumulative number of captured adults in searchlight traps was around 250 000 and the daily maximum for trapped moths was 86 000. During the peak period, the majority of *M. separata* moths arrived after 00:00 every night. The sex ratio (female:male) at each monitoring site was greater than 1 and greatly fluctuated with population dynamics. During the migration peak, prevailing downdraft winds benefited *M. separata* moths to land passively. Trajectory simulation showed that immigrants were from Anhui, Jiangsu and Hubei provinces and most of them could continue to fly into the northeastern regions of China. These results provide technical support for fine-scale forecasting of the outbreak of *M. separata* at meso- and micro-scale.

Keywords: *Mythimna separata*, population dynamics, migration trajectory

1. Introduction

Mythimna separata (Walker) (Lepidoptera: Noctuidae) is an important insect pest in China. Damages are caused by larvae on rice and wheat in southern China, wheat in central China, and corn, millet, sorghum and wheat in northern and northeastern China (Li 1993). Before the 1960s, the migratory capabilities of *M. separata* were unknown and it was very difficult to provide satisfactory forecasting and early warning information to farmers. During the 1960s, a

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research group led by Prof. Li Guangbo from the Institute of Plant Protection of the Chinese Academy of Agricultural Sciences established the National Research Collaboration Group for *M*. *separata*. *Via* a large-scale mark-release-recapture experiment, the group clarified the migration and infestation pattern of *M*. *separata* in eastern China and established a novel forecasting method for this insect (Li *et al.* 1964; Lin *et al.* 1964; Chen and Bao 1987; Chen *et al.* 1989). Since then, the occurrence of *M*. *separata* has been greatly reduced due to significant reductions of wheat planting area in southern China. Over the past two decades, large-scale outbreaks of *M*. *separata* have rarely occurred with the exception of heavy infestations of the third-generation in northern China in 2002 (Pan and Zhai 2009), and in northern and northeastern China in 2012 (Zhang *et al.* 2012).

Insect pest migration and outbreaks are closely related to local meteorological factors such as temperature, humidity and precipitation (Wang and Zhang 2001; Jiang *et al*. 2003; Yin *et al.* 2003). Previous studies have confirmed the general *M*. *separata* seasonal north-south migration patterns in China and its migration course, source area and immigration events can be largely predicted with the application of searchlight traps, radar observation and trajectory analysis model (Feng *et al.* 2008; Zhang Y H *et al.* 2013). However, it is very difficult to accurately forecast outbreaks at the meso- and micro-scale (Lin 1990). To accurately predict *M*. *separata* population dynamics, it is necessary to monitor and analyze its migration course at the meso- and micro-scale. More specifically, to make control decisions it is particularly vital to predict the probability of *M*. *separata* landing on a crop and subsequent re-migration. In this paper, *M*. *separata* migration events were analyzed to determine the influence of weather and terrain factors on its migration and landing. Trajectory simulation was used to determine the source area where these pests originated. These results offer aid in fine-scale forecasting and the prevention and control of *M*. *separata* in the future.

2. Materials and methods

2.1. Monitoring locations

Monitoring sites for aerial insect pest populations were located in Yanqing District, Beijing (40°31´N, 116°5´E) and the Luancheng Ecological Experiment Station of the Chinese Academy of Sciences (37°53´N, 114°41´E). Ground monitoring sites were located in Henan, Hebei, Shandong, Liaoning, Inner Mongolia, Jilin and Heilongjiang.

2.2. Population data collection

Daily interval sampling data were collected by searchlight and ground traps; parameters for the setup of searchlight traps have been previously described (Zhang 2013). The search light trap was turned on at sunset and switched off at sunrise the following day. Whole night samples were divided into nine intervals, and each interval lasted approximately 1 h. Quantities and sex ratios of captured *M*. *separata* were recorded from each interval during the 2013 migration season. Ovarian developmental stage is important in judging migration events as female migrators are often of underdeveloped ovarian stages (Lin 1990; Zhang Y H *et al.* 2013). On each migration day, 50 randomly sampled females were dissected to determine ovarian developmental stage and were divided into five categories (Lin 1990; Jiang *et al.* 2009). On dates when female numbers were less than 50, all available females were dissected. For local ground data, the automatic light traps were setup to capture daily catch sizes of *M*. *separata* by the local plant protection stations in the provinces mentioned above.

2.3. Meteorological and map data collection

The global meteorological data from the Final Operational Global Analysis Data (FNL) at 1°×1° was collected every 6 h and was provided by the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), China (http://rda.ucar.edu). Precipitation and topographic data were taken from the National Meteorological Information Center, China. Terrain data were downloaded from the official website of the Weather Research and Forecast (WRF) Center (http://www.wrf-model.org/). Chinese provincial administrative maps at a scale of 1:4 000 000 were downloaded from the website of the National Basic Geographic Information Center (http://nfgis.nsdi.gov.cn). Precipitation data were collected at 30-min intervals using the portable weather station deployed at the monitoring site in Yanqing.

2.4. Data analysis

Migration event assessments *M*. *separata* cannot overwinter north of the 0°C isotherm (also referred to as the area along 33–34°N) in January (Li *et al.* 1964). According to the law of effective accumulative temperature, native *M*. *separata* moths do not emerge until early July. This means that all moths trapped in Yanqing before July were immigrants of the first generation. In order to finely assess migration events, the capture data from the searchlight traps and ground traps were analyzed in tandem with the ovarian developmental data as previously described by Feng *et al.* (2004) and Zhang Y H *et al.* (2013), respectively. When *M. separata* migration was detected on any given night, we concurrently performed a more extensive analysis using the meteorological data.

Background weather analysis using the WRF model The WRF model is a numerical forecasting simulator used for weather research and real-time forecasting, developed jointly by the National Center for Atmospheric Research, the National Center for Atmospheric Environment Research and the University of Oklahoma. It can carry out nested analyses, where each nested area can be operated independently (Skamarock *et al.* 2008). In this paper, the WRF_3.4.1 model was used to simulate the background weather patterns from the FNL data. The simulation was carried out using double nests. The meteorological element field was at a scale of 36 km×36 km and 12 km×12 km (Table 1) and the final output data were scaled to 20 inches. Output data were then converted into a Grid Analysis and Display System (GrADS) organization using the ARWpost Program. With the NCEP/NCAR re-analysis data and the output data mentioned above, GrADS was used to extract hourly background weather patterns to acquire the general atmospheric circulation characteristics and weather conditions over northern China.

Trajectory analysis FLEXPART is a Lagrangian transport and dispersion model developed by the Norwegian Institute of Atmospheric Research (Favaretto *et al.* 2004). It is suitable for the macro- and meso-scale transportation, diffusion, wet and dry sedimentation, and radiation attenuation of tracers in the atmosphere by calculating the trajectories of large amounts of particles released by point, line, area or volumetric sources (Stohl *et al.* 2005). Trajectory analysis was carried out in FLEXPART using the output data from the WRF_3.4.1 model and monitoring sites were set up as starting point. For searchlight trap samples, the intervals with significantly larger catch numbers compared to the average (determined by a chi-square test) were considered the main pest migration periods, while the median time within the interval was defined as the starting time for trajectory analysis (Lin *et al.* 1963; Zhang and Li 1985; Cao *et al.* 1995; Chen *et al.* 1995; Feng *et al.* 2008). When catch numbers from each interval were not significantly different, the start time was designated at sunset for forward simulations and at sunrise for backward simulations. All backward simulations were terminated at sunset and forward simulations were terminated at sunrise. All simulations were performed over five continuous nights. The hourly migration trajectory data were imported into ArcGIS10.1 (ESRI, Redlands CA) for modeling. Trajectories that were not of biological significance were removed.

3. Results

3.1. Aerial population dynamics

In 2013, the earliest appearance of adult *M. separata* was on the night of May 17–18th in searchlight traps and on June 2nd–3rd in ground light traps in Yanqing. By June 22nd –23rd, the cumulative number of trapped adult *M. separata* in searchlight and ground light traps was around 250 000 and 5 300, respectively. The majority of moths (99%) were trapped in June. There were obvious fluctuations in the number of first-generation trapped adults in searchlight and ground light traps and when plotted, four peaks in captured populations could be observed. The largest peak appeared on the night of June 7–8th in the searchlight traps and on June 9–10th in ground light traps. Within searchlight and ground light traps, the maximum number of trapped moths was 86 000 and 1 600, respectively, and the cumulative number of trapped moths during the three nights accounted for 88.4 and 87.2% of the total migration process, respectively (Fig. 1). During peak periods, most moths were trapped after 00:00 in searchlight traps. On the night of June 6–7th and 7–8th, trapped moths in searchlight traps before 00:00 accounted for 18.13 and 22.92% of the total, but

Table 1 Parameterization scheme for the Weather Research and Forecasting (WRF) model

Domain sequence	Center point of model	Grid number	Horizontal resolution (km)	Start position	Vertical layer	Map projection	Integration time step (s)	Physical parameters[1]						
								Microphysical process scheme	Long-wave radiation scheme	Short-wave radiation scheme	Surface layer scheme	Land/Water surface scheme	Boundary layer scheme	Cumulus parameterization scheme
Domain 1 (d01)	115.9°E, 40.4°N	65×49	36	1,1	27	Lambert	180	WSM3	RRTM	Dudhia	Monin-Obukhov	Noah	YSU	Grell
Domain 2 (d02)	115.9°E, 40.4°N	91×61	12	19,15	27	Lambert	60	WSM3	RRTM	Dudhia	Monin-Obukhov	Noah	YSU	Grell

[1] WSM3, WRF Single-Moment 3-class; RRTM, the Rapid Radiative Transfer Model; YSU, Yonsei University, Republic of Korea.

accounted for 81.87 and 77.08% after 00:00, respectively.

3.2. Ground light trap population dynamics

From the end of May to the beginning of June, many peaks in moth catch amounts appeared in ground light traps in Shandong, Henan, and Hebei provinces. The earliest peak appeared during May 30th to June 3rd in Dancheng, Yongcheng, Mengzhou, and Qinyang, Henan Province (Table 2). The earliest peak period was postponed by 1–3 d in the Shandong and Hebei monitoring sites that were located north of the Henan monitoring site. The Hebei Province peak periods appeared on June 5–9th. Being located even more north, the peak period duration in Inner Mongolia and northeastern China was much longer, appearing after June 5th. Generally, sites in southern Beijing trapped more moths. The cumulative trapped moths by a single light trap was 3 748, 3 380, and 3 225 at Yongcheng, Mengzhou, and Dancheng in Henan Province, respectively; 597 and 541 at Qufu and Wenshang in Shandong, respectively; and 6 164 at Daming in Hebei Province. The largest catch size trapped by searchlights was in Luancheng County with 8 736 moths trapped and occurred on the night of June 5th. Numbers of trapped moths from Inner Mongolia and northeastern China were generally much smaller and the number of cumulative trapped moths at these locations during the whole migration period was less than 100 (Table 2).

3.3. Physiological characteristics

Up to June 22nd, sex identification was conducted on 31 683 moths (♀:♂=17 966:13 717) in total. We found that the sex ratio was significantly higher than 1 (χ^2=569.83, *df*=1, *P*<0.001). From the May 3rd through June 22nd,

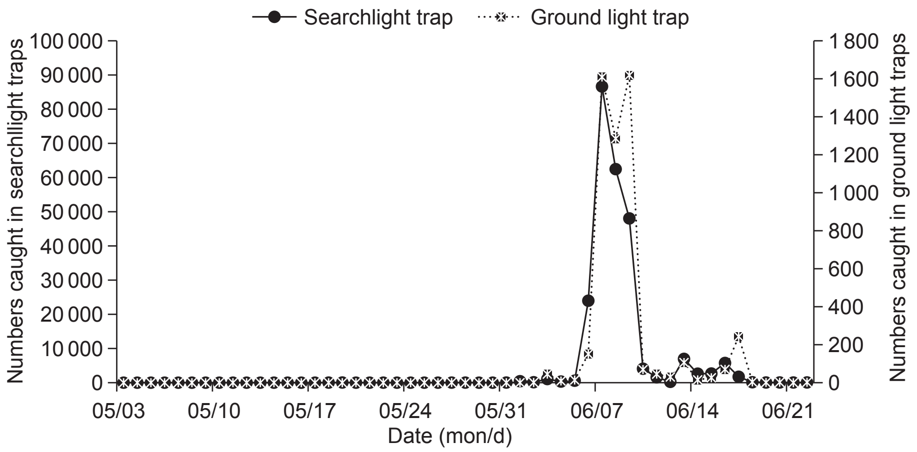

Fig. 1 Nightly catch amounts of adult *Mythimna separata* in searchlight traps and ground light traps at Yanqing, China in 2013.

Table 2 Migration peaks for *Mythimna separata* captured in China in 2013

Site	Location	Peak period (mon/d–mon/d)	Cumulative trapped moth	Sex ratio (♀:♂)	Ovary grade
Dancheng	115.18°E, 33.64°N	05/30–06/02	3 225	1.1	I–II (70%)
Yongcheng	116.45°E, 33.93°N	05/30–06/03	3 748	>1	I–II (70%)
Mengzhou	112.79°E, 34.91°N	05/30–06/03	3 380	1.7	I–II (70%)
Qinyang	112.93°E, 35.08°N	05/31–06/04	490	1.4	I–II (100%)
Jining	116.59°E, 35.41°N	06/01–06/05	1 100	>1	II–III (80%)
Daming	115.14°E, 36.28°N	06/03–06/05	6 164	>1	II–III (80%)
Ningjin	114.92°E, 37.62°N	06/05–06/06	1 186	>1	II–III (80%)
Xiyang	113.70°E, 37.61°N	06/06–06/09	826	>1	II–IV (80%)
Luancheng	114.64°E, 37.90°N	06/05–06/09	~40 000	1.2	II–III (80%)
Renqiu	116.08°E, 38.68°N	06/05–06/07	10 464	>1	II–III (80%)
Beipiao	112.93°E, 41.80°N	06/06–06/10	70	1.4	III–IV (80%)
Yushu	126.53°E, 44.84°N	06/05–06/14	85	>1	III–IV (90%)
Changling	123.97°E, 44.27°N	06/06–06/12	36	>1	III–IV (90%)
Tongliao	122.24°E, 43.65°N	06/05–06/13	87	3.1	III–V (90%)
Shuangcheng	126.31°E, 45.38°N	06/08–06/14	103	>1	III–V (90%)
Jixian	131.14°E, 46.73°N	06/08–06/14	256	>1	III–V (90%)

there were 25 d when identified moth numbers were more than 30 and statistical analysis was executed. Females were captured significantly more than males on 20 of the 25 days tested. In the remaining days when males were captured more than females, the highest ratio was 8.86 (♀:♂=390:44). Sex ratios changed with fluctuating population dynamics. As the peak period approached, the ratio largely fluctuated. Prior to May 30th, ratios were greater than or approaching 1, but after May 31st ratios increased rapidly and reached 8.86 on the night of June 1st–2nd. After this, the ratio declined to 1.39 on the night of June 5–6th. During the greatest peak period from June 6–9th, sex ratios fluctuated less dramatically than population sizes. In the late peak period from June 19th–21st, the ratio was less than 1. A chi-squared test showed that there were eight nights where captured females were significantly greater than males and twelve nights where the ratios were not significantly different from 1, including five nights with sex ratios less than 1, and seven nights with sex ratio greater than 1 (Fig. 2). In addition, all sex ratios determined from ground light traps were also greater than 1 (Table 2). More than 80% of trapped females were at grade II–III of ovarian development. During the peak period, ovarian stages did not change significantly for several days, following the physiological characteristics of typical migratory pests. Similar data were recorded in ground light traps (Table 2).

3.4. Relationship between catch sizes and wind direction

From late May to early June, winds in northern China were impacted by a subtropical anticyclone that gradually extended to the western region. From June 1st to 6th, there was a cyclone above the North China Plain and an anticyclone above the sea. As a result of the great difference between the winds in the center of anticyclone and cyclone, a southern low level jet was formed that benefited the migration of *M. separata*. From June 8th to 10th, a southwestern low level jet also accompanied the withdrawal of the subtropical anticyclone and benefited migration. During the peak period, frequent strong southern winds impacted northern China except during the nights of June 9–13th (Fig. 3). Captured *M. separata* population sizes were closely related to the direction of the wind. Trapped moths increased when southern winds occurred but decreased when the wind direction changed northward. On the night of June 3rd–4th, the first peak in captured moths appeared when the southern winds prevailed. On the night of June 4–5th, despite the southern winds, the captured population size decreased dramatically compared to the size of the previous night, possible due to heavy rainfall (Fig. 4). On the nights from June 6–9th, the heaviest migration night appeared when high speed southern winds (more than 10 m s^{-1}) prevailed. From the night of June 7–8th when the convergence of the wind field appeared along the latitude of 40.5°N, the captured population size gradually decreased.

3.5. Rainfall and downdraft frequency during migration period

From June 1st to 18th, there were five rainy days and three rainy nights (Fig. 4). During these days, downdrafts were popular on 13 of the nights except for the night of June 12–13th. On these nights, downdrafts were considered to be pressure gradient forces below 925 hPa while updraft

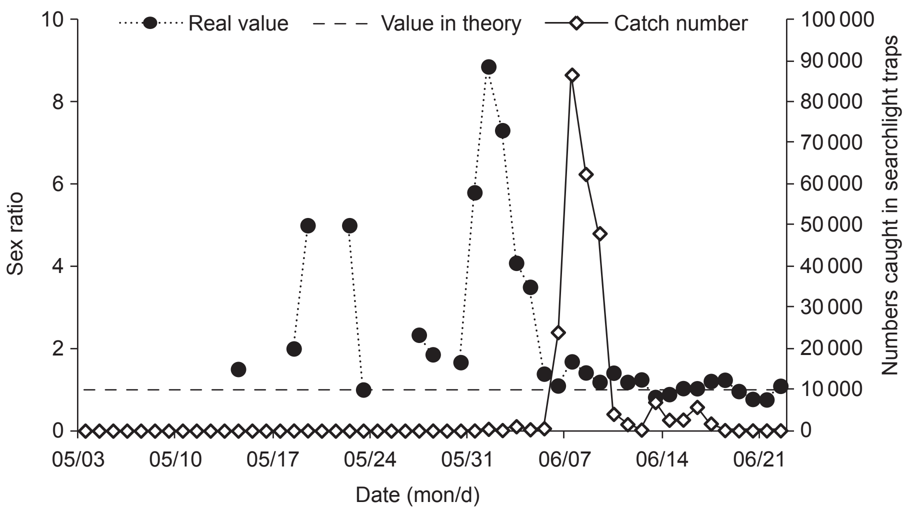

Fig. 2 The *Mythimna separata* sex ratio (female:male) and numbers caught in searchlight traps at Yanqing, China in 2013. According to Fisher's theory, the sex ratio should be 1, so sex value in theory in this figure was supposed to be 1.

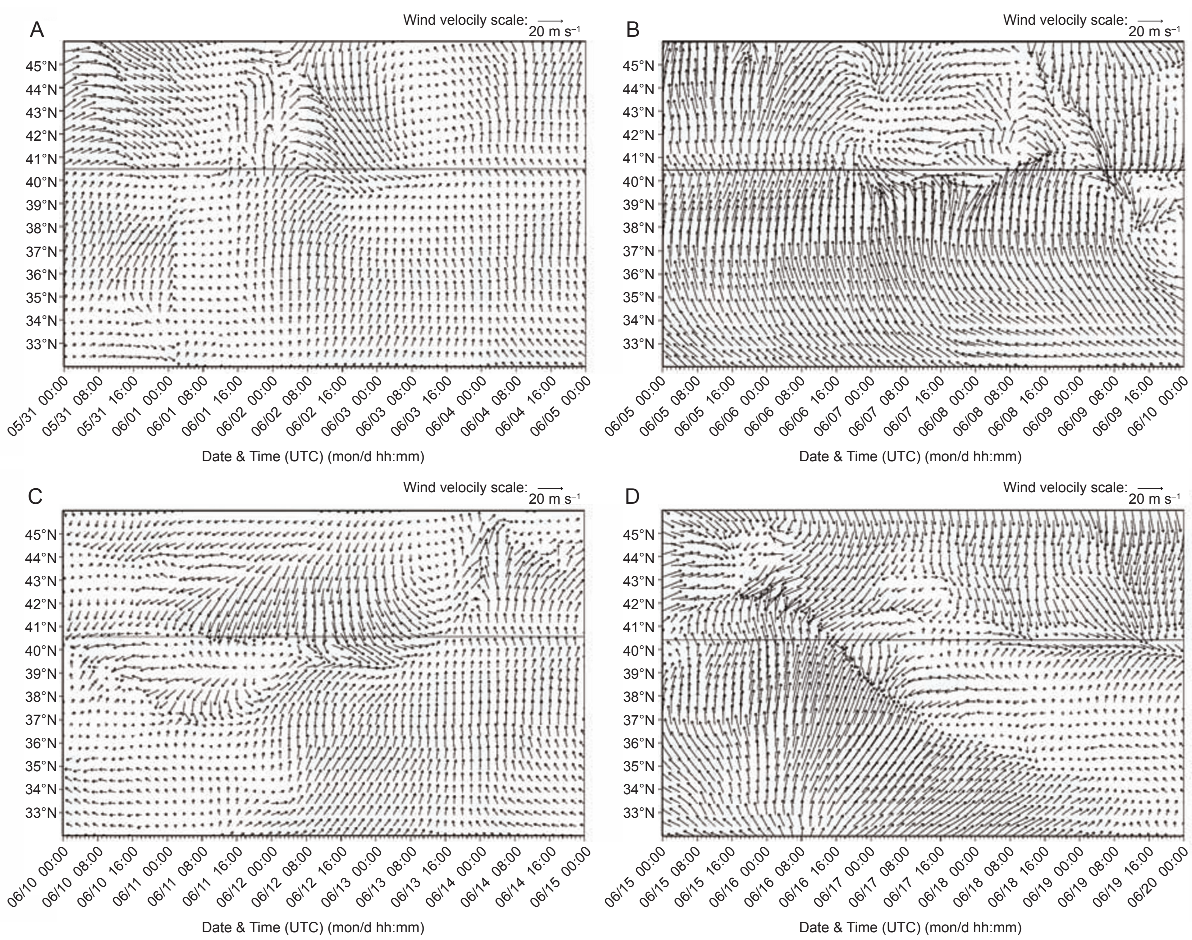

Fig. 3 Time-latitude profiles of wind fields along 116°E at 925 hPa in 2013 (m s^{-1}). A, May 31st–June 4th. B, June 5–9th. C, June 10–14th. D, June 15–19th. Transverse lines indicate latitude where monitor site was located. UTC, coordinated universal time.

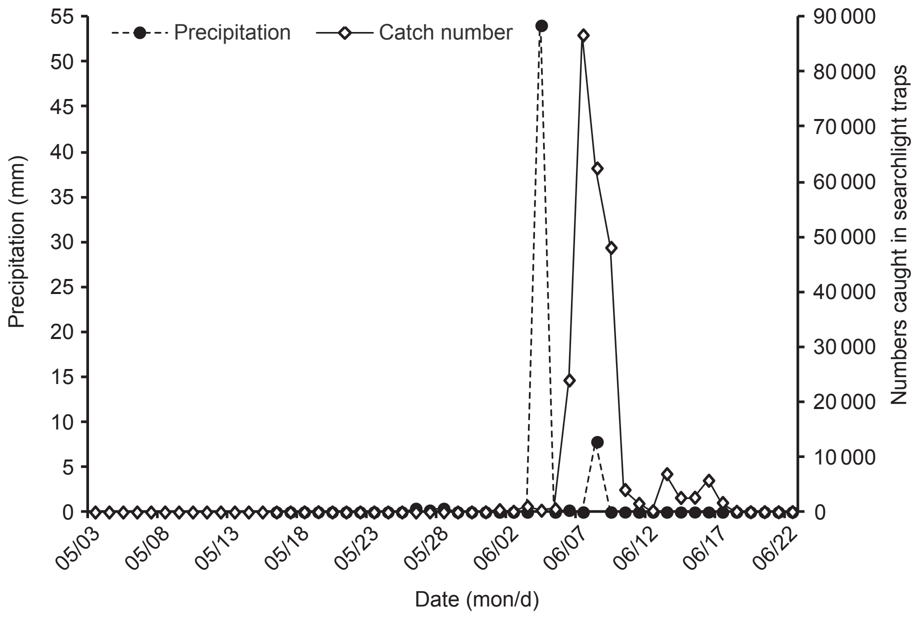

Fig. 4 Nightly precipitation and *Mythimna separata* numbers caught at monitoring site in Yanqing, China in 2013.

winds were measured above 925 hPa. When there were southern winds with downdrafts, the catch number increased. When the vertical velocity of the downdraft declined, the catch number decreased (Figs. 5 and 6). On the night of June 3rd–4th, the first peak in catch sizes appeared in Yanqing where southern winds and updrafts benefited the migration of *M. separata*. However, on the following night, a heavy rainfall with a strong downdraft developed among the Beijing-Tianjin-Hebei region and this heavy rainfall would block the departure of the migratory *M. separata*. This downdraft accompanied by rainfall resulted in passive landing and therefore the trapped number (324) was much smaller than that of the previous night (1 062). During the second peak in catch sizes, downdrafts took place over all the nights and vertical velocity averages of most nights (21:00–05:00) were greater than 0.002 m s^{-1} at 925 hPa, with the maximum being 0.008 m s^{-1} (Fig. 6). The vertical velocity measured during these nights could force *M. separata* to passively land. To our surprise, on the night of June 12–13th, although the wind direction was northward, the vertical fields were at an updraft, and peak catch numbers still transpired (Figs. 5 and 6).

3.6. Trajectory analysis

When backward and forward trajectories were stimulated

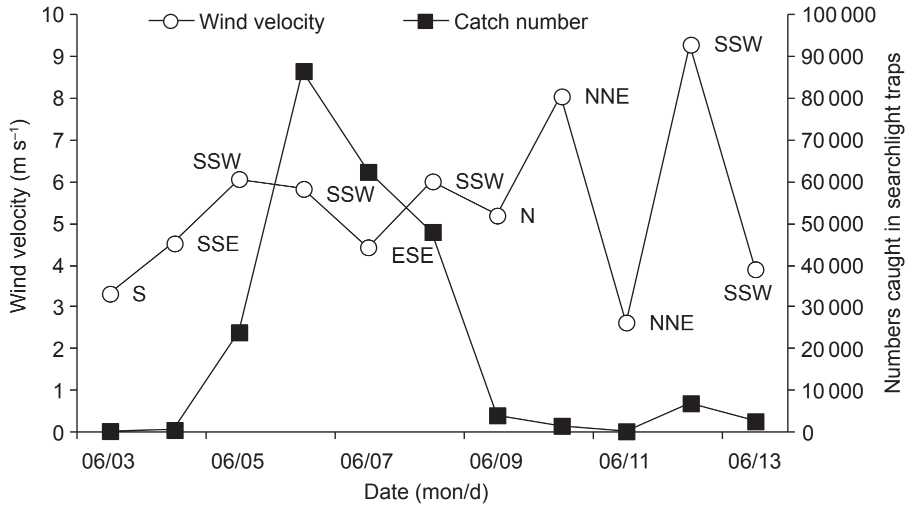

Fig. 5 Relationship between wind velocity at 925 hPa and *Mythimna separata* numbers caught at monitoring site in Yanqing, China in 2013. Letter near hollow circle were wind directions, S, W, E and N represent south, west, east and north, respectively.

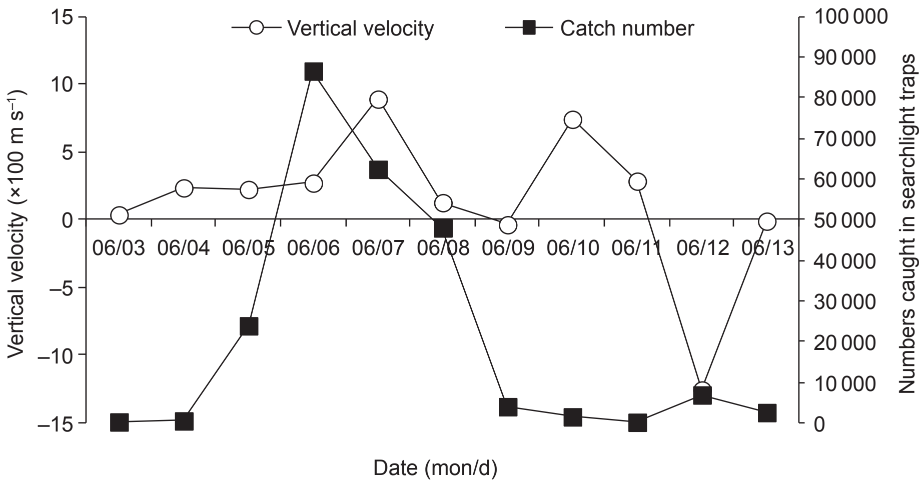

Fig. 6 Relationship between vertical velocity at 925 hPa and *Mythimna separata* numbers caught at monitoring site in Yanqing, China in 2013. For vertical velocity, negative values indicate updraft and positive values indicate downdraft. The vertical velocity values were very small and units were multiplied by 100.

where obvious migration events of *M. separata* appeared from local sites such as Daming County, Ningjin, Renqiu and Luancheng in Hebei Province, we found that first-generation moths were mainly originating from Shandong, Jiangsu, Anhui and Hubei (Fig. 7-A). The migratory trajectories seemed to be converged before migratory moths reached the Beijing-Tianjin-Hebei region. When they passed the Beijing-Tianjin-Hebei region, the migratory trajectories became dispersed (Fig. 7-B). Trapped moths from Yanqing mainly derived from Shiyan in Hubei, Nanyang in Henan, northern Jiangsu, Fuyang and Suqian in Anhui, and Jining in Shandong. The simulation of forward trajectories from Yanqing showed that *M. separata* moths could fly across Beijing or continue to migrate to western Liaoning, northeastern Heilongjiang and the junction of Inner Mongolia, Liaoning, and Jilin after a stopover in Beijing (Fig. 7-A). The simulated routes were in accordance with the trapped *M. separata* peak periods that appeared in the light traps at the plant protection stations in northeastern China (Table 2 and Fig. 7-A).

4. Discussion

Early studies have shown that first-generation *M. separata* moths have numerous bursts of high occurrence in early spring instead of one large peak occurrence. Furthermore, peak occurrence has also been shown to be consistent with strong southwest winds (Lin *et al.* 1963). Our monitoring data are in agreement with previous studies. In 2013, besides the main immigration peak found in the searchlight traps, there were also many small peaks before and after the main migration period. Data from ground light traps of local plant protection stations were similar to data from the searchlight trap in Yanqing, both indicating the presence of many occurrence peaks in the migration process. Furthermore, more northern regions seemingly had more peaks. Previous work showed that first-generation *M. separata* moths arrived in Liaoning, Jilin and Inner Mongolia from late May to early June, and in some places arrival date was delayed to late June (Chen *et al.* 1965, 1989). Peak occurrence dates derived from ground light traps were different, even at similar latitudes. Yanqing is located at the most northern part of China. In 2013, migratory first-generation moths above Yanqing was captured mainly during nights in early June (Fig. 1). This finding was consistent with the previous report. However, such an extensive migration of the first-generation *M. separata* moths has rarely been recorded prior to 2013. Extensive migration of this pest could cause serious damages to corn crops at this seasonal time because the highly sensitive corn seeding stage coincided with this migration. A future recommendation would be for the local plant protection stations to pay more attention to *M. separata* migration events in late June.

M. separata moths do not fly long distances during the daytime. To travel over long distances, they must fly over several nights. Simulation trajectory analysis illustrated

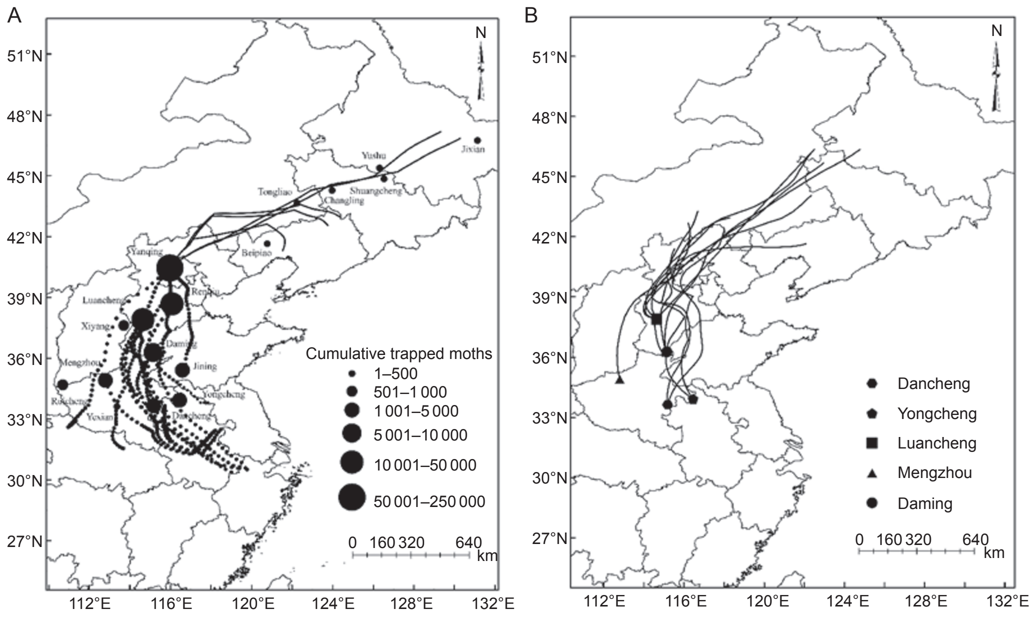

Fig. 7 The trajectories of *Mythimna separata* in north and northeastern China in 2013. A, the starting trajectory point began at the monitoring site in Yanqing, China, the black dotted line indicates backward trajectory while the solid line indicates forward trajectory. B, the starting trajectory point began at the monitoring sites from the plant protection stations presented in the legend, all were forward trajectories.

that moths passing by Yanqing could continue to fly to Inner Mongolia and the northeastern region. During the migration, some would stay for breeding and others would continue to fly, forming a progressive migration pattern. This could be the reason why total caught moths were fewer in traps from sites further north compared to those located more southern (Table 2). In addition, peak occurrences from the sites closer to the south appeared earlier and were delayed in northern sites.

Previous light trapping experiments showed that the numbers of captured females were different from that of captured males (Lin *et al*. 1963). The possible reason could be their flying ability. Migratory insects generally begin to migrate during the immature period after eclosion, so the ovarian development of the migratory females are often at lower stage, e.g., grades I and II (Lin 1990). In this study, we found that more than 80% of trapped females were at a developmental grades II–III, following the physiological characteristics of obligate migratory pests. In an early report, the sex ratio of different insect pest species trapped at various times were found to be different, and the sex ratio of a *M*. *separata* population enumerated from a light trap could be divided into three stages (Li *et al.* 1987). The first stage was 1–4 d after emergence, and gave a sex ratio close to 1. The second stage was 5–10 d after emergence, when ovaries were developing and the flight capacity of females weakened as a result of increasing weight. Therefore, the percentage of captured females reduced gradually. The third stage was 10 d after emergence when male moths accounted for the majority (Li *et al.* 1987; Lin 1990). Wang and Zhang (2001) found that the proportion of migratory females (52.47%) was significantly lower than that of migratory males (97.14%). For this season, our results were distinct from the previous report from Wang and Zhang (2001) but consistent with Lin (1990). When considering total examined *M*. *separata* moths, the trapped females were found at higher numbers compared to the males, with similar findings observed from the ground light trap moths. Furthermore, there were more days with a female to male ratio>1 than days with ratios<1. This ratio greatly fluctuated with the population dynamics. For other species such as *Scotogramma trifolii* and *Athetis lepigone*, sex ratios were similar to those of *M*. *separata* observed in this study. When the population rises, the sex ratio was significantly higher than 1, and when the population reaches a stable period, the sex ratio was close to or significantly less than 1 (Zhang *et al.* 2007; Zhang Z *et al.* 2013). The sex ratio pattern may be affected by different flying abilities. Further study is needed to test whether there are other factors affecting the sex ratio.

Landing is an important process of insect migration. How and where migrators land is considered to be vital for pest insect forecasting. The landing process can be affected by many factors, including passive effects from circadian rhythms, rainfalls and downdrafts, and initiative effects from suitable breeding habitats or pheromones from the female. Landing effects from topographic stress can be sorted into two sides. The first is the obstructing effect of rising elevation, where a migratory route can be blocked directly or *M*. *separata* could be forced to fly at greater heights and thus their flight blocked due to air temperature reduction with the increased elevation (Chapman *et al.* 2008, 2010; Nowinszky *et al.* 2012; Zhang Y H *et al.* 2013). The second is that rising terrain could induce warm and humid airflow and bring rainfall, which can result in *M*. *separata* landing (Hu *et al.* 2013, 2014). In 2013, although large numbers of *M*. *separata* were captured in the searchlight trap, we could not ascertain whether or not they landed passively due to the lack of radar observations. We made an assumption based on the weather pattern being beneficial for landing instead of declaring a single factor that could be important during the landing process. Yanqing is located in northern China and surrounded by the Taihang Mountains and Yanshan Mountains which could also have an effect on *M*. *separata* migration as mentioned above. We found that southern wind was necessary for migrants and this finding was consistent with a previous study (Lin *et al.* 1990). Rainfall and downdraft winds were also very important factors. On some nights with heavy rainfall, migration was blocked. On other nights when wind direction was suitable but vertical velocity was not suitable for landing, the captured numbers also decreased (Figs. 4–6). In the future, the landing process would be better understood if additional migration event data were collected using multiple tools especially entomological radars.

In the past, trajectory analysis models were an important tool in atmospheric transport and diffusion analysis. These models were introduced into the study of plant disease epidemics and pest migration, because migratory insects are windborne (Chapman *et al.* 2010). However, trajectory analysis in early research was only conducted with meteorological data with low spatial and temporal resolution, so it was difficult to guarantee the accuracy of the trajectory simulation output. Fortunately, new models such as WRF-FLEXPART were built in recent years. The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) is often run when doing trajectory analysis (Zhang *et al.* 2012; Zhang Y H *et al.* 2013). Compared with HYSPLIT, FLEXPART is designed with terrain factors in mind and more accurately simulates migration trajectory (Hu *et al.* 2013, 2014; Bao *et al.* 2016). In this study, WRF-FLEXPART was used instead of HYSPLIT. We found that trapped *M*. *separata* moths may originate from Shiyan in Hubei, Nanyang in Henan, northern Jiangsu and Fuyang and Suqian in Anhui, and Jining in Shandong. Furthermore, according to the bulletins from the National Agriculture

Technique Extension Service Centre, first-generation *M*. *separata* occurred in large numbers in Shanghai, northwest of Anhui, as well as in areas along the Yangtze River in Jiangsu, northern Hubei and in moderate numbers in the middle and lower reaches of the Yangtze River and most parts of Jianghuai. From south to north, migrating routes were aggregated into a narrow channel that was consistent with the ground light trap data. The trap data showed that there were a large number of *M*. *separata* moths in the northern areas compared to that in southern areas during the trajectory simulation periods. When the *M*. *separata* flew over Yanqing, although they could continue to migrate into some areas in northeastern China, only a few migrators were able to successfully arrive at these monitoring sites. Perhaps during the migration, many migrators landed prematurely. This is why we should deploy additional monitoring sites along the migration routes. Finally, high-density second-generation larvae occurred in many areas of Shandong in 2013, demonstrating that the WRF-FLEXPART model trajectory simulation offered high accuracy.

Insect migration is a very complex progress that can be affected by many factors such as wind fields, rainfall, temperature and humidity. In this study we reported the migration pattern of first-generation *M*. *separata* appearing in China in 2013. The number of trapped *M*. *separata* moths was astonishing compared to previous records. With our analysis, we found that several features were related to the migratory population. The first was that populations occur in waves and can suddenly increase as we saw with our captured moth data. The second was that peak occurrence was consistent with strong southwestern winds. Lastly, we found that the number of trapped females was significantly higher than males and the captured female moths were at a lower grade developmental stage, consistent with other migratory species. The statistics on the relationship among catch size, rainfall and downdraft showed that rainfall and downdraft have the greatest influence on migratory *M*. *separata* landing and that WRF-FLEXPART was able to provide high accuracy trajectory stimulations. Unfortunately, without an entomological radar, we have not observed the landing progress directly. *M*. *separata* forecasting would benefit from surveying when heavy populations occur in a source area with southern winds ensuing concurrently.

5. Conclusion

According to our observation data, heavy migration of first-generation of *M*. *separata* appeared in northern China in 2013. In Yanqing District, Beijing, the cumulative number of captured adults in searchlight traps was around 250 000 and the daily maximum for trapped moths was 86 000. The sex ratio at each monitoring site was greater than 1 and greatly fluctuated with population dynamics. With the assistance of WRF model and related outputs, we found that prevailing downdraft winds benefited *M*. *separata* moths to land passively during the migration peak and trajectory simulation showed that immigrants were from Anhui, Jiangsu and Hubei provinces and most of them could continue to fly into the northeastern regions of China. Migration is a very complicate process, includes takeoff, transmission and landing. Whether migrants could land or not is vital to judge their damages at defined place. In the future, we could provide more accurate pest information to farmers at meso- and micro-scale with this method mentioned in this article.

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