agronomy

MDPI

Article

Use of Food Attractant to Monitor and Forecast Population Dynamics of *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae), a Long-Distance Migratory Pest

Lingyun Gao [1,2,†], Ran Yan [3,†], Wei He [4] and Kongming Wu [3,*]

[1] College of Plant Protection, Henan Agricultural University, Zhengzhou 450002, China; gao1278625279@163.com
[2] The Laboratory of Lingnan Modern Agriculture, Guangzhou 510000, China
[3] State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing 100193, China; yanrandyx@163.com
[4] State Key Laboratory of Ecological Pest Control for Fujian and Taiwan Crops, Fujian Agriculture and Forestry University, Fuzhou 350002, China; hewei6006@163.com
* Correspondence: wukongming@caas.cn
† These authors contributed equally to this work.

Abstract: The rice leaf folder, *Cnaphalocrocis medinalis*, is a significant migratory pest that restricts rice production in Asia and Africa, and monitoring and early warning measures are the basis for its management. Based on its regional migratory path in China, the pest population dynamics were monitored from 2020 to 2021 using food attractants. In this study, we also used internal reproductive system dissection to determine the adult age and reproductive developmental state. The monitoring results indicated that the trapping dynamics of *C. medinalis* males using food attractants and sex pheromones were approximately similar. Both trapping methods yielded *C. medinalis* males of different ages, with an identical age structure for both trap types. Dissection analysis of the reproductive system of females trapped using the food attractants indicated that in 2020, the population of *C. medinalis* in Liling, Hunan Province, was indigenous, while populations in other monitoring sites mainly comprised migrants from other areas. The ovarian development level of females trapped using food attractants showed a positive correlation with the age of males, and there was also a significant positive correlation between the index of ovarian development of females and the mating time. Furthermore, a dynamic prediction method for fecundity in field populations was established based on the quantity of eggs held by the females. This study provides a new method for the monitoring and early warning of the existence of *C. medinalis* populations.

Keywords: *Cnaphalocrocis medinalis*; food attractants; reproductive development state; population prediction

check for updates

Citation: Gao, L.; Yan, R.; He, W.; Wu, K. Use of Food Attractant to Monitor and Forecast Population Dynamics of *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae), a Long-Distance Migratory Pest. *Agronomy* **2023**, *13*, 2141. https://doi.org/10.3390/agronomy13082141

Academic Editor: Christos Athanassiou

Received: 22 July 2023
Revised: 13 August 2023
Accepted: 14 August 2023
Published: 16 August 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Rice is one of the world's major food crops, with about 3 billion people worldwide relying on rice as a staple food. The rice leaf folder, *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae), is one of the most significant pests affecting rice. The larvae prefer to feed on young rice leaves, often causing white streaks on the surface, which affects leaf photosynthesis, leading to an increase in the rate of rice blight and a decrease in grain weight [1–3]. Frequent outbreaks of *C. medinalis* in many Asian countries such as China, India, and Japan have caused huge losses to Asian rice production [4–8]. *C. medinalis* caused 5%–25% annual rice losses in Bangladesh [9]. From 1991 to 2019, the average annual area of occurrence of *C. medinalis* in China was 16.05×10^8 ha, accounting for 66.3% of the rice planting area, resulting in a rice loss of 70.27×10^8 kg [10,11].

C. medinalis has a long-distance migratory habit; Fu et al. used radar to monitor the migration dynamics of *C. medinalis* in the Bohai Bay area [12] and provided the flight speed,

flight altitude, and migration duration of *C. medinalis*. *C. medinalis* exhibits a north-south migration pattern in East Asia and migrates northward from southern overwintering areas in five large-scale northward migrations every spring and summer, which is harmful to the vast rice areas south of the Huaihe River in China's Qinling Mountains. As autumn temperatures drop and rice ripens in northern China, *C. medinalis* embarks upon three large-scale migrations southward, harming the Jianghuai, Jiangling, and Hainan perennial rice areas [13]. The main method of controlling *C. medinalis* is the application of chemical pesticides, but long-term overuse of chemical pesticides often leads to increased pest resistance, environmental pollution, and other problems [14]. Understanding the migration pattern of *C. medinalis* can predict the time of insect outbreak damage and improve control efficiency.

Currently, the commonly used monitoring methods for adult *C. medinalis* are moth repellent methods, searchlight trapping methods, and sex pheromone trapping methods [15,16]. The moth count using the moth repellent method is not easily obtained, and the correlation between the number of moths and the actual population density in the field is low [17]. Due to the weak phototaxis of adult *C. medinalis*, the searchlight trapping method cannot accurately reflect the population dynamics of *C. medinalis* [18]. Sex pheromone monitoring is widely used in the monitoring of *C. medinalis*, as it possesses high specificity and sensitivity [19–21]. However, pheromone-based trapping can only trap *C. medinalis* males; it does not accurately predict fecundity and offspring larva numbers based on *C. medinalis* female dynamics [22,23].

Food attractants based on the pest's preferred food source possess the advantages of high specificity and sensitivity, as well as the ability to trap both female and male pests [24,25]. Previous studies have shown that valeraldehyde, benzaldehyde, and methyl salicylate are attractive to *C. medinalis*, and further studies have shown that benzaldehyde, phenylacetaldehyde, and methyl salicylate have the strongest attraction to *C. medinalis* at a concentration of 10 g/L [26,27].

Previous studies have shown that food attractants display a good trapping effect on adult *C. medinalis* in the field [28,29], but the reproductive development status and prediction methods of adult *C. medinalis* have not been thoroughly investigated. Based on trapping adult *C. medinalis* in the field using food attractants and employing internal reproductive system dissection, we aim to determine the adult reproductive development state and to establish a monitoring and early warning method for the *C. medinalis* population. This study could also provide new technical means to further improve the level of surveillance and early warning technology to guide the precise prevention and control of *C. medinalis*.

2. Materials and Methods

2.1. Experimental Materials and Methods

Field monitoring trials were conducted in Guangxi, Hunan, Jiangsu, and Zhejiang provinces, China, in 2020 and 2021, and the specific test locations and test duration are shown in Table 1. During the 2020 monitoring period, one rice field in seven different sites in Guangxi, Hunan, Jiangsu and Zhejiang provinces, each with an area of 1334 m^2, with uniform growth and consistent field management, was selected as the experimental field. Six bell inverted funnel traps (height 364 mm, diameter 264 mm, consisting of three parts: insect collection barrel, inverted funnel, and core lure handle), with food attractants, were placed equidistantly in the center of each experimental field, according to the standard of one trap per 50 m. In the experimental fields of Zhangjiagang, Jiangsu Province, and Liling, Hunan Province, in addition to traps equipped with food attractants, six bell inverted funnel traps with sex pheromones were placed as controls, and the traps using two different baits were separated by 100 m. During the monitoring period in 2021, one experimental field, with an area of 1334 m^2, was selected in three different sites in Hunan and Jiangxi provinces. Six bell inverted funnel traps, fitted with food attractants, were placed equidistant in the center of each test field. In Shaodong, Hunan Province, in

addition to placing traps baited with food attractants, six bell inverted funnel traps with sex pheromones were also placed as a control.

Table 1. Monitoring locations and times for field trials in 2020–2021.

Experimental Year	Experimental Site/Province	Experimental Time (Month/Day)	Longitude/Latitude
2020	Guigang/Guangxi	28 May–20 June	109°43′48″/22°46′12″
2020	Liling/Hunan	8 July–8 Aug.	113°31′12″/27°36′36″
2020	Shaodong/Zhejiang	3 July–21 July	111°43′11″/27°18′36″
2020	Zhangjiagang/Jiangsu	16 July–12 Aug.	120°31′48″/31°48′36″
2020	Changzhou/Jiangsu	17 July–18 Aug.	119°29′24″/31°40′12″
2020	Quzhou/Zhejiang	23 July–25 Aug.	119°11′24″/29°7′12″
2020	Xiangshan/Zhejiang	16 July–26 Aug.	121°54′36″/29°24′36″
2021	Shaodong/Zhejiang	26 June–15 Aug.	111°43′12″/27°18′36″
2021	Zhijiang/Hunan	19 June–14 Aug.	109°40′48″/27°26′24″
2021	Taihe/Jiangxi	1 June–27 June	114°52′48″/26°47′24″

The *C. medinalis* food attractant (ingredients and ratio: methyl salicylate:limonene: camphor = 1:0.5:2.5) was a solid block [28], with an active ingredient content of 4 g/package. *C. medinalis* sex pheromones were composed of Z13-18: Ald, Z11-18: Ald, Z13-18: OH, and Z11-18: OH, at a 500:60:120:60 ratio [14], with 740 μg/pc active ingredient provided on a PVC capillary. Bell inverted funnel traps were fixed at 50 cm above the rice plant, and the height was adjusted regularly with the growth of the plant. The food attractants were replaced once every 15 days, and the sex pheromones were changed once every 30 days. The bell inverted funnel traps, food attractants, and pheromones were provided by Shenzhen Bioglobal Agricultural Science Co., Ltd. (Shenzhen, China). This is a company focused on green pest management, and its food attractant products for use with agricultural pests, such as *Helicoverpa armigera* and *Spodoptera frugiperda*, indicate good prospects for pest monitoring [30,31].

The number of adult *C. medinalis* females and males per trap was investigated every morning, and all trapped *C. medinalis* were transferred to the laboratory for dissection and determination of reproductive development status. On a daily basis, up to 50 male and female individuals (per type of attractant) were dissected, and all were dissected if the trapping number was less than 50.

2.2. Methods of Adult Dissection and Determination of the Age of Males

Referring to the anatomical methods of Feng et al. [23], adult *C. medinalis* trapped with food attractants and sex pheromones in the field were dissected every day. The adult abdomen was cut with a pair of scissors (12 cm long), placed in a Petri dish (5 cm diameter), and the abdominal body wall was torn through the fracture under a TS75-X trinocular microscope (Shanghai Shangguang New Optical Technology Co., Ltd. Shanghai, China) to separate the ovaries (Figure 1A) and testes (Figure 1D). Next, the testes were removed and placed in a 5 cm diameter plastic Petri dish filled with saline solution. The Petri dish was placed under a stereoscope (TS-75X; Shanghai Shangguang New Optical Technology Co., Ltd., Shanghai, China), and the major axis length of the testis (i.e., testis size) was measured with an OLD-SGD imaging system (Shanghai Shangguang New Optical Technology Co., Ltd.). The age of the males was judged by referring to the dividing criteria of *C. medinalis* (Table 2) suggested by Chen et al. [32]. After completion of the ovarian dissection, the index of ovarian development and the number of mating times (number of spermatophore in the bursa copulatrix) were determined and recorded by referring to the ovarian development classification criteria of Zhang et al. [33]. The number of spermatophores (Figure 1C) in the bursa copulatrix (Figure 1B) of female *C. medinalis* can indicate the number of mating times. That is, the presence of X spermatophores in the bursa copulatrix indicates mating X times [23].

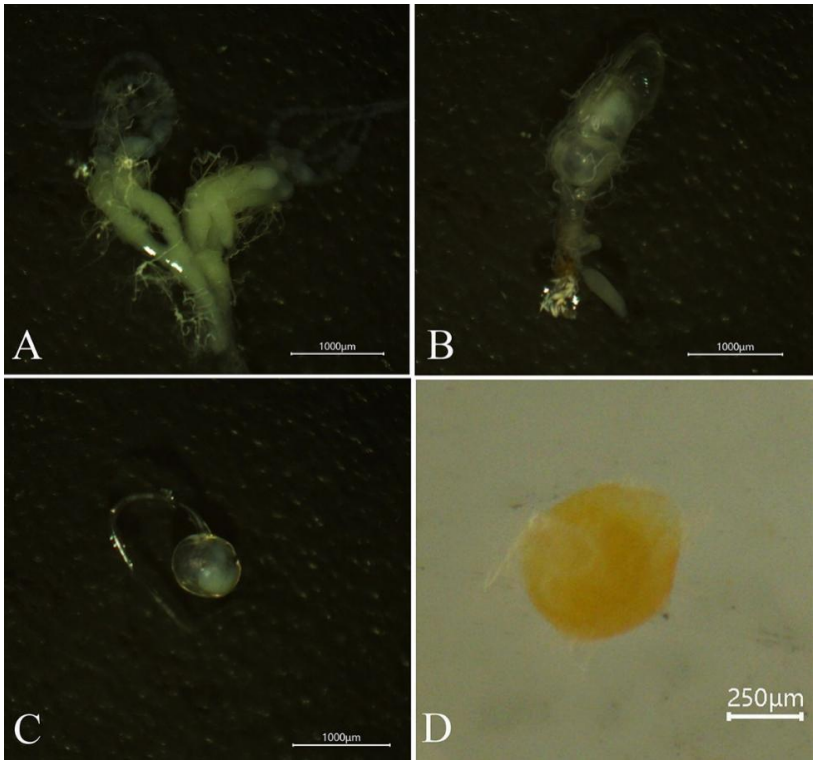


Figure 1. Anatomy of reproductive organs of *C. medinalis*. Ovary (**A**); bursa copulatrix (**B**); spermatophore (**C**); testis (**D**).

Table 2. Division criterion for the semi-major axis length of testes of 1–8-day-old male adults of *C. medinalis*.

Adult Age (Day)	Range of the Semi-Major Axis Length of Testes (μm)
1	>421.1
2	387.6–421.1
3	367.3–387.6
4	348.0–367.3
5	327.9–348.0
6	307.4–327.9
7	277.8–307.4
8	<277.8

2.3. Determination of Adult Source Properties and Dynamic Prediction of Oviposition

Referring to Zhang et al. [33], the property of insect origin of *C. medinalis* was determined by the following criteria: if the proportion of individuals with an index of ovarian development of 1 regarding females trapped using food attractants is 10%–30%, and the proportion of individuals with an index of ovarian development of 3–5 is 30%–62.18% during the monitoring period, then the population of *C. medinalis* at the experimental site is a native population. If the proportion of individuals with an index of ovarian development of 3–5 of females trapped using food attractants is about 80% or more, the population of *C. medinalis* at the experimental site is mainly a migrant population from other regions.

Prediction of egg-laying dynamics of females: based on the ovarian development law of females of *C. medinalis* [33], the females exhibit the highest amount of egg holding when the ovaries develop to grade 3, and this result can be used as the total egg amount of the females before egg laying. The egg yield of a female in the field on a given day can be calculated using the following formula: $p = 1 - \frac{X}{N}$. In the formula, p is the percent of oviposition of females in the field on a given day; X is the average number of eggs held by females trapped using food attractants on a certain day; N is the average egg holding

capacity of *C. medinalis* trapped in the field with an index of ovarian development of 3. The daily percent of oviposition of females during the monitoring period was calculated to obtain the oviposition dynamics of females in the field.

2.4. Statistical Analysis

A Student's *t*-test was used to compare the daily trap counts between traps with food attractants and those with sex pheromones. A Chi-square test was used to assess differences in the sex ratio of female to male (1:1), as well as the male age structure for individuals caught in traps using food lures or sex pheromones. Pearson correlation analysis was used to compare the index of ovarian development, age of males, and number of matings. All data were analyzed using SPSS 26.0 (IBM, Armonk, NY, USA).

3. Results

3.1. Comparison of Monitoring Effects of Food Attractants and Sex Pheromones

The peak in both the food attractant and sex pheromone mediated monitoring of *C. medinalis* in Liling occurred in mid-July (Figure 2A), while the peak of both food attractant and sex pheromone monitoring of *C. medinalis* in Zhangjiagang occurred twice: once in late July and once in late August (Figure 2B). At the two sites, the peak occurrence of *C. medinalis* was essentially the same using either of the two trapping methods. At Shaodong in 2021, *C. medinalis* monitored using food attractants showed one peak period in early July, and those monitored using sex pheromones also exhibited one peak period in early July (Figure 2C). The peak period of *C. medinalis* was essentially the same for both food attractant and sex pheromone monitoring, but the peak period for sex pheromone monitoring was longer, and the number of trappings was higher in early and mid-July.

In 2020 in Liling, a total of 4142 adult *C. medinalis* were trapped using food attractants, and 253 adult *C. medinalis* were trapped using sex pheromones. A total of 2569 adults were trapped using food attractants, and 211 adults were trapped using sex pheromones in Zhangjiagang. Food-based trapping thus yielded a higher daily trap capture than pheromone-based approaches in Liling and Zhangjiagang (Liling: $t = 8.46$, $df = 60$, $p < 0.05$; Zhangjiagang: $t = 6.81$, $df = 48$, $p < 0.05$). In 2021, a total of 6615 adults were trapped using food attractants, and 6429 adults were trapped using sex pheromones. There was no significant difference in the average daily trapping amount of *C. medinalis* using food attractants or sex pheromones in Shaodong. ($t = -1.93$, $df = 86$, $p = 0.06$).

The anatomical results regarding *C. medinalis* males trapped during the year 2020 using food attractants and sex pheromones showed that the highest percentage of 1-day-old males trapped using food attractants and sex pheromones in Liling was 17.8% and 23.72%, respectively. The lowest percentage of 7-day-old males trapped using food attractants was 8.67%, and the lowest percentage of 8-day-old moths trapped using sex pheromones was 5.53% (Figure 2D). The highest proportion of 8-day-old males trapped using food attractants and sex pheromones in Zhangjiagang was 35.71% and 32.65%, respectively. The lowest proportion of 1-day-old males trapped by food attractants and sex pheromones was 1.02% and 2.04%, respectively (Figure 2E). Both food attractants and sex pheromones trapped males at almost all ages (i.e., 1–8 days old), and there was no significant difference in the age structure of males trapped using either trapping method (Liling: $\chi^2 = 13.33$, $df = 7$, $p = 0.064$; Zhangjiagang: $\chi^2 = 9.264$, $df = 7$, $p = 0.234$). The highest percentage of 8-day-old males trapped using food attractants and sex pheromones in Shaodong in 2021 was 27.50% and 22.50%, respectively, while that of 1-day-old males was the lowest, with both capturing 4% (Figure 2F). The age structure of field-caught males did not differ between either trapping method (Shaodong: $\chi^2 = 4.482$, $df = 7$, $p = 0.722$).

In 2020, the results of the field monitoring using food attractants in seven different locations showed significant differences in the number of females and males of *C. medinalis* captured in different locations. With the exception of Zhangjiagang, the number of females was higher than the number of males, and the number of males in the remaining six sites was significantly higher than the number of females (Table 3). In 2021, the number of males

trapped by *C. medinalis* was significantly higher than that of females at the two sites, except for the number of females and males trapped using food traps in Taihe, which was not significantly different (Table 3).

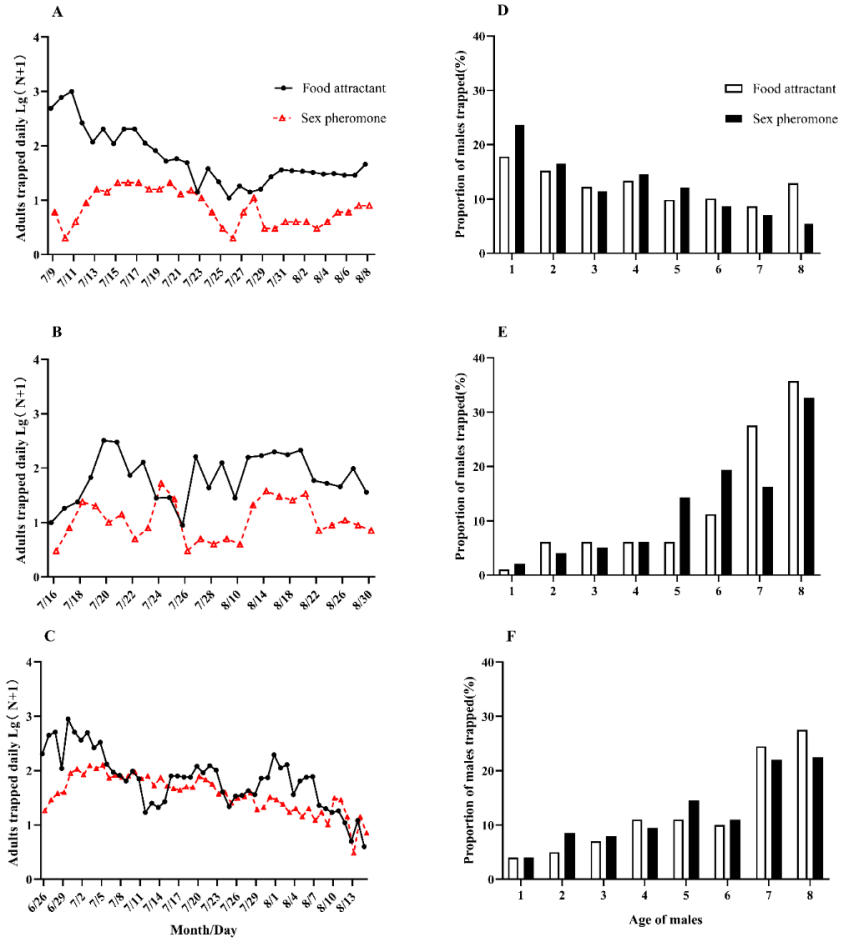


Figure 2. The population dynamics of *C. medinalis* trapped using food attractants and sex pheromones and the distribution of male age structure in different years and places. Dynamics of the number of *C. medinalis* trapped by food attractants and sex pheromones at Liling in 2020 (**A**); Zhangjiagang in 2020 (**B**); and Shaodong in 2021 (**C**); age distribution of males trapped at Liling in 2020 (**D**); Zhangjiagang in 2020 (**E**); and Shaodong in 2021 (**F**).

Table 3. The number of female and male *C. medinalis* trapped using food attractants at each experimental site in 2020 and 2021.

Experimental Year	Experimental Site/Province	Number of Females	Number of Males	χ^2	p
2020	Guigang/Guangxi	800	1503	214.59	<0.001
2020	Liling/Hunan	1729	2413	112.95	<0.001
2020	Shaodong/Hunan	1272	2075	192.65	<0.001
2020	Changzhou/Jiangsu	538	1591	520.81	<0.001
2020	Zhangjiagang/Jiangsu	1593	976	148.19	<0.001
2020	Quzhou/Zhejiang	419	677	60.73	<0.001
2020	Xiangshan/Zhejiang	493	988	165.45	<0.001
2021	Shaodong/Hunan	2442	4173	452.97	<0.001
2021	Taihe/Jiangxi	185	207	1.24	0.270
2021	Zhijiang/Hunan	464	648	30.45	<0.001

3.2. Monitoring Seasonal Population Migration Dynamics of *C. medinalis* Using Food Attractants

During the monitoring period in 2020, the *C. medinalis* peak occurred in mid to late July (Figure 3B–D), except for Guigang, in which the peak of *C. medinalis* was observed in early June (Figure 3A). The maximum number of trapped *C. medinalis* was 1631/day in Shaodong, and the lowest was 220/day in Quzhou.

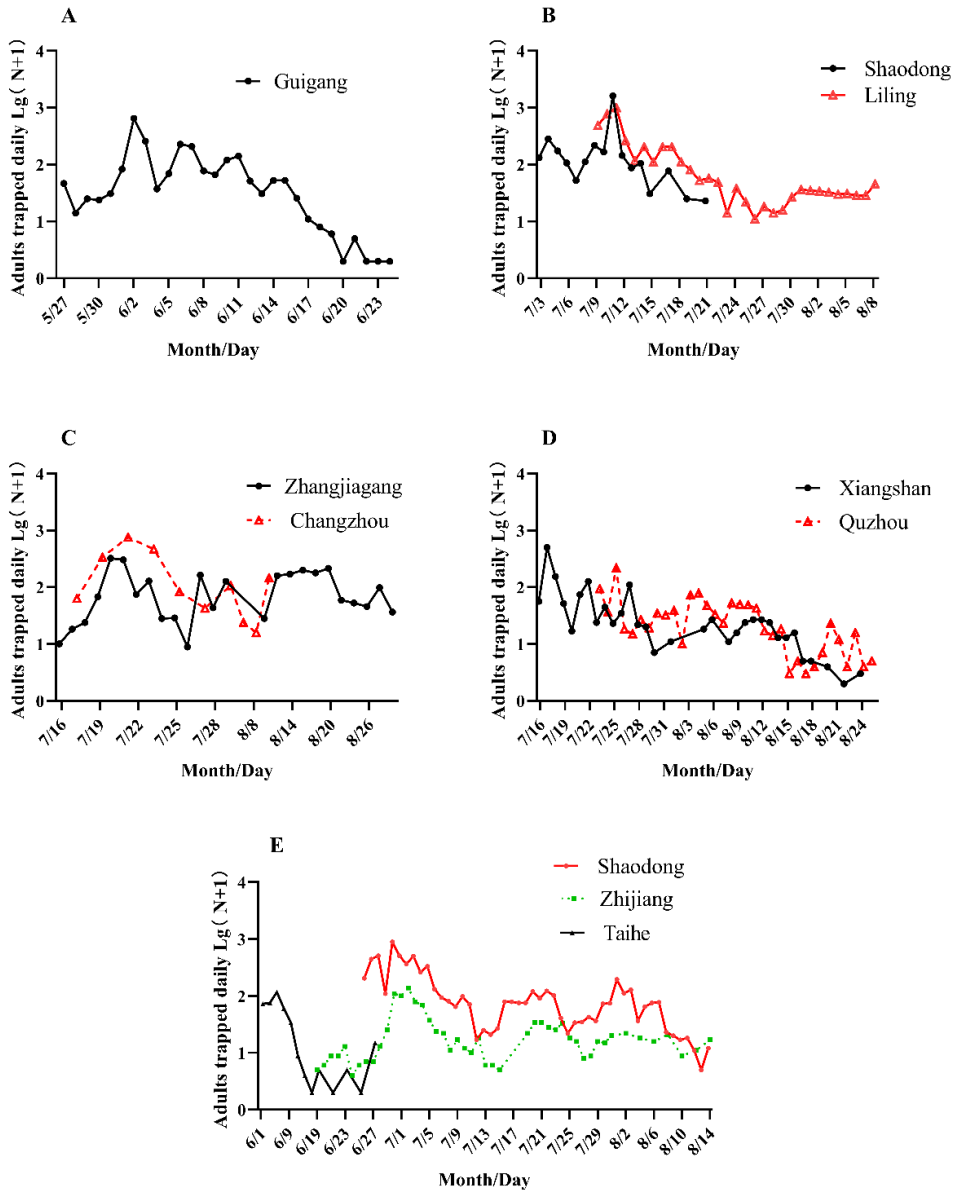


Figure 3. Dynamics of the number of *C. medinalis* trapped using food attractants in different years and locations. Dynamics of the number of *C. medinalis* trapped using food attractants at Guigang in 2020 (**A**); Shaodong and Liling in 2020 (**B**); Zhangjiagang and Changzhou in 2020 (**C**); Xiangshan and Quzhou in 2020 (**D**); and Shaodong, Zhijiang and Taihe in 2021 (**E**).

In 2021, the peak periods of *C. medinalis* at Shaodong and Zhijiang were basically the same (Figure 3E). Shaodong recorded the highest number of *C. medinalis* trapped on June 30, with a maximum of 883 adults per day. Zhijiang reached its highest trapping number of *C. medinalis* on 2 July, with a maximum of 136/day. At Taihe, there was a peak of *C. medinalis* in early June, and the highest trapping number was reached on June 5, with a maximum of 117/day (Figure 3E).

3.3. Monitoring the Reproductive Development Status of C. medinalis using Food Attractants

The anatomical results of females trapped using food attractants in different locations in 2020 showed that the proportion of individuals with an index of ovarian development of 1 in females trapped using food attractants in Guigang was 11.96%, and that of individuals with an index of ovarian development of 3–5 was 82.68% (Figure 4A). The proportion of individuals with an index of ovarian development of 1 trapped using food attractants in Liling was 10.92%, and the proportion of individuals with an index of ovarian development of 3–5 was 62.78% (Figure 4B). The percentage of individuals with an index of ovarian development of 1 and 3–5 in Shaodong was 0.77% and 94.59%, respectively (Figure 4C). In Changzhou, the proportion of trapped females with an index of ovarian development of 1 and 3–5 was 0 and 94.59%, respectively (Figure 4D). In Zhangjiagang, the proportion of trapped females with an index of ovarian development of 1 and 3–5 was 2.88% and 94.01%, respectively (Figure 4E). In Quzhou, the proportion of trapped females with an index of ovarian development of 1 and 3–5 was 9.30% and 77.41%, respectively (Figure 4F). In Xiangshan, the proportion of trapped females with an index of ovarian development of 1 and 3–5 was 1.60% and 94.57%, respectively (Figure 4G). Based on the criteria for determining the nature of *C. medinalis* origin, it can be judged that in 2020, except for the Liling *C. medinalis* population as a local population, the populations of *C. medinalis* in the other six locations were mainly migrant species.

The anatomical results of females trapped by food attractants in different locations in 2021 showed that the ovarian developmental level 1 females trapped using food attractants in Shaodong accounted for 7.44%, and the ovarian development level 3–5 females accounted for 87.18% (Figure 4H). The proportion of ovarian developmental level 1 females trapped using food attractants in Zhijiang was 2.05%, and the proportion of ovarian developmental level 3–5 females was 94.36% (Figure 4I). The number of individuals of ovarian developmental level 1 females trapped using food attractants in Taihe accounted for 2.86%, and the proportion of ovarian developmental level 3–5 females was 94.49% (Figure 4J). In 2021, the *C. medinalis* populations of Shaodong, Zhijiang, and Taihe were mainly species which had migrated from other locations.

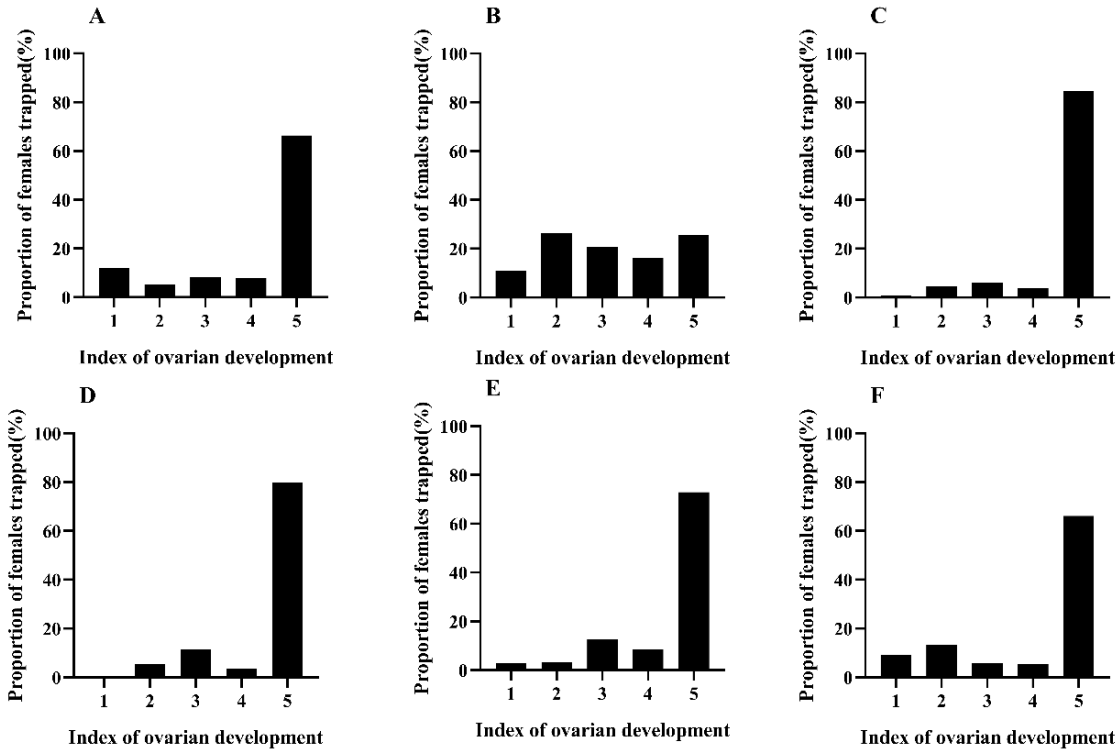


Figure 4. *Cont.*

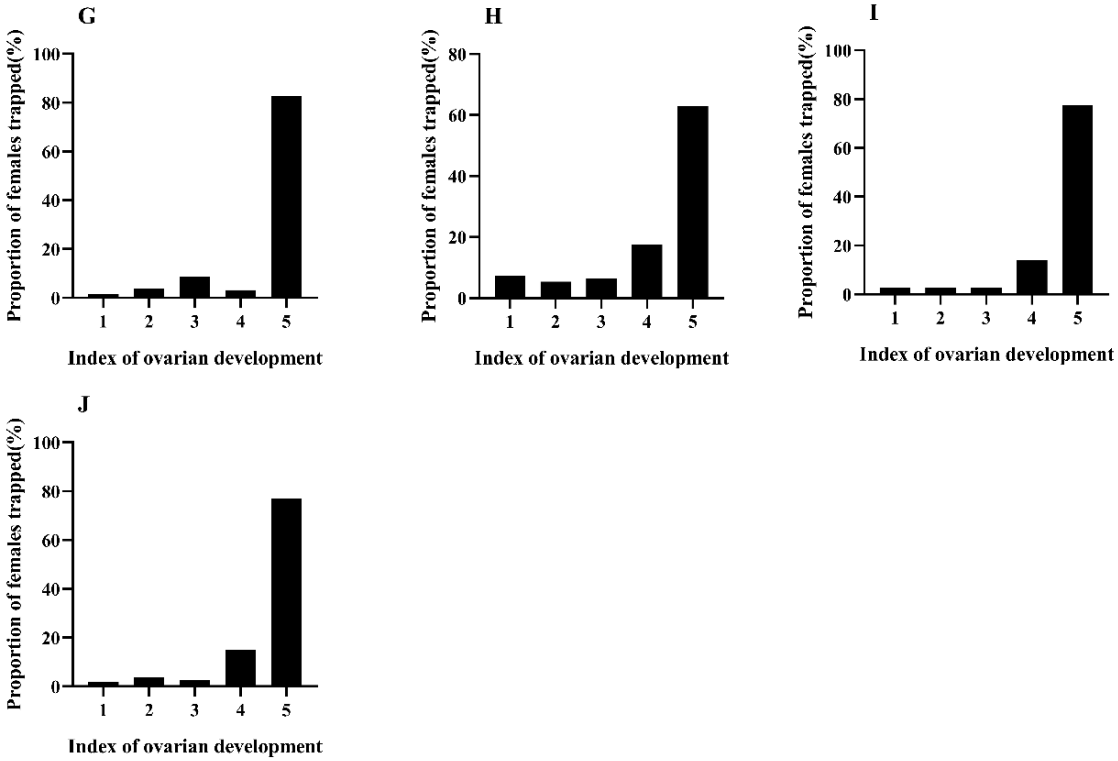


Figure 4. Analysis of the proportion of ovarian development levels of females of *C. medinalis* trapped at Guigang in 2020 (**A**); Liling in 2020 (**B**); Shaodong in 2020 (**C**); Changzhou in 2020 (**D**); Zhangjiagang in 2020 (**E**); Quzhou in 2020 (**F**); Xiangshan in 2020 (**G**); Shaodong in 2021 (**H**); Zhijiang in 2021 (**I**); and Taihe in 2021 (**J**).

The correlation analysis between the index of ovarian development of females and the male age of *C. medinalis* trapped using food attractants showed that there was a significant positive correlation between the index of ovarian development and the male age at Quzhou and Xiangshan in 2020, as well as Shaodong and Zhijiang in 2021. (Quzhou: $r = 0.570$, $p = 0.007$, Figure 5A; Xiangshan: $r = 0.604$, $p = 0.002$, Figure 5B; Shaodong: $r = 0.401$, $p = 0.011$, Figure 5C; Zhijiang: $r = 0.527$, $p = 0.017$, Figure 5D).

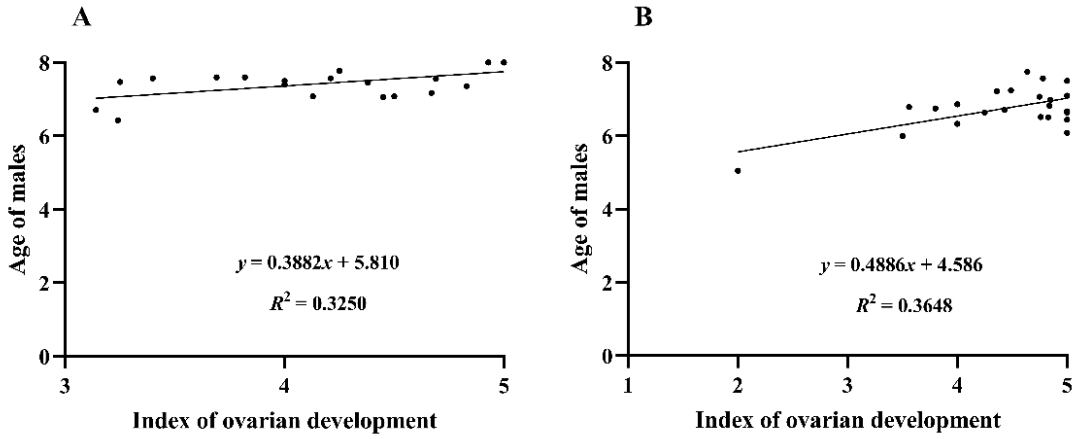


Figure 5. *Cont.*

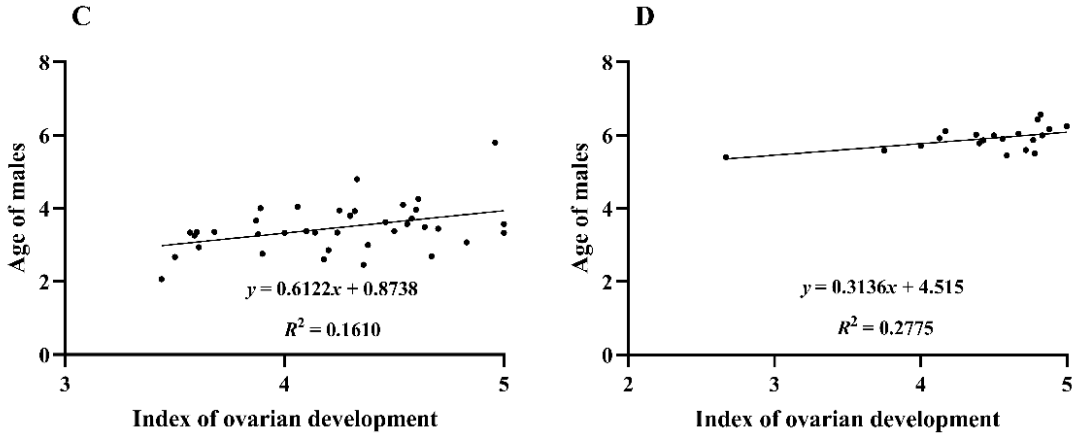


Figure 5. Correlation between the index of ovarian development and male age of adult *C. medinalis* trapped using food attractants at Quzhou in 2020 (**A**); Xiangshan in 2020 (**B**); Shaodong in 2021 (**C**); and Zhijiang in 2021(**D**).

The correlation analysis of the ovarian development level and mating time of *C. medinalis* trapped using food attractants at different sites in 2020 and 2021 showed that the ovarian development level and mating time of females in Guigang, Liling, Zhangjiagang, and Quzhou in 2020 and Shaodong and Zhijiang in 2021 were significantly positively correlated (Guigang: $r = 0.905$, $p < 0.001$, Figure 6A; Liling: $r = 0.937$, $p < 0.001$, Figure 6B; Zhangjiagang: $r = 0.837$, $p < 0.001$, Figure 6C; Quzhou: $r = 0.880$, $p < 0.001$, Figure 6D; Xiangshan: $r = 0.760$, $p < 0.001$, Figure 6E; Shaodong: $r = 0.766$, $p < 0.001$, Figure 6F; Zhijiang: $r = 0.797$, $p < 0.001$, Figure 6G).

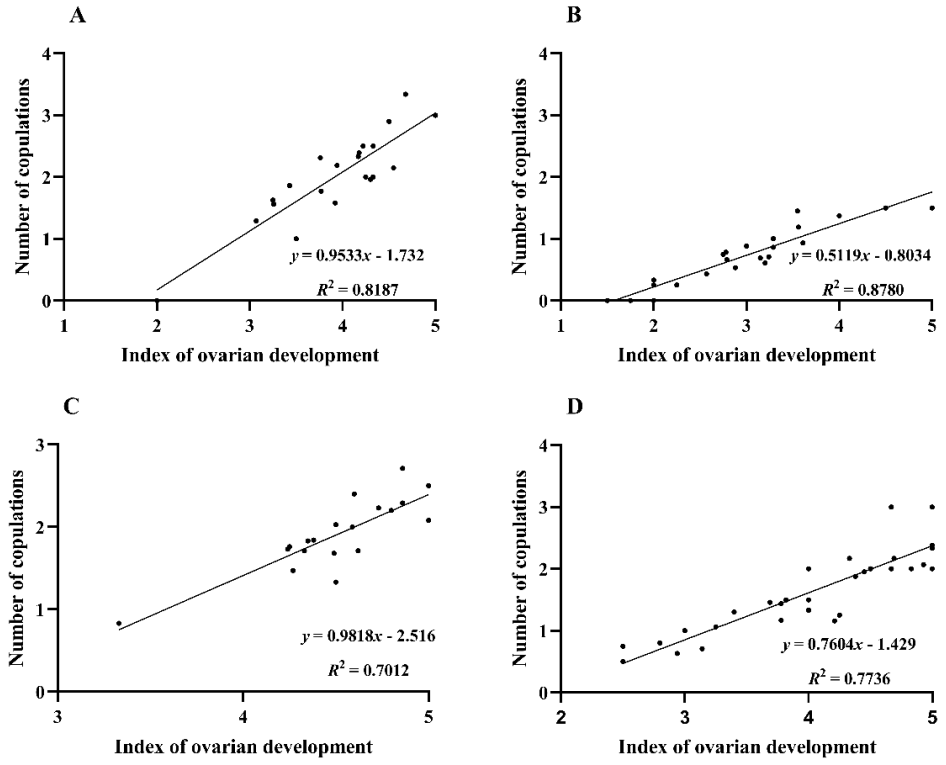


Figure 6. *Cont.*

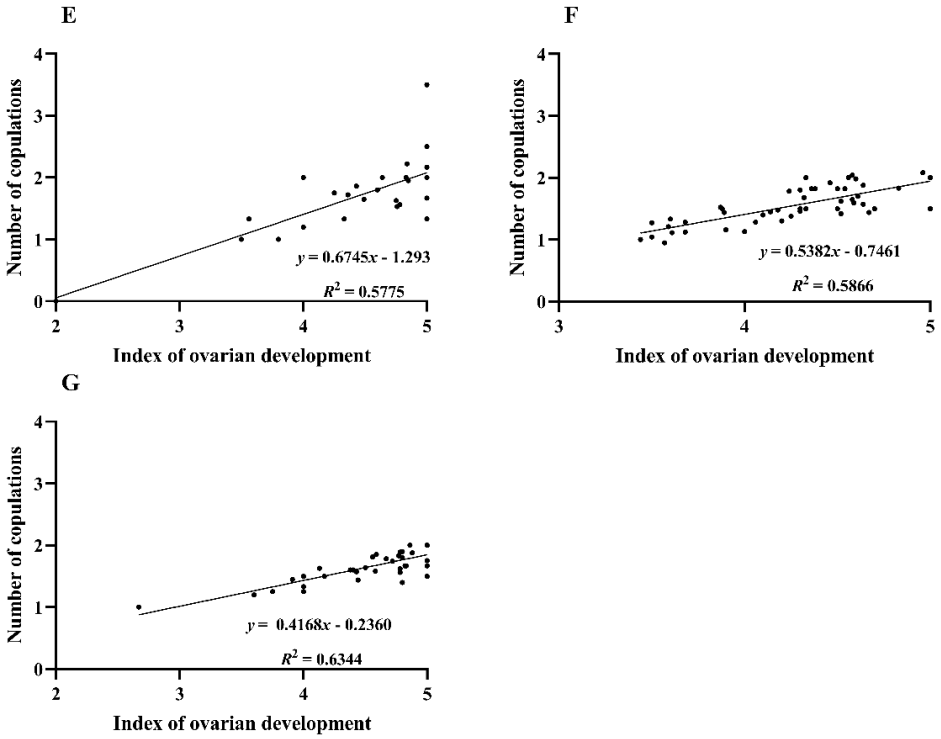


Figure 6. Correlation between the ovarian development level and mating time in attractant trapping of *C. medinalis* at Guigang in 2020 (**A**); Liling in 2020 (**B**); Zhangjiagang in 2020 (**C**); Quzhou in 2020 (**D**); Xiangshan in 2020 (**E**); Shaodong in 2021 (**F**); and Zhijiang in 2021 (**G**).

3.4. Prediction of Oviposition Dynamics of C. medinalis Based on Food Attractants Monitoring Data

In 2020, the egg holding amount of *C. medinalis* in Guigang was low during the monitoring period. The lowest egg holding volume was 9.80 ± 5.07 on May 29, and the highest egg holding volume was 56.00 ± 4.00 on June 21 (Figure 7A). The prediction of oviposition dynamics showed that the highest percentage of oviposition in Guigang was 86.00% on May 29, and the lowest was 20.00% on 21 June (Figure 7A). At Liling in 2020, the lowest egg holding capacity was 21.67 ± 3.09 on 9 July, and the highest egg holding capacity was 40.35 ± 2.65 on July 19 (Figure 7B). Liling showed a maximum percentage of oviposition of 69.05% on 9 July and a minimum percent oviposition of 42.35% on 19 July (Figure 7B).

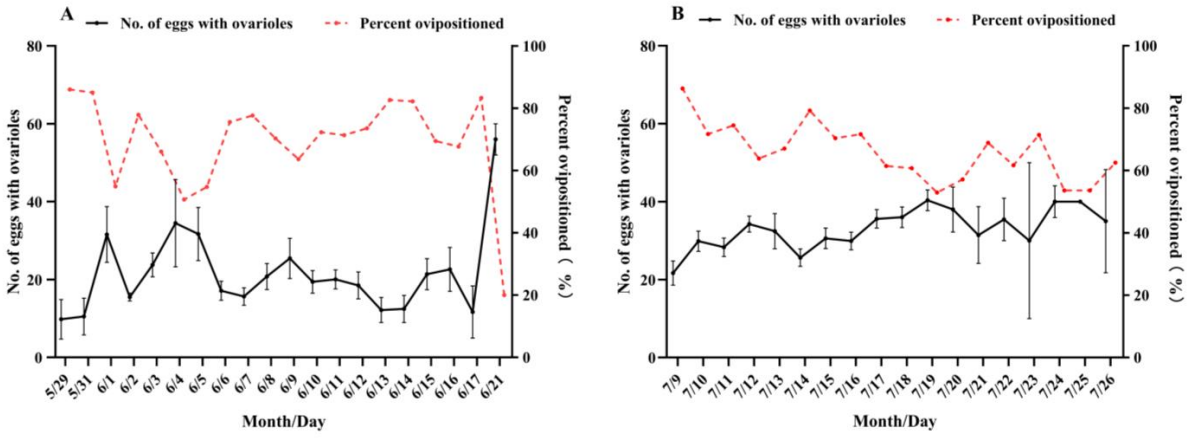


Figure 7. Changes in the number of eggs within the ovarioles and the percentage of oviposition of the females of *C. medinalis* trapped using food attractants at Guigang (**A**) and Liling (**B**) in 2020.

4. Discussion

The real-time and accurate monitoring of the population dynamics of migratory pests can provide important data for prediction and control decisions, laying a solid foundation for integrated pest management concepts [34,35]. This study showed that the monitoring of insect age and reproductive development state is possible using food attractant traps. We also showed how reproductive system analysis can be used to determine the nature of the origin of *C. medinalis* at different sites. In addition, we investigated the relationship between ovarian development, male age, and mating time of adult *C. medinalis* trapped using food attractants and predicted the fecundity dynamics of *C. medinalis*. In addition, in this study, a new monitoring and early warning method based on food attractants trapping of *C. medinalis* was explored, which is valuable for guiding the regional management of this pest.

In this study, the monitoring effects of the use of food attractants and sex pheromones on *C. medinalis* were compared, and the results showed that the peak occurrence period of adults trapped using food attractants and sex pheromones in three different locations was basically consistent during the two-year monitoring period. However, the trapping efficiency of food attractants was superior to that of sex pheromones. For example, in 2020, the number of adults trapped using food attractants in Liling and Zhangjiagang was significantly higher than that obtained using sex pheromones. Zeng et al. trapped adult *C. medinalis* in different ways, and found that the number of adults trapped using food attractants was higher than that obtained using sex pheromones, and this method could trap both sexes simultaneously [28]. This result is consistent with the results of the current study using food attractants to monitor *C. medinalis*. We also compared the age structure of males trapped using food attractants and sex pheromones and found that almost all males of each age (1–8 days old) could be trapped using either trapping method, and there was no significant difference in the age structure of males between the two methods. This is consistent with the results obtained by He et al. using food attractants to trap adult *S. frugiperda* [31]. Different food attractants often result in different sex ratios when trapping different species of pests. For example, the sex ratio of *Spodoptera exigua* trapped using food attractants was close to 1:1 [36], while the number of female *S. frugiperda* trapped was significantly higher than the number of male moths [31]. This may be caused by the different volatile components of food attractants. Cheng et al. found that male *C. medinalis* showed strong potential responses to n-valeraldehyde, benzaldehyde, and methyl salicylate [26]. In addition, based on the monitoring results of food attractants in 2020–2021, it can be seen that the peak occurrence period of *C. medinalis* in different locations in the same province was basically the same. For example, in 2020, the peak periods of *C. medinalis* in Liling and Shaodong in Hunan Province, Changzhou and Zhangjiagang in Jiangsu Province, and Quzhou and Xiangshan in Zhejiang Province are basically the same, and the peak periods of *C. medinalis* in Shaodong and Zhijiang in Hunan Province in 2021 was basically the same. We infer that *C. medinalis* may migrate to different locations in the same province on a large scale at similar times. Therefore, the control strategy for *C. medinalis* must not only be limited to a single area, but needs to be managed in the pest source province for reducing its possibility of regional outbreaks by long distance migration. Insect ovary dissection technology is one of the most important methods for studying pest occurrence patterns and predicting their times of onset. By the dissection of female ovaries in the field, the process of ovarian development of females can be determined, and subsequently, the nature of insect origin can be determined [37]. In this study, by dissecting the ovaries of females trapped using food attractants, it was found that the sources of trapped *C. medinalis* were different in different years and places. For example, in 2020, the population of *C. medinalis* in Liling was a native population, and the populations of *C. medinalis* in the rest of the sites were mainly migrant populations from other regions. According to the migration principle, *C. medinalis* began migrating north from Guangxi and Hainan Province from late May to mid-June, mainly landing in the Jiangling rice area in eastern and northern China. In mid-to-late June, a large number of *C. medinalis* migrated from the Jiangling rice area

to the vast Jianghuai rice area in the Huaihe River Basin and the Hanzhong Basin. From late July to early August, it continued to move north, reaching the northern rice areas of North and Northeast China. From late August to early September, *C. medinalis* began to migrate southward to the perennial rice areas of Jianghuai, Jiangling, and Hainan [38,39]. In this study, adult *C. medinalis* monitored in Hunan, Guangxi, Jiangsu, Zhejiang, and Jiangxi provinces were predominantly migrant populations, which were consistent with the *C. medinalis* north-south migration law in China. This study also showed that ovarian development was positively correlated with both the moth age and mating times of *C. medinalis*. Therefore, when the number of females trapped using food attractants is low, the ovarian development level of females can be inferred based on the age of male *C. medinalis* to accurately monitor the reproductive development status of adult *C. medinalis*. When anatomical samples are damaged, the accuracy of determining the ovarian development index can be improved by analyzing the mating time of female *C. medinalis*. Based on the egg holding capacity of female *C. medinalis* trapped in the field, we can also speculate on the percentage of oviposition of the *C. medinalis* population in the field, which is helpful in establishing a larval hatching model.

In this study, by analyzing the reproductive development status of adult *C. medinalis* trapped in the field using an attractant and number dynamics, the origin of the field population of *C. medinalis* can be more accurately explored, and fecundity dynamics can be predicted. In the future, for comprehensive control of *C. medinalis*, the monitoring of food attractants may be combined with physical control, and light trapping may be used to trap adults during peak periods [40]. Based on the analysis of the nature of the insect source, trapping measures along the migration path may be established to reduce migration in crop growing areas. In addition, the combination of the use of food attractants and push-pull strategies may reduce the infestation of *C. medinalis*, i.e., in field trials, by combining food attractants and push-pull strategies to reduce the fecundity of *Drosophila suzukii* and *Delia radicum* [41–43].

Similar to the results of this study, the use food attractants has also showed a strong ability to monitor other pests. For example, the use of food attractants (pear esters) in apple orchards can effectively capture female and male codling moths, and the trapping peak for the use of food attractants is consistent with those obtained using sexual attractants [44,45]. However, trapping efficiency was often low regarding the use of food attractants. For example, the average daily fall armyworm collection number was only 0.5/trap [29], and the average daily trapping number of females and males of the grape berry moth was less than 1/trap [46]. In this study, the average daily number pests trapped using food attractants was higher than that obtained using sex pheromones, providing more accurate monitoring results. Moreover, since food attractants are usually composed of plant volatiles, they are also attractive to non-target insects. For example, food attractants often trap beneficial insects, while monitoring population dynamics [47]. In this study, the proportion of *C. medinalis* trapped using food attractants in the field monitoring process was as high as 90%, and this method was also highly specific and less harmful to non-target insects, such as beneficial insects.

Food attractants are convenient and environment friendly, but they still exhibit some problems. Under field conditions, the effective period for *C. medinalis* food attractants are short, most of which are only 15–20 d [48]. Moreover, the high concentration of volatiles in food attractants at the early stage of the test resulted in some repellent effect on *C. medinalis*, while the decreased volatile concentration at the later stage of use reduced adult trapping, which had a greater impact on the long-term monitoring of population dynamics. Factors such as the color, shape, and height of the trap may also have an impact on trapping efficiency. Therefore, in order to improve the monitoring accuracy of food attractants, further studies are needed in terms of food attractant carrier materials, volatile compound field release rate, trap settings, and field distribution. This study showed that food attractants can accurately monitor *C. medinalis* population dynamics in the field. Combined with reproductive anatomy techniques, the reproductive development status

and origin characteristics of *C. medinalis* in field populations can be further analyzed. In addition, we have established a link between the reproductive development of females and males trapped using food attractants, which can improve the accuracy of monitoring. Our research is useful in advancing the development of field population surveillance technology for *C. medinalis*, which is of great value to guide the regional management of this pest.

Author Contributions: Conceptualization, L.G., R.Y., W.H. and K.W.; methodology, L.G., R.Y., W.H. and K.W.; software, L.G., R.Y. and W.H.; validation, W.H. and K.W.; writing—original draft preparation, L.G.; writing, all authors; visualization, all authors; supervision, K.W.; project administration, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Laboratory of Lingnan Modern Agriculture Project (NT2021003).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Padmavathi, C.; Katti, G.; Padmakumari, A.P.; Voleti, S.R.; Subba Rao, L.V. The effect of leaf folder *Cnaphalocrocis medinalis* (Guenee) [Lepidoptera: Pyralidae] injury on the plant physiology and yield loss in rice. *J. Appl. Entomol.* **2013**, *137*, 249–256. [CrossRef]
2. Sun, X.; Liu, Z.; Zhang, A.; Dong, H.B.; Zeng, F.F.; Pan, X.Y.; Wang, Y.; Wang, M.Q. Electrophysiological responses of the rice leaf folder, *Cnaphalocrocis medinalis*, to rice plant volatiles. *J. Insect Sci.* **2014**, *14*, 70. [CrossRef]
3. Chintalapati, P.; Balakrishnan, D.; Venu Gopal Nammi, T.V.; Javvaji, S.; Muthusamy, S.K.; Lella Venkata, S.R.; Neelamraju, S.; Katti, G. Phenotyping and Genotype × Environment Interaction of Resistance to Leaf folder, *Cnaphalocrocis medinalis* (Guenee) (Lepidoptera: Pyralidae) in Rice. *Front. Plant Sci.* **2019**, *10*, 49. [CrossRef] [PubMed]
4. Khan, Z.R.; Barrion, A.T.; Litsinger, J.A.; Castilla, N.P.; Joshi, R.C. A Bibliography of Rice Leaf folders (Lepidoptera: Pyralidae). *Int. J. Trop. Insect Sci.* **1988**, *9*, 129–174. [CrossRef]
5. Shanmugam, T.R.; Sendhil, R.; Thirumalvalavan, V. Quantification and prioritization of constraints causing yield loss in rice (Oryza sativa) in India. *Agric. Trop. Et Subtrop.* **2006**, *39*, 194–201.
6. Luo, S.J. Occurrence of rice leaf roller in China and its identification and prevention. *Plant Dis. Pests* **2010**, *1*, 13–18. [CrossRef]
7. Li, S.W.; Yang, H.; Liu, Y.F.; Liao, Q.R.; Du, J.; Jin, D.C. Transcriptome and gene expression analysis of the rice leaf folder, *Cnaphalocrosis medinalis*. *PLoS ONE* **2012**, *7*, e47401. [CrossRef]
8. Sun, B.B.; Zhang, L.; Jiang, X.F.; Luo, L.Z. Effects of temperature on reproduction in the rice leaf roller. *Chin. J. Appl. Entomol.* **2013**, *50*, 622–628. [CrossRef]
9. Morshed, M.N.; Howlader, M.T.H.; Rafiqul, M.; Islam, N.S.; Hera, M.H.R. Effect of abiotic factors on the seasonal incidence of Rice yellow stem borer, *Scirpophaga incertulas* (Walker) and rice leaf folder, *Cnaphalocrocis medinalis* (Guenee) population at the south-east coastal region of. *J. Entomol. Zool. Stud.* **2020**, *8*, 1321–1326.
10. Lu, M.H.; Liu, W.C.; Hu, G.; Zhai, B.P.; Hoang, A.T.; Do, H.K. Analysis of the relationships of rice planthopper and rice leaf folder occurrence between China and Vietnam. *Plant Prot.* **2018**, *44*, 31–36. [CrossRef]
11. Jiang, Y.Y.; Liu, J.; Zeng, J.; Huang, C.; Zhang, T. Occurrence of, and damage caused by, major migratory pests and techniques for monitoring and forecasting these in China. *Chin. J. Appl. Entomol.* **2021**, *58*, 542–551.
12. Fu, X.W.; Li, C.; Feng, H.Q.; Liu, Z.F.; Chapman, J.W.; Reynolds, D.R.; Wu, K.M. Seasonal migration of *Cnaphalocrocis medinalis* (Lepidoptera: Crambidae) over the Bohai Sea in northern China. *Bull. Entomol. Res.* **2014**, *104*, 601–609. [CrossRef] [PubMed]
13. Bao, Y.X.; Cao, Y.; Xie, X.J.; Lu, M.; Li, X.; Wang, C.Z.; Liu, W.C. Migration pattern of rice leaf roller and impact of atmospheric conditions on a heavy migration event in China. *Acta Ecol. Sin.* **2015**, *35*, 3519–3533. [CrossRef]
14. Liang, Y.Y.; Luo, M.; Fu, X.G.; Zheng, L.X.; Wei, H.Y. Mating disruption of Chilo suppressalis from sex pheromone of another pyralid rice pest *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae). *J. Insect Sci.* **2020**, *20*, 19. [CrossRef]
15. Wu, J.; Wu, X.; Chen, H.; Xu, L.; Liu, G.; Mao, B.; Quo, R.; Du, Y. Optimization of the sex pheromone of the rice leaf folder moth *Cnaphalocrocis medinalis* as a monitoring tool in China. *J. Appl. Entomol.* **2013**, *137*, 509–518. [CrossRef]
16. Sun, G.J.; Liu, S.H.; Luo, H.L.; Feng, Z.L.; Yang, B.J.; Luo, J.; Tang, J.; Yao, Q.; Xu, J.J. Intelligent Monitoring System of Migratory Pests Based on Searchlight Trap and Machine Vision. *Front. Plant Sci.* **2022**, *13*, 897739. [CrossRef]
17. Zhu, F.; Zeng, J.; Tian, Z.H. Monitoring of population dynamics and development status of rice leaf folder moth by sex pheromone trapping. *China Plant Prot.* **2018**, *38*, 43–47. [CrossRef]
18. Kawazu, K.; Kamimuro, T.; Kamiwada, H.; Nagata, K.; Matsunaga, T.; Sugie, H.; Fukumoto, T.; Adati, T.; Tatsuki, S. Effective pheromone lures for monitoring the rice leaffolder moth, *Cnaphalocrocis medinalis* (Lepidoptera: Crambidae). *Crop. Prot.* **2004**, *23*, 589–593. [CrossRef]

19. Cho, J.R.; San Choi, K.; Park, H.H.; Lee, S.; Yum, K.H.; Jung, J.K.; Seo, B.Y.; Lee, M. Electroantennogram and field responses of Korean population of the rice leaf folder, *Cnaphalocrocis medinalis* (Lepidoptera: Crambidae), to sex attractant candidates. *J. Asia-Pac. Entomol.* **2013**, *16*, 61–66. [CrossRef]
20. Zeng, J.; Du, Y.J.; Jiang, Y.Y.; Liu, W.C. Development and application of sex pheromone in population monitoring of crop insect pests in China. *Plant Prot.* **2015**, *41*, 9–15.
21. Zeng, F.F.; Liu, H.; Zhang, A.; Lu, Z.X.; Leal, W.S.; Abdelnabby, H.; Wang, M.Q. Three chemosensory proteins from the rice leaf folder *Cnaphalocrocis medinalis* involved in host volatile and sex pheromone reception. *Insect Mol. Biol.* **2018**, *27*, 710–723. [CrossRef]
22. Zhu, P.J.; Shen, H.R.; Chen, Z.G.; Li, H.M.; Jiang, Y.P. Screening test on lure core of rice leaf folder detection. *China Plant Prot.* **2010**, *30*, 41–42. [CrossRef]
23. Feng, B.; Guo, Q.S.; Zhu, F.; Wang, X.; Liu, W.C.; Jiang, Y.Y.; Zhong, L.; Du, Y.J. Ovarian development and synthetic sex pheromone lure trapping of adults of the rice leaf folder, *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae). *Acta Entomol. Sin.* **2017**, *60*, 211–221. [CrossRef]
24. Gregg, P.C.; Del Socorro, A.P.D.; Henderson, G.S. Development of a synthetic plant volatile-based attracticide for female noctuid moths. II. Bioassays of synthetic plant volatiles as attractants for the adults of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Aust. J. Entomol.* **2010**, *49*, 21–30. [CrossRef]
25. Eigenbrode, S.D.; Birch, A.N.E.; Lindzey, S.; Meadow, R.; Snyder, W.E. A mechanistic framework to improve understanding and applications of push-pull systems in pest management. *J. Appl. Ecol.* **2016**, *53*, 202–212. [CrossRef]
26. Cheng, J.J.; Zhu, J.; Liu, F. EAG response of *Cnaphalocrocis medinalis* to 43 graminaceous plant volatiles. *Chin. J. Appl. Entomol.* **2016**, *53*, 472–481. [CrossRef]
27. Wei, B.; Gao, H.Y.; Zheng, X.S.; Xu, H.X.; Ruan, Y.M.; Lv, Z.X.; Zhu, P.Y. EAG responses of adult *Cnaphalocrocis medinalis* to plant volatiles. *Chin. J. Appl. Entomol.* **2022**, *59*, 988–996. [CrossRef]
28. Zeng, J.; Zhang, T.; Wang, L.Y.; Wu, Q.L.; Lu, M.H.; Wu, K.M. Preliminary application of food attractant trapping in monitoring population dynamics of leaf folder, *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae) in China. *Plant Prot.* **2021**, *47*, 203–214. [CrossRef]
29. Cheng, J.Y.; Xia, H.X.; Zhang, C.; Chang, X.Q.; Zhang, S.; Lv, L.; Chang, W. Preliminary study on monitoring the occurrence of rice leaf folder by biological food attractants in field. *Hubei Plant Prot.* **2022**, *3*, 31–33. [CrossRef]
30. He, W.; Zhao, X.C.; Ali, A.; Ge, S.S.; Zhang, H.W.; He, L.M.; Wu, K.M. Population dynamics and reproductive developmental analysis of *Helicoverpa armigera* (Lepidoptera: Noctuidae) trapped using food attractants in the field. *J. Econ. Entomol.* **2021**, *114*, 1533–1541. [CrossRef] [PubMed]
31. He, W.; Wang, L.Y.; Lv, C.Y.; Ge, S.S.; Zhang, H.W.; Jiang, S.; Chu, B.; Yang, X.M.; Wyckhuys, K.A.; Wu, K.M. Use of food attractants to monitor and forecast *Spodoptera frugiperda* (JE Smith) seasonal abundance in southern China. *J. Pest Sci.* **2023**, *96*, 1–13. [CrossRef]
32. Chen, Q.H.; Zeng, J.; Zeng, W.; Li, Q.; Chen, X.J.; Zou, Y. Application of the morphological indicators of the male internal reproductive system in forecasting the population dynamics of the rice leaf roller, *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae) by sex pheromone trapping. *Acta Entomol. Sin.* **2017**, *60*, 927–935. [CrossRef]
33. Zhang, X.X.; Lu, Z.Q.; Geng, J.G. Application of anatomy of female rice leaf folder in measuring and reporting. *Chin. Bulletion Entomol.* **1979**, *3*, 97–99.
34. Wu, K.M.; Guo, Y.Y. The evolution of cotton pest management practices in China. *Annu. Rev. Entomol.* **2005**, *50*, 31–52. [CrossRef]
35. Chouinard, G.; Pelletier, F.; Vincent, C. Pest Activity and Protection Practices: Four Decades of Transformation in Quebec Apple Orchards. *Insects* **2021**, *12*, 197. [CrossRef] [PubMed]
36. He, W.; Zhao, X.C.; Ge, S.S.; Wu, K.M. Food attractants for field population monitoring of *Spodoptera exigua* (Hübner). *Crop. Prot.* **2021**, *145*, 105616. [CrossRef]
37. Wu, K.M.; Guo, Y.Y.; Wu, Y. Ovarian development of adult females of cotton bollworm and its relation to migratory behavior around Bohai bay of China. *Acta Ecol. Sin.* **2002**, *22*, 1075–1078. [CrossRef]
38. Zhang, X.X.; Lu, Z.Q.; Geng, J.G.; Li, G.Z.; Chen, X.L.; Wu, X.W. Study on migration route of rice leaf folder. *Acta Entomol. Sin.* **1980**, *3*, 130–140.
39. Liu, W.; Cai, X.W.; Liu, Y.; Guo, A.H.; Wang, C.Z.; Lu, M.H.; Bao, Y.X. Study on immigration path of rice leaf roller based on FLEXPART and atmospheric background. *Meteorol. Mon.* **2017**, *43*, 460–467. [CrossRef]
40. Chakraborty, K.; Deb, D.C. Incidence of adult leaf folder, *Cnaphalocrocis medinalis* (Lepidoptera: Pyralidae) on paddy crop in the agro climatic conditions of the northern parts of West Bengal, India. *World J. Agric. Sci.* **2011**, *7*, 738–742.
41. Toledo-Hernández, R.A.; Lasa, R.; Montoya, P.; Liedo, P.; Rodríguez, D.; Sánchez, A.; Toledo, J. Efficacy of food-based attractants for monitoring *Drosophila suzukii* (Diptera: Drosophilidae) in berry crops. *Crop. Prot.* **2021**, *150*, 105797. [CrossRef]
42. Wallingford, A.K.; Cha, D.H.; Loeb, G.M. Evaluating a push–pull strategy for management of Drosophila suzukii Matsumura in red raspberry. *Pest Manag. Sci.* **2018**, *74*, 120–125. [CrossRef] [PubMed]
43. Lamy, F.; Dugravot, S.; Cortesero, A.M.; Chaminade, V.; Faloya, V.; Poinsot, D. One more step toward a push-pull strategy combining both a trap crop and plant volatile organic compounds against the cabbage root fly Delia radicum. *Environ. Sci. Pollut. Res.* **2017**, *25*, 29868–29879. [CrossRef] [PubMed]

44. Thwaite, W.G.; Mooney, A.M.; Eslick, M.A.; Nicol, H.I. Evaluating pear-derived kairomone lures for monitoring *Cydia pomonella'*(L.) (Lepidoptera: Tortricidae) in Granny Smith apples under mating disruption. *Gen. Appl. Entomol.* **2004**, *33*, 55–60.
45. Knight, A.L.; Light, D.M. Seasonal flight patterns of codling moth (Lepidoptera: Tortricidae) monitored with pear ester and codlemone-baited traps in sex pheromone-treated apple orchards. *Environ. Entomol.* **2005**, *34*, 1028–1035. [CrossRef]
46. Loeb, G.M.; Cha, D.H.; Hesler, S.P.; Linn, J.C.E.; Zhang, A.J.; Teal, P.E.; Roelofs, W.L. Monitoring grape berry moth (Paralobesia viteana: Lepidoptera) in commercial vineyards using a host plant based synthetic lure. *Environ. Entomol.* **2011**, *40*, 1511–1522. [CrossRef]
47. Broughton, S.; Harrison, J. Evaluation of monitoring methods for thrips and the effect of trap colour and semiochemicals on sticky trap capture of thrips (Thysanoptera) and beneficial insects (Syrphidae, Hemerobiidae) in deciduous fruit trees in Western Australia. *Crop. Prot.* **2012**, *42*, 156–163. [CrossRef]
48. Zhu, H.; Fan, M.J.; Wang, K.F.; Lu, Y. Preliminary study on the monitoring effect of the rice leaf folder's food attractions. *China Plant Prot.* **2021**, *41*, 43–44. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.