Migration Monitoring and Route Analysis of the Oriental Armyworm *Mythimna separata* (Walker) in Northeast China

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Abstract: The oriental armyworm *Mythimna separata* (Walker) is a worldwide migratory pest that threatens food security in China. Previous studies have clarified the general migration regularity of *M. separata* in East Asia, but knowledge of migration routes over northeast China, especially in autumn as well as the impact by climate change in recent years, is still limited. From 2017 to 2020, we monitored the migration of *M. separata* in northeast China by searchlight traps and simulated moth trajectories by the HYSPLIT model. The *M. separata* moths had three main migration periods in northeast China, and there were obvious seasonal differences at different latitudes. The spring and summer migrants (late May to early-mid June and late July to early August) came from the southern Shandong Province and migrated to the north via Hebei/Shandong-Liaoning-Jilin-Heilongjiang. Moreover, more than half of the autumn trapped insects from late August to mid-late September migrated in the provinces where the sites are located, southward via Heilongjiang-Jilin-Liaoning. These results clarified the migration route of *M. separata* in northeast China and their relationship with the insect source in north China, thereby providing a theoretical basis for regional monitoring, early warning, and management of the pest.

Keywords: Northeast China; oriental armyworm; migration routes; distribution of insect sources; regional management

1. Introduction

Oriental armyworm, *Mythimna separata* (Walker) (Lepidoptera: Noctuidae), is a typical migratory agricultural pest that causes damage to 104 crops, including maize, wheat, rice, sorghum, and sugar cane, and is mainly distributed in the region between 45° N and 45° S, 60° E and 170° W, including 27 countries and regions in Asia and Oceania [1]. *M. separata* has no diapause characteristic, which provides an advantage for continuous population propagation under suitable environmental conditions, and *M. separata* can achieve annual breeding in low-latitude areas, but not in middle and high-latitude areas in due to its weak overwintering ability [2]. Historically, there are many reports of regional outbreaks of *M. separata* worldwide, such as the severe occurrence of pastures in New Zealand in 1959 [3], and the outbreak in Japan in 1984 [4,5]. Outbreaks that occurred in many parts of India reduced crop yields by 60–80% from 1977 to 1981 [6–8]. More than 6.667 million hectares occurred annually from 1950 to 2013 in China, and particularly in 2012, outbreaks of *M. separata* caused food losses of 6.578 million tons in northeast China [9]. These *M. separata* occurrence cases of *M. separata* usually exhibit regionality, burstiness, and destructiveness, which are used to bring great difficulties to the management of this
pest and cause enormous losses to crop production globally. Therefore, it is necessary to clarify the regional migration regularity of *M. separata* and to develop both monitoring and early-warning technologies.

*M. separata* obtains the greatest reproductive benefits from long-distance seasonal migration activities across latitudes, which is one of the main reasons for heavy regional attacks [10]. The migration activities of *M. separata* in eastern China could be divided into four stages: I, overwintering individuals immigrate to the Jianghuai area in spring (March–April); II, the first generation in the Jianghuai area immigrate to northeast China in early summer (May–June); III, the second generation in northeast China immigrate into northern China at the end of summer (July–August); IV, the third generation in northern China immigrate to southern China in early autumn (August–September) [11–13]. During northward migration, partial migrants caused infestation by flying into Japan and South Korea across the Yellow Sea [14]. By sea surface trapping, vertical searchlight trapping, and entomological radar and other measures, Chinese researchers have successfully observed the large-scale seasonal north-south migration activities of adults in north China and areas around Bohai Gulf [15–19]. In northeast China, *M. separata* mainly be observed flying at 300–600 m in spring, 500–700 m in summer and below 500 m above ground in autumn [18], which revealed seasonal changes in the flight height layer of *M. separata* and greatly promoted the research of migration activities.

Global warming, frequent extreme weather events, regional adjustment of crop structure, and other factors directly or indirectly affect the occurrence and migration pattern of *M. separata* [13,20,21]. The previous study indicated that global warming led to faster reproduction, increased population, longer occurrence period and northern overwinter limit-line, extending of pests [22]. An increase in temperature within a certain range enhanced the flight ability of *M. separata* [23–25], which may cause an increasing number of *M. separata* migrants to fly into higher latitudes and altitudes. In the past 20 years, the total area of maize, wheat, and other crops with pest infestation has increased by 24%, due to climate warming [26,27]. Northeast China is located at high latitudes, and the grain output in 2017 was 118.755 million tons, accounting for 19.22%, making it the most important grain production base in China [28]. With the restructuring of crop cultivation, the development of modern intensive agricultural cultivation patterns, and the shrinking biodiversity of farmland ecosystems, there is an increasing risk of regional outbreaks of *M. separata* in northeast China.

The overall migration pattern of *M. separata* in China has been studied deeply [11,16,18,19], however, there is a lack of accurate analysis and simulation of the trajectory of *M. separata* in northeast China under a warming climate in recent years. In this paper, the migration of *M. separata* populations in northeast China from 2017 to 2020 was monitored, the influences of seasonal winds on migration behavior and migration routes were analyzed, and immigration sources were simulated and quantified, which will provide a theoretical foundation for accurate, monitoring and prediction of migration dynamic and regional management of *M. separata* in northeast China.

### 2. Materials and Methods

#### 2.1. Migration Monitoring of *M. separata*

Harbin City (HB, 45°44’17” N, 126°43’34” E) in Heilongjiang Province, Changchun City (CC, 43°48’25” N, 125°24’18” E) in Jilin Province, and Shenyang City (SY, 41°29’24” N, 123°19’48” E) in Liaoning Province were selected as monitoring sites in northeast China (Figure 1). Vertical searchlight traps (equipped with 1000 W metal halide bulbs, Shanghai Yaming Lighting Co., Ltd., Shanghai, China) were used for sampling migrants at altitudes up to 500 m [29]. All light traps were turned on at sunset (BST pm 19:00) and turned off at sunrise (BST am 06:00) every day, and all captures were frozen to death in a −20 °C freezer every morning. *M. separata* moths were sorted out by morphological identification and the number of daily captures of *M. separata* was recorded as population dynamics data in each study site. To determine the peak migration event of *M. separata*, the classification method
proposed by Lin Changshan [30] was adopted and formulated as the following criteria based on daily captures of *M. separata* (N).

![Figure 1. Monitoring sites for *M. separata* migration in Northeast China. HB: Harbin city in Heilongjiang Province; CC: Changchun city in Jilin Province; SY: Shenyang city in Liaoning Province; BH: Beihuang Island in Shandong Province.](image)

1. If $N_{\text{date-m}} \geq 10$, and $N_{\text{date-m}} \geq 2N_{\text{date-(m-1)}}$, then date-m was regarded as a peak date.
2. If $N_{\text{date-m}}$ is peak date, and $N_{\text{date-(m+1)}} \geq 10$, then date (m + 1) was still regarded as peak date.
3. If $N_{\text{date-m}} < 10$, date-m was regarded as a non-peak date.
4. Each peak date or continuity peak period with an interval of more than 2 non-peak dates was regarded as the next peak migration event.

2.2. Wind Transportation on Migratory Activity

To explore the atmospheric conditions during the migration of *M. separata*, we used the reanalysis meteorological data in “ERA5 hourly data on single levels from 1959 to present”, which with a spatial resolution of 0.25° × 0.25° global grids hourly from the European Centre for Medium-Range Weather Forecasts (ECMWF). To indicate the overall wind field during the migration period, we extracted the daily zonal component $u$ and meridional wind component $v$ on the 925 hPa at 1200 to 2200 UTC (BST pm 20:00 to BST am 6:00 the next day) in the monitoring period from 2017 to 2020 and synthesized the average nocturnal wind fields map using the wind vector data during the migration periods of *M. separata*. In addition, *M. separata* moths were not trapped every day during the migration period. Therefore, to investigate the wind field of the peak migration events during the migration period, we created wind rose diagrams to represent the frequency of wind direction and wind speed in these peak migration events.

2.3. Analysis of Migration Routes and Insect Emigration Source

HYPLIT model (Hybrid Single Particle Lagrangian Integrated), developed by the National Oceanic and Atmospheric Administration (NOAA) and the Australian Bureau of Meteorology (BOM), was used for migratory trajectory analysis [31]. The model parameters were set as follows [32]:

1. Setting up the monitoring site as the start-point for backward simulations, with BST 06:00 as the starting time and the duration of each simulation was 10 h.
2. Each simulation was set at flight heights of 300, 500, and 700 m above ground level [18].
3. The previous night’s endpoint was set to be the start point of the current trajectory. The calculation was repeated for maximum 3 nights.
4. A trajectory endpoint in the sea was invalid. In this study, trajectory routes were mapped by ArcGIS Pro 2.5.2, and the base maps were obtained from the National Geographic Information Center of China (http://www.webmap.cn/ accessed on 10 October 2022).

Based on the migration periods divided by Fisher’s optimal segmentation and the composition of captures of *M. separata*, we predicted the source areas of northward migration from May to June and southward migration from August to October by using the simulated trajectories in peak migration events. Long-term systematic monitoring of *M. separata* migration between northern and northeastern China was conducted at Changdao Field Experimental Station for Pest Monitoring and Control, Institute of Plant Protection, Chinese Academy of Agricultural Sciences (Beihuang Island, Shandong Province, 38°23′12″ N, 120°54′30″ E) (Changdao for short). Based on ovarian development level (ODL) data of *M. separata* moths monitored each month/year at Changdao [33], age proportion and duration of each peak migration event were calculated based on the following correlation: level I moths migrate for 1 night, level II and III moths migrate for 2 nights, and IV and V level moths migrate for 3 nights (Table 1) [34–36]. For each peak event, when the number of trapped moths in each site was known, quantity and migration duration in each peak event was calculated based on the historical age proportion data in Changdao. For the trajectory simulation, backtrack the endpoints and weighted quantity of trajectory endpoints distribution. Finally, the quantity of endpoints distribution was drawn by a geographic information system. The Kernel Density method in Spatial Analyst Tools was used to interpolate and fit the quantity at different endpoints to estimate the insect sources distribution of northeast China. As a contrast, we calculated endpoints of the backward trajectories distribution without weights and counted the percentage of insect sources distribution in different provinces with two methods (weighted and unweighted endpoints). These endpoints of simulated trajectory into the sea were regarded as invalid.

**Table 1.** Ovarian development levels of captures of *M. separata* at the Beihuang site from May to October 2003 to 2008 (Reprinted/adapted with permission from Ref. [33]. 2009, Xincheng Zhao).

<table>
<thead>
<tr>
<th>Month</th>
<th>Level I</th>
<th>Levels 2–3</th>
<th>Levels 4–5</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>25%</td>
<td>60%</td>
<td>15%</td>
</tr>
<tr>
<td>June</td>
<td>20%</td>
<td>60%</td>
<td>20%</td>
</tr>
<tr>
<td>August</td>
<td>76%</td>
<td>17%</td>
<td>7%</td>
</tr>
<tr>
<td>September</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>October</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

2.4. Data Analysis

Two-way analysis of variance (ANOVA) was used for differences in monthly *M. separata* captures among different sites and months. One-way ANOVA was used for the difference in captures of *M. separata* among different months for each site. Data of monthly captures was square root transformed for normal distribution and variance of homogeneity. The Nonparametric *Kruskal-Wallis H* test was used for differences in annual captures of *M. separata*, the number of peak migration events, and durations of migration at different sites. The sample size of these data is small and does not conform to the normal distribution, inevitably, the choice of the Nonparametric *Kruskal-Wallis H* test will have some random effects on the results. Fisher’s optimal segmentation method was used to divide the migration period of *M. separata* according to time series data of average daily captures (every 10 days as a time-series unit, 1 May to 14 October, a total of 17 time-series units) after normalization. Determining the inflection points of the minimum loss function was regarded as the optimal splitting point of the time series. A two-sample *Z*-test with a two-tailed test was used to compare the wind speed and direction in the migration events with the average wind vector, both in different migration peak periods. It is important to emphasize that when the sample size is less than 30, we use a two-sample *T*-test with a two-tailed test, and if there is a difference, it proves that there is selectivity for wind. The
Kruskal-Wallis H-test was processed by SPSS 13.0; Fisher’s optimal segmentation, two-way ANOVA, one-way ANOVA, Z-test, and T-test were processed by SAS 9.4.

3. Results

3.1. Population Monitoring of Migration Moths

From 2017 to 2020, the first appearance of trapped *M. separata* in northeast China was concentrated in mid-late May and early June, with the earliest on May 10 (CC, 2017), and the final appearance of *M. separata* was concentrated in late September and October, with the latest on October 25 (HB, 2019) (Table 2). The annual captures of *M. separata* (*H* = 4.27, *df* = 2, *p* = 0.12), duration of migration (*H* = 3.07, *df* = 2, *p* = 0.22), and the number of migration peaks (*H* = 4.71, *df* = 2, *p* = 0.09) at HB, CC, and SY sites differed, but not significantly. The annual captures of *M. separata* were 285.5 ± 75.5, 643.0 ± 204.0, and 786.3 ± 171.9 at HB, CC, and SY sites, respectively; the number of peak migration events (defined in Methods 2.1) was 4.3 ± 1.9, 18.7 ± 3.9, and 16.0 ± 3.1, respectively; the durations of migration were 107.3 ± 40.2 d, 108.3 ± 3.9 d and 134 ± 7.2 d, respectively.

Table 2. Migration periods and amounts of trapped *M. Separata* from 2017 to 2020 at three sites in northeast China.

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>Initial Date</th>
<th>Final Date</th>
<th>Number of Migration Peak</th>
<th>Duration of Migration (day)</th>
<th>Captured Moths/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY</td>
<td>2017</td>
<td>2 June</td>
<td>30 September</td>
<td>15</td>
<td>121</td>
<td>1138</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>12 May</td>
<td>14 October</td>
<td>10</td>
<td>16.0 ± 3.1</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>24 May</td>
<td>8 October</td>
<td>23</td>
<td>137</td>
<td>410</td>
</tr>
<tr>
<td>CC</td>
<td>2017</td>
<td>10 May</td>
<td>16 August</td>
<td>21</td>
<td>98</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>15 May</td>
<td>24 August</td>
<td>7</td>
<td>101</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>27 May</td>
<td>18 September</td>
<td>29</td>
<td>18.7 ± 3.9</td>
<td>1234</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>6 June</td>
<td>30 September</td>
<td>18</td>
<td>116</td>
<td>804</td>
</tr>
<tr>
<td>HB</td>
<td>2018</td>
<td>20 May</td>
<td>20 October</td>
<td>8</td>
<td>153</td>
<td>258</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>20 May</td>
<td>25 October</td>
<td>5</td>
<td>4.3 ± 1.9</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>23 May</td>
<td>31 May</td>
<td>0</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

In terms of seasonal dynamics of the *M. separata* population, there were significant differences in the captures of *M. separata* among different months (*F*5, 59 = 4.41, *p* < 0.01) and study sites (*F*2, 59 = 3.97, *p* = 0.02) (Table 3). Further, captures of *M. separata* were highest in September at HB, highest in June at CC, and highest in June and September at SY. In general, captured moths in June and September were higher than that in other months in northeast China (Figure 2).

Table 3. Results of two-way ANOVA for monthly trapped *M. Separata* moths in vertical searchlight traps at three sites in northeast China from 2017 to 2020.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean of Squares</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>972.12</td>
<td>5</td>
<td>194.42</td>
<td>4.41</td>
<td>0.002</td>
</tr>
<tr>
<td>site</td>
<td>350.40</td>
<td>2</td>
<td>175.20</td>
<td>3.97</td>
<td>0.0249</td>
</tr>
<tr>
<td>Error</td>
<td>2295.02</td>
<td>52</td>
<td>44.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3617.54</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The migration activities of *M. separata* in northeast China could be divided into seven periods by Fisher’s optimal segmentation. Among those, the three periods with the highest number of migrants were defined as the northward migration (from late May to mid-June), the transition migration (from late July to early August), and the southward migration (from late August to late September) (Figure 2). There was a certain difference in the migration peak periods among sites and years. The HB site had three migration peak periods in 2018 and 2019, while only one (northward migration) in 2020. At CC, only one migration peak (northward migration) was found in 2017 and 2018, while three migration
peaks existed in 2019 and 2020 (Figure 3). At SY, the first (northward migration) and the third (southward migration) migration periods had more migrants than the second period from 2017 to 2019 (Figure 3). In general, the *M. separata* moth’s peak migration events occurred mostly in the northward migration in late spring and early summer (May to June) and the southward migration in autumn (September to October) in northeastern China during 2017–2020.

Figure 2. Fisher’s optimal segmentation for time series data of captures of *M. separata* by vertical searchlight traps in northeast China from 2017 to 2020. Upper cases indicate different periods, (A): preliminary period of northward migration; (B): heyday of northward migration; (C): terminal period of northward migration; (D): transition period from northward migration to southward migration; (E): preliminary period of southward migration; (F): heyday of southward migration, (G): terminal period of southward migration.

Figure 3. Captures of *M. separata* moth (N) in vertical searchlight traps from 2017 to 2020 at (a): the Harbin (HB) site, (b): the Shenyang (SY) site, (c): the Changchun (CC) site.
3.2. Effect of Wind Conditions on Migratory Activity

Analysis of the average nocturnal wind field at 925 hPa showed westerly and southerly winds prevailed in northeast China during the migration periods (i.e., Figure 3B,D,F), which benefits migration of *M. separata* into northeastern China but not southward migration (Figure 4). During northward migration (late May to mid-June B-period), southwesterly winds prevailed in northeastern and northern China. In peak migration events, both SY (65.52%) and CC (36.36%) sites prevailed in southwesterly winds, despite the wind distribution being relatively scattered, moths migrated into HB site mostly with westerly or southerly winds in high-speed (>6 m/s) (57.14%). During the transition migration (late July to early August, D-period), southwesterly winds prevailed in northern and northeast China, and the wind speed increased compared with the northward period. Then, only the CC site had peak migration events with southwesterly winds (83.33%). During the southward migration (late August to mid-September, F-period), westerly winds prevailed in northern and northeast China. In peak migration events, migrations were mostly with southwesterly winds at SY (48.04%), CC (40.00%), and HB (34.62%), but southwesterly winds frequency decreased. Analysis of the 925 hPa wind field during three migration periods showed that the wind field in northeast China was favorable for migration from northern China and Inner Mongolia into northeast China and favorable to the northward migration of *M. separata* from northeast China into Far East Russia, but unfavorable for southward migration for *M. separata* in northeast China.

Figure 4. Average nocturnal wind field (left) and peak migration events’ nocturnal downwind directions (right) (the downwind direction is the direction to which the wind is blowing) at three sites during migration periods from 2017 to 2020 in northeast China. (a): northward migration; (b): transition migration; (c): southward migration.
The peak migration events’ nocturnal wind direction showed various deflections in comparison with the average nocturnal wind direction at each site during each of the three migration periods. During northward migration, wind direction at SY had a 19° clockwise rotation \( (Z = -1.70, df_{1,2} = 160, 16, p = 0.09) \) (Table 4), CC had a 12° anticlockwise rotation \( (Z = 1.08, df_{1,2} = 160, 92, p = 0.28) \), and HB had an anticlockwise rotation of 43° \( (Z = 2.39, df_{1,2} = 160, 56, p = 0.03) \). Only the wind direction at SY clockwise shifted to the west. During transition migration, wind direction at CC had a 22° clockwise rotation \( (Z = -0.89, df_{1,2} = 168, 12, p = 0.39) \). During southward migration, the wind direction at HB had a 5° clockwise rotation \( (Z = -0.36, df_{1,2} = 224, 54, p = 0.72) \), CC had a 31° anticlockwise rotation \( (Z = 2.30, df_{1,2} = 224, 60, p = 0.02) \), and SY had a 43° anticlockwise rotation \( (Z = 2.97, df_{1,2} = 224, 64, p < 0.01) \). Only the wind direction at HB shifted clockwise to the west. Additionally, the migrants in peak migration events had no preference for any wind speed (Table 4). Overall, in migration events during the northward migration period, the migrants showed a significantly preference for westerly winds at SY, relatively, southward migration preferred easterly winds at HB (Table 4).

### Table 4. Comparison of the average nocturnal wind speed/direction and peak migration events’ nocturnal wind speed/direction at three sites during migration periods from 2017 to 2020 in northeast China.

<table>
<thead>
<tr>
<th>Period</th>
<th>Wind</th>
<th>HB Average</th>
<th>Daily</th>
<th>Z-Value</th>
<th>p</th>
<th>CC Average</th>
<th>Daily</th>
<th>Z-Value</th>
<th>p</th>
<th>SY Average</th>
<th>Daily</th>
<th>Z-Value</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northward migration</td>
<td>Speed</td>
<td>7.77</td>
<td>6.37</td>
<td>1.70</td>
<td>0.10</td>
<td>8.48</td>
<td>7.90</td>
<td>0.93</td>
<td>0.35</td>
<td>7.90</td>
<td>8.33</td>
<td>-0.68</td>
<td>0.50</td>
</tr>
<tr>
<td>Transition migration</td>
<td>Direction</td>
<td>196.86</td>
<td>153.82</td>
<td>2.39</td>
<td>0.03</td>
<td>199.82</td>
<td>187.87</td>
<td>1.08</td>
<td>0.28</td>
<td>196.35</td>
<td>215.35</td>
<td>-1.70</td>
<td>0.09</td>
</tr>
<tr>
<td>Southward migration</td>
<td>Speed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.72</td>
<td>8.68</td>
<td>-1.83</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Southward migration</td>
<td>Direction</td>
<td>8.29</td>
<td>8.38</td>
<td>-0.13</td>
<td>0.90</td>
<td>8.70</td>
<td>8.29</td>
<td>0.48</td>
<td>0.63</td>
<td>7.44</td>
<td>6.88</td>
<td>0.99</td>
<td>0.32</td>
</tr>
</tbody>
</table>

### 3.3. Migration Routes and Distribution of the Insect Sources

Backward trajectory simulation using the HYSPLIT model showed that the migratory route of *M. separata* was Shandong/Hebei/Inner Mongolia-Liaoning-Jilin-Heilongjiang during northward migration (Figure 5). Specifically, the Liaoning-Jilin route accounted for 46.55% (27 times), followed by the Shandong-Liaoning route (nine times, 15.52%), the Inner Mongolia-Jilin route (nine times, 15.52%), the Jilin-Heilongjiang route (seven times, 12.07%), and the Hebei-Liaoning route (six times, 10.34%) (Figure 5). During transition migration, the migratory route of *M. separata* was Shandong-Liaoning-Jilin. Specifically, the Liaoning-Jilin route accounted for 66.67% (four times), followed by Shandong-Liaoning route (one time, 16.67%), and the Inner Mongolia-Jilin route (one time, 16.67%). During southward migration, the migration of *M. separata* mostly occurred within areas of northeast China. Specifically, migration within Heilongjiang province accounted for 43.75% (14 times), and the Heilongjiang-Jilin route (eight times) and Jilin-Liaoning route (five times) accounted for 25% and 15.63%, respectively. Other migrations of *M. separata* were the Inner Mongolia-Liaoning route (three times, 9.38%) and, the Inner Mongolia-Jilin route (two times, 6.25%). In general, the route was Shandong/Hebei/Inner Mongolia-Liaoning-Jilin-Heilongjiang for northward migration and the Heilongjiang-Jilin-Liaoning route for southward migration.

For northward migration, the simulated insect source further confirmed that *M. separata* migrated into northeast China via the Shandong-Liaoning-Jilin-Heilongjiang route (Figure 6). However, the *M. separata* population in northeast China could not emigrate effectively during the southward migration period in autumn. During northward migration (May to June), the source of the *M. separata* population in northeast China mainly came from Shandong (33.05%), Inner Mongolia (32.51%), and Hebei (14.23%). Within northeast China, immigrants at HB were predicted to come from the southern part of CC, Jilin Province (43.44%) and Mudanjiang City, Heilongjiang Province (30.31%); immigrants at CC were predicted to come from southern Liaoning Province (26.96%) (near Diaoingshan City and Fuxin City), Inner Mongolia (20.3%), and Heilongjiang (10.38%) (near Shuangyashan City);
immigrants at SY mainly were from Shandong Province (35.68%) (near Zibo City and Linyi City), Inner Mongolia (22.18%) (near Hulunbeier City). During the transition migration, immigrants at CC mainly came from eastern Liaoning Province (62.96%) (near Fushun City and Benxi City). During southward migration, more than half of the immigrants were from the areas nearby the monitoring sites in northeast China. Among them, 55.71% of immigrants at HB came from the northern part of Yichun City, Heilongjiang Province, 52.54% of immigrants at CC came from Fuxin City and Benxi City in Liaoning Province, 63.4% of immigrants at SY migrated from local areas in Liaoning Province. Compared with the weighted insect source distribution results, the unweighted endpoints of trajectory distribution were more evenly distributed and made it difficult to identify important insect sources.

Figure 5. Main migration routes and frequencies of north-south migrations of *M. Separata* from 2017 to 2020 in northeast China. (a): northward migration; (b): transition migration; (c): southward migration.
endpoints of trajectory distribution were more evenly distributed and made it difficult to identify important insect sources.

Figure 6. Insect source distribution with a quantity of *M. Separata* (left) and proportional distribution of insect sources in different provinces counted by population and location (right) during three periods from 2017 to 2020 in northeast China. (Population: weighted quantity of trajectory endpoints distribution; location: unweighted endpoints of trajectories distribution) (a): HB during northward migration, (b): HB during southward migration; (c): CC during northward migration; (d): CC during southward migration; (e): SY during northward migration; (f): SY during southward migration; (g): CC during transition migration.
4. Discussions

Based on the monitoring data of the *M. separata* population in northeast China from 2017 to 2020, the migratory routes of *M. separata* in northeast China were analyzed, and the distribution of insect sources was simulated by the HYSPLIT trajectory analysis model. In terms of seasonal migration, three main migratory activities of *M. separata* occurred from 2017 to 2020 in northeast China. The first one was the first-generation *M. separata* that migrated from the North China Plain (late May to early mid-June). The second one was the second-generation of *M. separata* that migrated from the North China Plain (from late July to early August), and the third one was the second-generation *M. separata* within northeast China (late August to mid-to-late September). Migration activities varied slightly in different years. From 2017 to 2019, the first and third migratory activities were frequent, but the second migratory activity was occasional in Liaoning Province. In Jilin Province, northward migration occurred mainly from 2017 to 2018, and three flight activities occurred from 2019 to 2020. The number of *M. separata* that migrated to Heilongjiang was relatively low, and three migratory activities occurred from 2018 to 2019, and only the first migratory activity occurred in 2020. In terms of migration routes and insect source distribution, the *M. separata* population from Shandong, Hebei, and Inner Mongolia mainly migrated via Liaoning, Jilin, and Heilongjiang with southwesterly winds during the northward migration period. The migratory routes were Hebei/Shandong/Inner Mongolia-Liaoning-Jilin-Heilongjiang, and the main routes during the southward migration period were the Russian Far East/Heilongjiang-Jilin/North Korea-Liaoning-Shandong/Hebei. Due to the prevalence of southwesterly winds in autumn, the second generation was obstructed in northeast China. In addition, the occurrence duration of *M. separata* at SY was higher than at CC and HB, while peak migration events, at SY and CC, were higher than that at HB. It was speculated that the temperature difference caused by different latitudes may be a factor affecting the occurrence and migration activities of *M. separata*. This result is similar to the migration of ladybugs observed by radar in the UK [37].

The north overwinters boundary of *M. separata* was near 33° N in eastern China [38], so captures of *M. separata* in spring and summer in northeast China were migratory populations. It was reported that the first and second generations of *M. separata* occurred mostly in Jilin Province, and the third generation of *M. separata* was occasional, which is consistent with our observations in 2017–2018 [39]. The previous study explored the spring insect sources in Jilin and concluded that the sources of immigration were mainly from Shandong, Hebei, Jiangsu, and Anhui provinces, as well as some from the Korean Peninsula [40], which is slightly different from our study. Trajectory simulation for the third generation of *M. separata* in Jilin indicated that the important insect sources were surrounding areas nearby Gongzhuling, even the Russian Far East and the Korean Peninsula [41,42]. Entomological radar observation and analysis showed that the emigration of *M. separata* in northeast China could move into the Northern Plain and eastern China within a week [43].

In this study, wind directions in peak migration events were quite different from that in the corresponding whole month. *M. separata* migrated across Bohai Gulf in autumn and showed strong orientation behavior, and migrating in layers was connected to wind speed and atmosphere temperature [44]. Studies have shown that flight headings in seasonally-advantageous directions [45,46]. Our results showed that the seasonal peak migration events exhibited a significant degree of mean wind direction of the migration period, for example, during northward migration, immigrants of SY preferred to fly with wind direction shifted to the east. Furthermore, during southward migration, immigrants of SY and HB preferred to fly with the wind direction shifted to the west. However, during southward migration, the selected wind direction of migrating population at CC was not close to an advantageous direction. We guessed that may be caused by high-speed wind in Jilin Province. Meanwhile, the wind selectivity of *M. separata* reduced the flight speed in most cases, which may be similar to the long-distance migration mechanism of death’s-head hawk moths at low-altitude [47]. The quantity of *M. separata* migration was always accompanied by strong southwest winds and south winds [30]. In spring, the persistent
southwesterly wind was favorable for the migration of *M. separata* into northeast China. In the autumn, the cold high-pressure system generated by the Northeast Plain showed a chaotic and variable wind field and low-temperature environment, which inhibits the emigration ability of the *M. separata* population, therefore the southward migration of *M. separata* was blocked in northeast China, forming an obvious “Pied piper” phenomenon [38]. Several outbreaks of *M. separata* in northeast China occurred due to unsuccessful emigration of the local population caused by meteorological conditions [48].

In this study, oviposition dissection was not performed synchronously during our observation for *M. separata*, and the local population influenced the route analysis and immigration source stimulation [18,49,50]. The HYSPLIT model is a meteorological analysis platform for tracing and predicting the transference of inorganic particles, but the flight ability of migrating insects was not introduced into the model, which might lead to a short trajectory distance and orientation deviations. Based on real-time aerial behavior parameters of migrating insects, an integrated entomological radar-trajectory analysis model will improve the accuracy of trajectory and forecasting [51].

In addition, favorable wind fields are a prerequisite for the long-distance migration of adults of *M. separata*. Under being carried by the wind fly towards a preferred direction, moths can fly over several nights and reach areas hundreds of kilometers away. In the spring migration, because of limited wind speed and insect flight capacity, the first generations had a 1–2-day delay in migration peak under the northward migration route [52]. In addition, from upstream to downstream areas of the migration route, numbers of migrants decreased.

This study analyzed the migration pattern of *M. separata* in northeast China from 2017 to 2020 based on monitoring migration data in Liaoning (Shenyang), Jilin (Changchun), and Heilongjiang (Harbin), and analyzed the migration routes and insect sources in combination with wind fields and HYSPLIT models. The migration pattern of *M. separata* in China showed a southwest-northeast direction. The occurrence generation, migration pattern, and regional planting structure of crops should be fully considered in a comprehensive management strategy of regional management of *M. separata* based on accurate monitoring of *M. separata* migration. Therefore, based on the results of this paper, the following suggestions are proposed for the management of *M. separata*: (1) implement the source management strategy of *M. separata*. To control this destructive migratory pest earlier in northeast China, in spring (May to June), the government of important source areas such as central and southern Shandong and Hulunbeier City in Inner Mongolia should strengthen the monitoring of the occurrence period, occurrence density, occurrence area, and other occurrence situations of *M. separata* populations in the field. In autumn (September to October) the government should monitor the occurrence of the third generation of *M. separata* local populations in northeast China through monitoring means such as search-light traps, UV lamps, food lures, and sex lures, and suppress the local populations through preventive measures such as agricultural control and ecological regulation to avoid increasing the number of returning population in autumn. (2) Based on the results of this paper on the population dynamics, migratory routes, and insect sources distribution of *M. separata*, the Plant Protection Stations should focus on trapping outgoing and incoming adults of *M. separata* in insect sources, and intercepting the migrating populations of transit and returning populations in autumn, during the important north-south migration period (June and September), in the main source areas and key migration routes, such as Bohai Bay, Beijing Changping, and other areas. (3) Establish a perfect integrated control strategy for *M. separata* (IPM) [26]. The government should advocate for the application of biological control methods and the development of regional integrated control rules in the non-major source and occurrence of *M. separata*; farmers can reasonably use the means of chemical control to resolve the problem while the pest density is sufficiently high to ensure the safety of food production.
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