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4 **Seasonal migration of *Cnaphalocrocis medinalis* (Lepidoptera:**

5 **Crambidae) over the Bohai Sea in northern China**

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25 **Abstract:** The rice leaf roller, *Cnaphalocrocis medinalis* (Guenée), is a serious
26 insect pest of rice with a strong migratory ability. Previous studies on the migration of
27 *C. medinalis* were mostly carried out in tropical or subtropical regions, however, and
28 what pattern of seasonal movements this species exhibits in temperate regions (i.e.
29 northern China, where they cannot overwinter) remains unknown. Here we present
30 data from an 11-year study of this species made by searchlight trapping on Beihuang
31 Island (BH, 38°24' N; 120°55' E) in the centre of the Bohai Strait, which provides
32 direct evidence that *C. medinalis* regularly migrates across this sea into northeastern
33 agricultural region of China, to take advantage of the abundant food resources there
34 during the summer season. There was considerable seasonal variation in number of *C.*
35 *medinalis* trapped on BH, and the migration period during 2003-2013 ranged from 72
36 to 122 days. Some females trapped in June and July showed a relatively higher
37 proportion of mated individuals and a degree of ovarian development suggesting that
38 the migration of this species is not completely bound by the 'oogenesis-flight
39 syndrome'. These findings revealed a new route for *C. medinalis* movements to and
40 from northeastern China, which will help us develop more effective management
41 strategies against this pest.

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43 **Keywords:** *Cnaphalocrocis medinalis*, seasonal migration, searchlight trapping,
44 over-sea movements, sexual maturation

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Introduction

49 The rice leaf roller, *Cnaphalocrocis medinalis* (Guenée) (Lepidoptera: Crambidae),
50 one of the most important pests of rice, is distributed widely in the humid tropical and
51 temperate regions of Asia, Oceania and Africa between 48°N and 24°S latitude
52 (Pathak & Khan, 1994; Kawazu *et al.*, 2001). *C. medinalis* has a broad host range,
53 including rice, corn, sugarcane, wheat and sorghum, as well as some graminaceous
54 weed species (Luo, 2010); rice is the most preferred host plant (Yadava *et al.*, 1972).
55 The larvae damage the rice plant by folding leaves and scraping green leaf tissues
56 within the fold during the tillering to heading stage, causing great yield losses by
57 reducing photosynthetic activity (Wang *et al.*, 2011).

58 'Migration' is a movement which involves the temporary suppression of an animal's
59 station-keeping responses – responses which would otherwise retain the animal within
60 its current habitat patch – thus allowing displacements of much longer duration and
61 typically over much greater distances than those arising from normal foraging
62 activities (Dingle & Drake, 2007). Long-distance migration plays a key role in the
63 life-history of *C. medinalis* by enhancing its opportunities to use favorable resources
64 across huge areas; this, in turn, leads to severe area-wide damage to crops. In recent
65 decades, a series of major outbreaks of *C. medinalis* has been reported in Asian paddy
66 fields, and severe infestations commonly reduce yields by 30%-80% (Yang *et al.*,
67 2004; Nathan *et al.*, 2005; Nathan, 2006; Zhai & Cheng, 2006; Padmavathi *et al.*,
68 2012). In China, *C. medinalis* has 1-11 generations from north to south each year, and

69 the species' range can be divided into three zones: the 'year-round breeding region',
70 'winter diapause region' and 'summer breeding region' (Fig. 1) (Zhang *et al.*, 1981;
71 Zhang & Tang, 1984; Luo, 2010). Evidence from capture-mark-recapture studies and
72 from light-traps on ships in the East China Sea suggests that *C. medinalis* moths make
73 long-distance migration from the tropics towards the northeast in a series of five
74 northward mass-migrations from March to August, and possibly three southward
75 'return' migrations from September to November each year in the eastern part of
76 China (Chang *et al.*, 1980; Zhang *et al.*, 1981). The Chinese populations of *C.*
77 *medinalis* are also able to migrate over water, reaching Japan every year in the East
78 Asian rainy season (June-July) (Mochida, 1974; National Coordinated Research Team
79 on Rice Leafroller, 1981; Oya & Hirao, 1982; Liu *et al.*, 1983; Kisimoto, 1984; Geng
80 *et al.*, 1990; Miyahara *et al.*, 1981), and such movements are similar to those of the
81 rice planthoppers, *Sogatella furcifera* (Horváth) and *Nilaparvata lugens* (Stål) (Otuka
82 *et al.*, 2005a; 2005b; 2006; 2008; 2012; Syobu & Otuka, 2012).

83 Previous studies on the migration of *C. medinalis* have been mostly carried out in
84 tropical or subtropical rice planting regions. However, whether the migration of *C.*
85 *medinalis* in northern China, where they cannot overwinter (National Coordinated
86 Research Team on Rice Leafroller, 1981; Zhang *et al.*, 1981; Riley *et al.*, 1995; Luo,
87 2010), is a regular ecological event remains unknown. Considering the poleward
88 expansion of many insect species under current global warming scenarios (Wilson *et*
89 *al.*, 2005; Pöyry *et al.*, 2009; Robertson *et al.*, 2009; Pateman *et al.*, 2012), and the
90 increasing areas of rice planting in northeastern China (China Agricultural Yearbook

91 [Editing Committee, 2012](#)), it is critical to enhance our understanding of the migration
92 patterns of this species in such regions. In the present study, long-term (11 years)
93 observations on the seasonal migration of *C. medinalis* over the Bohai Sea were
94 carried out by means of searchlight trapping on a small island located in the centre of
95 the Bohai Strait. Although it cannot illuminate the backgrounds and evolution process
96 of the population fluctuations of *C. medinalis* on the mainland, this study provides
97 direct evidence that this species regularly migrates across the sea into northeastern
98 agricultural region of China, to take advantage of the abundant food resources there
99 during the summer season. These findings will improve our knowledge of the
100 migration pattern and outbreaks of *C. medinalis* in eastern Asia, and will help us
101 develop more effective management strategies against this pest.

102 **Materials and methods**

103 *Light-trapping and field observation*

104 The searchlight trapping studies were carried out from 2003 to 2013 at Beihuang (BH,
105 38°24' N, 120°55' E), the northernmost island of Changdao county in Shandong
106 province ([Fig. 1](#)). This small (~2.5 km²) island is located in the centre of the Bohai
107 Strait at a distance of ~ 40 km from the mainland to the north and ~ 60 km to the
108 south. A vertical-pointing searchlight trap (model DK.Z.J1000B/t, 65.2 cm in diameter,
109 70.6 cm in height and approximately 30° in spread angle; Shanghai Yaming Lighting
110 Co.Ltd., Shanghai, China) ([Feng & Wu, 2010](#)) was placed on a platform ~ 8 m above
111 sea level, and used to attract and capture high-altitude migrants (up to ~ 500 m above

112 ground level) (Feng *et al.*, 2009). The trap was equipped with a 1,000-W metal halide
113 lamp (model JLZ1000BT; Shanghai Yaming Lighting Co.Ltd., Shanghai, China),
114 which produces a vertical beam of light with a luminous flux of 105000 lm, a color
115 temperature of 4000 K; and a color rendering index of 65.

116 The searchlight trap was turned on at sunset and turned off at sunrise on all nights
117 from April to October during 2003-2013. Incomplete data sets that resulted from
118 power cuts or heavy rains were excluded from the analysis. Trapped insects were
119 collected with a nylon net bag (60 mesh) beneath the trap, which was changed
120 manually every 2 h each night. The trapped insects were kept in a freezer at -20 °C for
121 4 h before being identified and the female *C. medinalis* dissected.

122 There are some pine trees and graminaceous weeds on BH, but no arable lands and
123 host crops of *C. medinalis*. To investigate whether any *C. medinalis* moths were
124 produced on BH itself, visual observations were carried out daily to detect larvae of
125 this species on any potential wild hosts from spring through autumn during
126 2003-2013.

127 *Ovarian dissection*

128 From 2010 to 2013, a subsample of 20 females (or all individuals if the total capture
129 of females was < 20) was randomly taken from adults trapped each night, and
130 dissected under a stereomicroscope (model JNOEC-Jsz4; Motic China Group Co.Ltd.,
131 Xiamen, China). The level of ovarian development were estimated according to the
132 criteria described in Table 1 (Zhang *et al.*, 1979). Females with ovarian development

133 level 1-2 were regarded as “sexually immature individuals”, and others with level 3-5
134 were regarded as “sexually mature individuals” (Zhang *et al.*, 1979; Zhu *et al.*, 2009).
135 These data were used to generate an average monthly level of ovarian development
136 (i.e. the sum of individual levels of ovarian development divided by the number of
137 females dissected). Mating rate and mating frequency of *C. medinalis* was determined
138 by the number of spermatophores in the female spermatheca.

139 *Data analysis*

140 All data obtained from the studies are presented as means \pm SEM. Population size of
141 *C. medinalis* captured in the searchlight trap varied in different years and months, so
142 the inter-year and inter-month variations in the number of trapped *C. medinalis*, and
143 the proportion of females, mated females and sexually mature females were analyzed
144 by two-way analysis of variance (ANOVA) with month and year as the variables
145 (Zhao *et al.*, 2009). If the ANOVA indicated a significant difference, Tukey's HSD
146 tests were followed to separate the means. All the proportion data were arcsine
147 transformed before ANOVA to meet the assumptions of normality. Differences of the
148 sex ratio (females: males) in each month were analyzed by chi-squared test. All
149 statistical analyzes were carried out with SAS software (SAS Institute, 1990).

150 The index of occurrence (O) was calculated by the formula: $O = (p / n) \times 100\%$,
151 where p is the number of nights in which *C. medinalis* were trapped in a month, and n
152 is the number of nights in which all insect species were trapped in a month (Zanuncio
153 *et al.*, 1998). Occurrence status of *C. medinalis* captured in the searchlight trap were

154 divided by the following criteria (Serafim *et al.*, 2003): as an accidental species with
155 $O = 0\% - 25\%$, as an accessory species with $O = 25\% - 50\%$, and as a constant species
156 with $O = 50\% - 100\%$.

157

158

Results

159

Annual and seasonal pattern of migration

160 No *C. medinalis* larvae were found on BH by daily field investigations although some
161 graminaceous weeds were available as potential wild hosts. However, *C. medinalis*
162 were regularly captured in the searchlight trap during the period from 2003 to 2013
163 (Fig. 2). This means *C. medinalis* moths migrated at least 40-60 km (and probably
164 much greater distances) across the Bohai Strait waters. The strength of this over-sea
165 migration varied annually. Mass migrations took place in 2003, 2005, 2007 and 2011,
166 with the annual total catches reaching 49,187, 7,032, 9,918 and 8,560 individuals,
167 respectively. Very weak migrations took place in 2009 and 2012, with the annual total
168 catches falling to 72 and 133 individuals, respectively. In other years, the annual total
169 catches of *C. medinalis* ranged between 1,000 and 5,000 individuals (Fig. 2).

170 The number of *C. medinalis* captured in the searchlight trap varied monthly ($F = 2.63$,
171 $df = 4$, $P = 0.048$) during 2003-2013. The mean percentages of *C. medinalis* trapped
172 through the months were $53.9 \pm 9.3\%$ in autumn (September - October), $46.1 \pm 9.3\%$
173 in summer (June - August), and none in spring (April - May) (Fig. 3). During
174 2003-2013, *C. medinalis* were captured frequently in the searchlight trap and

175 considered as a constant species in September. In July, August and October, *C.*
176 *medinalis* were captured occasionally and considered as an accessory species, while in
177 other months this species occurred as an accidental species. The migration period of *C.*
178 *medinalis* over the Bohai Strait during 2003-2013 ranged from 72 to 122 days, with
179 the earliest and latest trapping on 1 June 2009 and 20 October 2006, respectively
180 (Table 2).

181 *Sex ratio, mating rate, mating frequency and ovarian development*

182 From June to October during 2010-2013, the vast majority of trapped *C. medinalis*
183 were females. Chi-squared tests showed that the sex ratio (females: males) was
184 significantly greater than 1:1 in all months, except in June 2010 ($\chi^2 = 0.39$; $df = 1$; $P =$
185 0.528) and June 2013 ($\chi^2 = 0.89$; $df = 1$; $P = 0.346$) (Fig. 4A). There were no
186 significant inter-month differences in the proportion of females, which ranged from
187 $61.4\% \pm 3.1\%$ (June) to $70.2\% \pm 5.6\%$ (October) (linear model, $y = 0.01x + 0.55$, $R^2 =$
188 0.35 , $n = 5$, $F = 1.58$, $P = 0.298$) (Fig. 6A). Most of the trapped females were virgins
189 (Fig. 4B), and there were significant inter-month differences in the proportion of
190 mated females (mating rate), which ranged from $6.0\% \pm 1.0\%$ (September) to 43.2%
191 $\pm 8.0\%$ (June) (Fig. 6B). The seasonal variation in the proportion of mated females
192 showed a weak downward trend from June to October (linear model, $y = -0.09x + 0.87$,
193 $R^2 = 0.75$, $n = 5$, $F = 9.06$, $P = 0.057$) (Fig. 6B). There was significant difference in
194 the mating frequency among the mated females, the vast majority ($82.6 \pm 6.9\%$) had
195 mated once, the $17.4 \pm 6.9\%$ had mated twice, and no individuals mated ≥ 3 times.

196 In all years, no *C. medinalis* females with ovarian development level 5 were found on
197 BH (Fig. 5). The vast majority of the early-summer migrants (June) had a certain
198 degree of ovarian development, and the proportion of sexually mature females
199 reached 65.4 ± 4.3 %, which was significantly higher ($\chi^2 = 11.00$; $df = 1$; $P = 0.001$)
200 than the proportion of sexually immature females (Figs 5 and 6C). However, there
201 was no significant difference ($\chi^2 = 2.47$; $df = 1$; $P = 0.116$) between the proportion of
202 sexually mature females and immature females in mid-summer migrants (July) (Fig.
203 6C). In other months, the proportion of sexually mature females was significantly
204 lower than that of sexually immature females (Fig. 5). Overall, the seasonal variation
205 in the proportion of sexually mature females showed a significant downward trend
206 from June to October (linear model, $y = -0.15x + 1.46$, $R^2 = 0.86$, $n = 5$, $F = 17.81$, P
207 $= 0.024$) (Fig. 6C).

208

209

Discussion

210 The long-term (11 years) searchlight trapping study on BH Island provided direct
211 evidence that both male and female *C. medinalis* moths regularly migrate across the
212 sea into northeastern China, because no host crops or larvae of this species were found
213 on this small island. The long-range movements of *C. medinalis* observed in this study
214 were similar to previous observations of other insects in the orders Lepidoptera,
215 Odonata, and Coleoptera migrating over the Bohai Sea (Feng *et al.*, 2005; 2006;
216 2009).

217 In June and July, *C. medinalis* mainly migrate from the northern part of their winter

218 diapause region (25~30° N) (Fig. 1) into northern China (Zhang *et al.*, 1981). Our
219 data clearly show that the mating rate and the index of ovarian development of *C.*
220 *medinalis* females during this period are significantly higher than in other months.
221 This may be due to these moths emigrating from sites far from the trapping site and
222 therefore having several successive nights of migratory flight. It is clear from
223 flight-mill studies (Wang *et al.*, 2010) that both male and female *C. medinalis* have a
224 strong re-migration capacity and more than 50% of tested moths could fly for 4-5
225 successive nights. Active flight results in a significant increase in body temperature
226 (Heinrich, 1993) and juvenile hormone (JH) biosynthesis (Bühler *et al.*, 1983; Cusson
227 *et al.*, 1990); for example, when *C. medinalis* females were transferred from 10 to
228 15 °C there was significant increase in JH biosynthesis within 24 h, which
229 significantly accelerated reproduction via reduction of the period from eclosion to first
230 egg-laying and increases in mating rate, mating frequency and the total fecundity (Sun
231 *et al.*, 2013). Thus, just considering these points alone it is to be expected that some
232 degree of sexual maturation would occur within several days of initiating migration,
233 and this onset of maturation would be advantageous for immigrant females, allowing
234 them to mate and initiate oviposition as soon as possible after finding a suitable
235 habitat (Wada *et al.*, 1988). The relatively higher mating rate and more advanced
236 ovarian development in this period suggests that the migratory behavior in this species
237 is not inhibited by the onset of ovarian development and/or mating, as might be
238 expected from the oogenesis-flight syndrome (Kennedy, 1961; Johnson, 1963; 1969).
239 However, it is clear that *C. medinalis* females undertaking the northward migration in

240 August (mainly migrating from 30~35° N; [Fig. 1; Zhang *et al.*, 1981](#)) and the return
241 migration in early autumn (mainly migrating from 40~45° N; [Fig. 1; Zhang *et al.*,](#)
242 [1981](#)) have little or no ovarian development, supporting the idea that the onset of
243 migration is initiated mainly by sexually immature individuals. These findings are
244 consistent with the autumn migration of *C. medinalis* in eastern China studied by
245 Riley *et al.* ([1995](#)) between 1988 and 1991. In this study, more than 90% of female
246 moths caught by hand-net near the radar site at Dongxiang county (28°N, 121°E) in
247 northern Jiangxi province in late October 1991, were in stage I or early stage II. At
248 the same time and place, females caught by aerial netting during the actual process of
249 high-altitude southwards migration, were also immature. The sexual immaturity of the
250 moths caught later in the season at BH may be accentuated because individuals are
251 emigrating from sites not too far from the trapping site ([Fu *et al.*, unpublished data](#)).

252 The relationship between long-duration flight and the state of oogenesis appears to be
253 similar to that of *Agrotis ipsilon* (Rotttemberg) (the black cutworm) in North America
254 ([Showers, 1997](#)). Here the northward-moving spring migrants developed
255 reproductively, and it was suggested ([Showers, 1997](#)) that there was no need to shut
256 down reproductive development because the movement takes place rapidly, aided by
257 the low-level jet stream. The southward movement in late summer and autumn is
258 generally much slower (8-15 nights) due to the lighter winds, and in this case the
259 moths did enter reproductive diapause. Cases such as these where there is a partial or
260 limited suppression of reproductive development/behaviour until late in the migration
261 period are distinct from those where the oogenesis-flight syndrome clearly does not

262 apply, such as the tortricid *Choristoneura fumiferana* (Clem.) (the spruce budworm),
263 the females of which typically lay about 50% of their eggs around their natal site,
264 before they ascend above the forest canopy and engage in windborne migration
265 ([Greenbank et al., 1980](#); [Rhains & Kettela, 2013](#)).

266 Migratory insect pests have been studied for many years because of their economic
267 and ecological importance, and a good understanding of the migratory behavior is
268 essential for the development of forecasting systems and IPM strategies for
269 management of such pest species ([Irwin, 1999](#); [Wu & Guo, 2005](#); [Wu et al., 2006](#)).

270 For example, real-time prediction systems have been developed for migratory rice
271 planthoppers, *S. furcifera* and *N. lugens*, in recent years based on a comprehensive
272 knowledge of their flight parameters ([Tang et al., 1994](#); [Otuka et al., 2005b](#); [2012](#)).

273 The current study provides direct evidence that *C. medinalis* make regular
274 long-distance migrations across the Bohai Strait, in order to exploit the abundant but
275 transient resources that develop over vast areas of northeast Asia during spring and
276 summer. The fact that many of the moths were flying at high altitude before their
277 capture, as well as other evidence (e.g. the radar studies of [Riley et al., 1995](#)) strongly
278 suggest that the flights are windborne and occur over a broad front. Nonetheless,
279 further studies are needed to better understand the migration trajectories and
280 high-altitude flying characteristics of this species.

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470

471

Tables

472 Table 1. Criteria of ovarian development level of *C. medinalis* moths.

473

Development level	Characteristics of ovary
1	Transparent and light milky white ovarioles with length of about 5.5 - 8 mm
2	Developing eggs appeared in milky white ovarioles with length of about 8 - 10 mm
3	Well-developed yellowish green ovarioles with length of about 11-13 mm and 5-10 fully chorionated eggs stored in the egg calyx
4	Approximately 15 mature eggs stored in the egg calyx, with the ovarioles length > 13 mm
5	The ovary has atrophied and contains almost no mature eggs, with the ovarioles about 9 mm long

474

475 Table 2. Duration and occurrence status of *C. medinalis* captured in the searchlight

476 trap on Beihuang (BH) Island from April to October during 2003-2013.

Year	Occurrence status ¹							Date of first capture ²	Date of final capture ²	Duration (d)
	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.			
2003								07 June (1)	21 September (1)	106
2004								10 July (143)	18 October (3)	100
2005								14 July (8)	08 October (2)	86
2006								26 June (1)	20 October (1)	116
2007								02 July (1)	04 October (17)	94
2008								19 June (2)	30 August (56)	72
2009								01 June (2)	16 September (27)	107
2010								13 June (12)	13 October (7)	122
2011								26 June (8)	08 October (6)	104
2012								12 June (4)	10 October (1)	120
2013								19 June (1)	05 October (16)	108

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477 ¹ ■ occurrence index between 50% - 100%, ■ occurrence index between 25% -

478 50%, ■ occurrence index between 0% - 25%.

479 ² The numbers of *C. medinalis* captured are given in parentheses next to name of the

480 months.

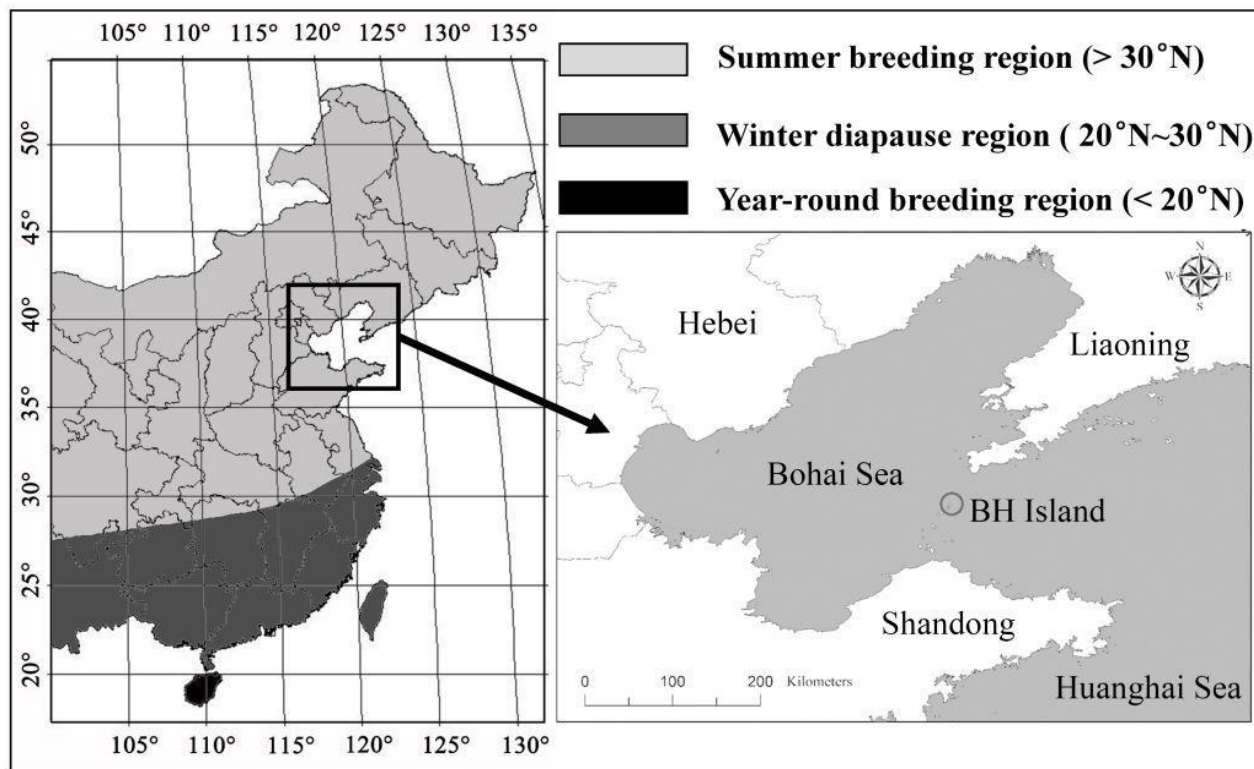
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Figures

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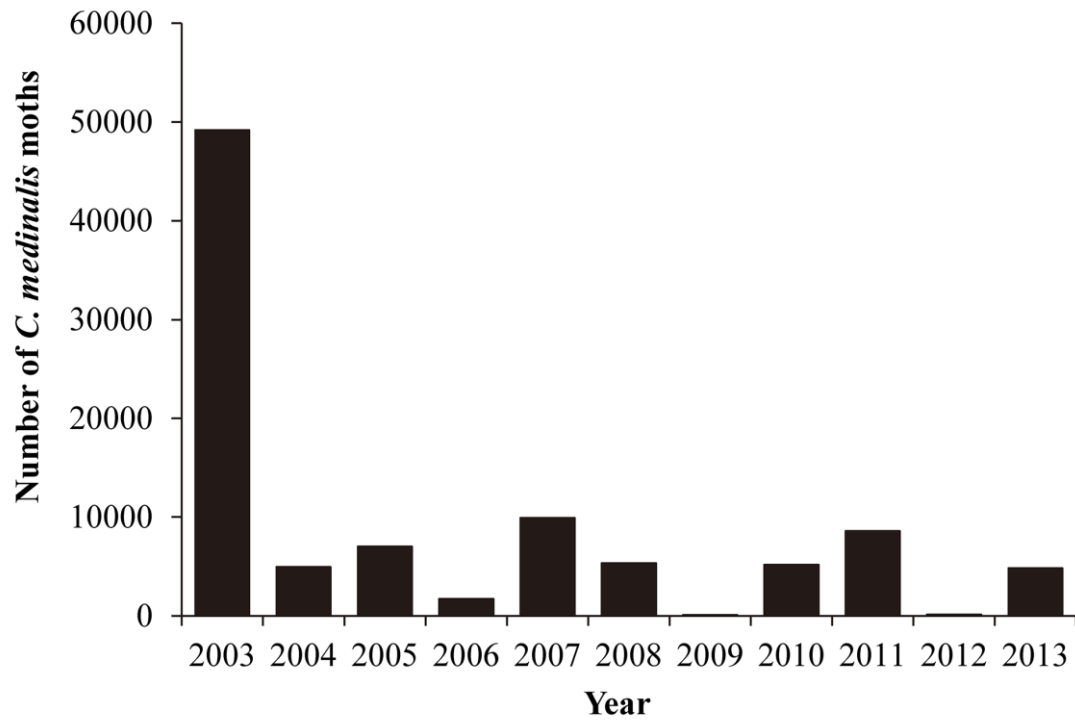
486

487 Fig. 1. Maps showing the district distribution of *C. medinalis* in China (left-hand map)

488 and the position of Beihuang (BH) Island, the searchlight trap site (right-hand

489 map), relative to the Bohai and Huanghai (Yellow) Sea.

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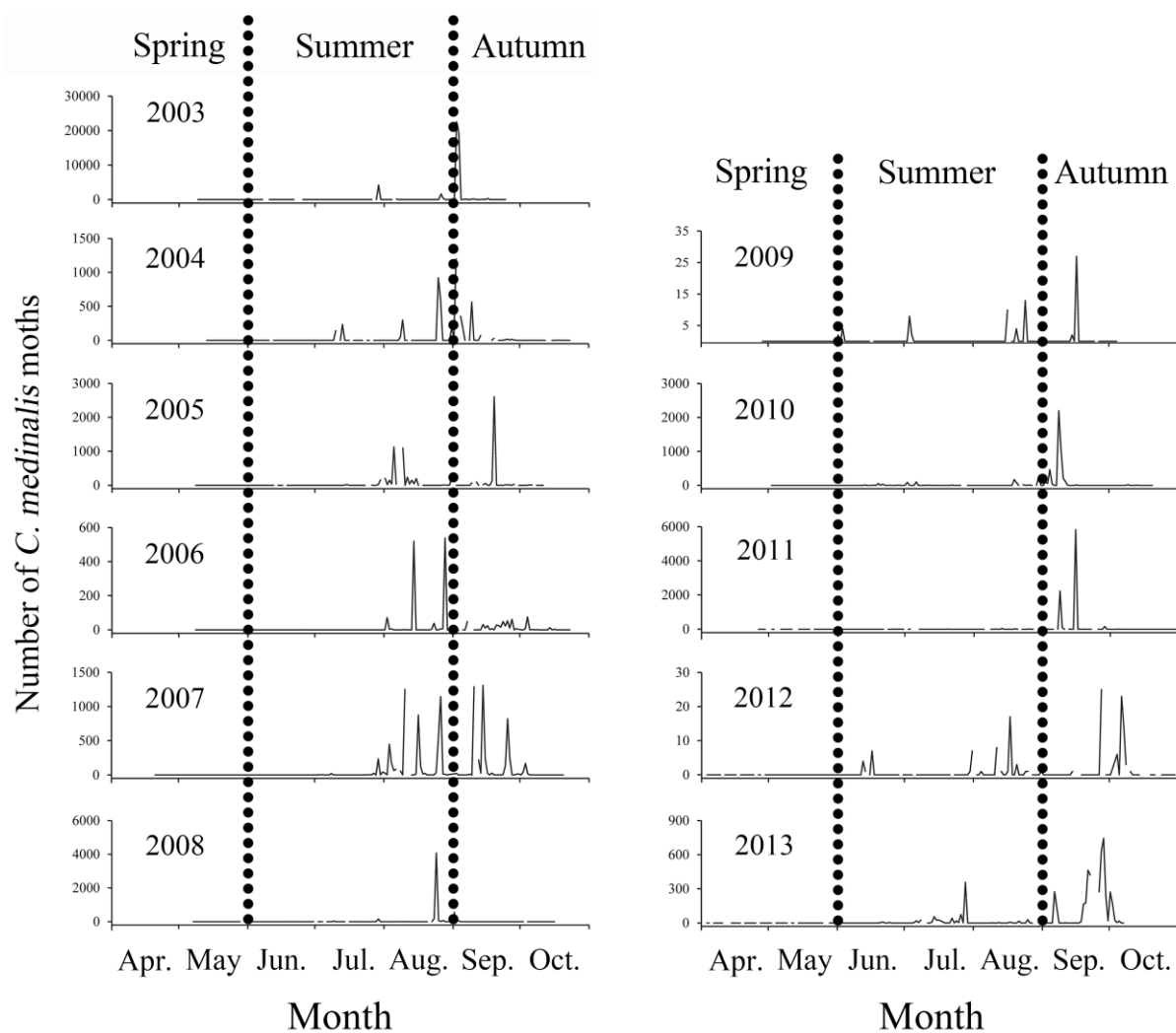
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493 Fig. 2. Annual catch of *C. medinalis* in the searchlight trap on BH from 2003 to 2013.

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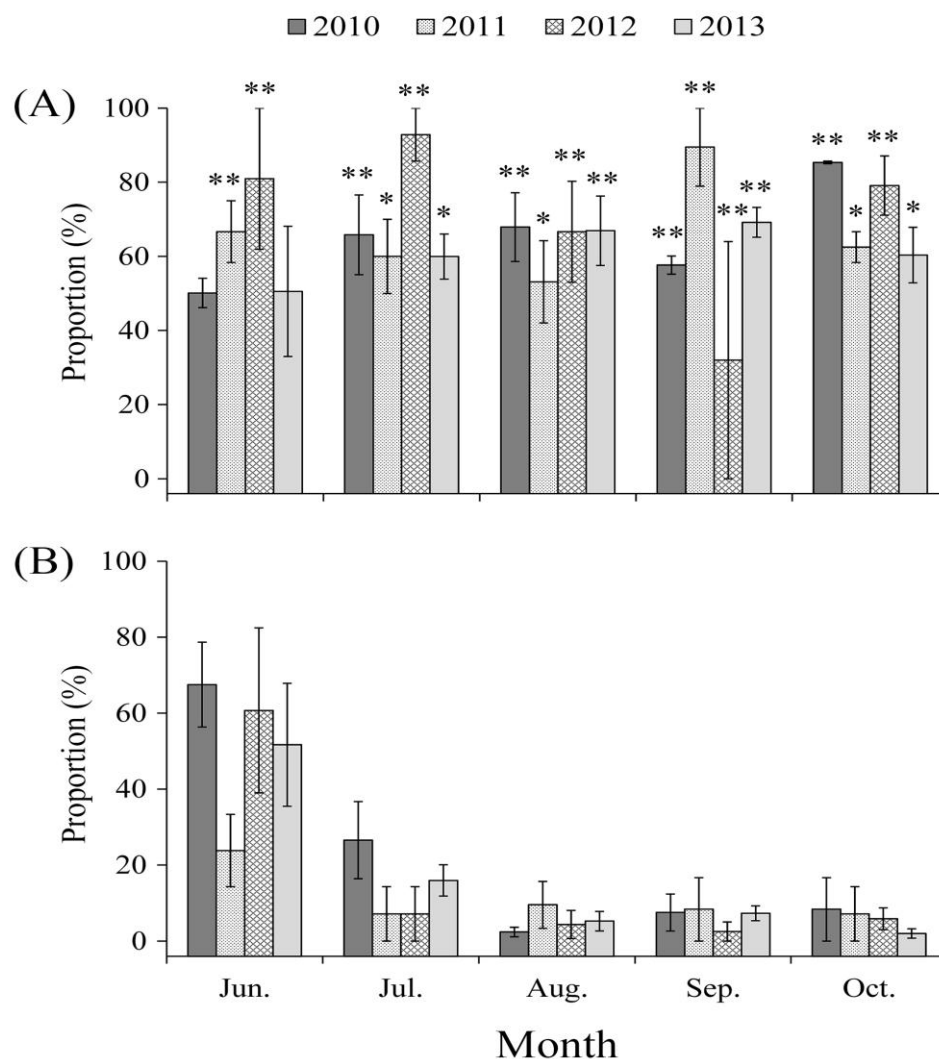
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498 Fig. 3. Nightly catch of *C. medinalis* in the searchlight trap on BH from April to

499 October.

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504 Fig. 4. Proportions of *C. medinalis* females (A) and mated females (B) captured in the

505 searchlight trap on BH during 2010-2013. The histograms indicate mean

506 proportions that were calculated by averaging the daily proportions in each of the

507 months, and the bars represent standard errors between days in that month.

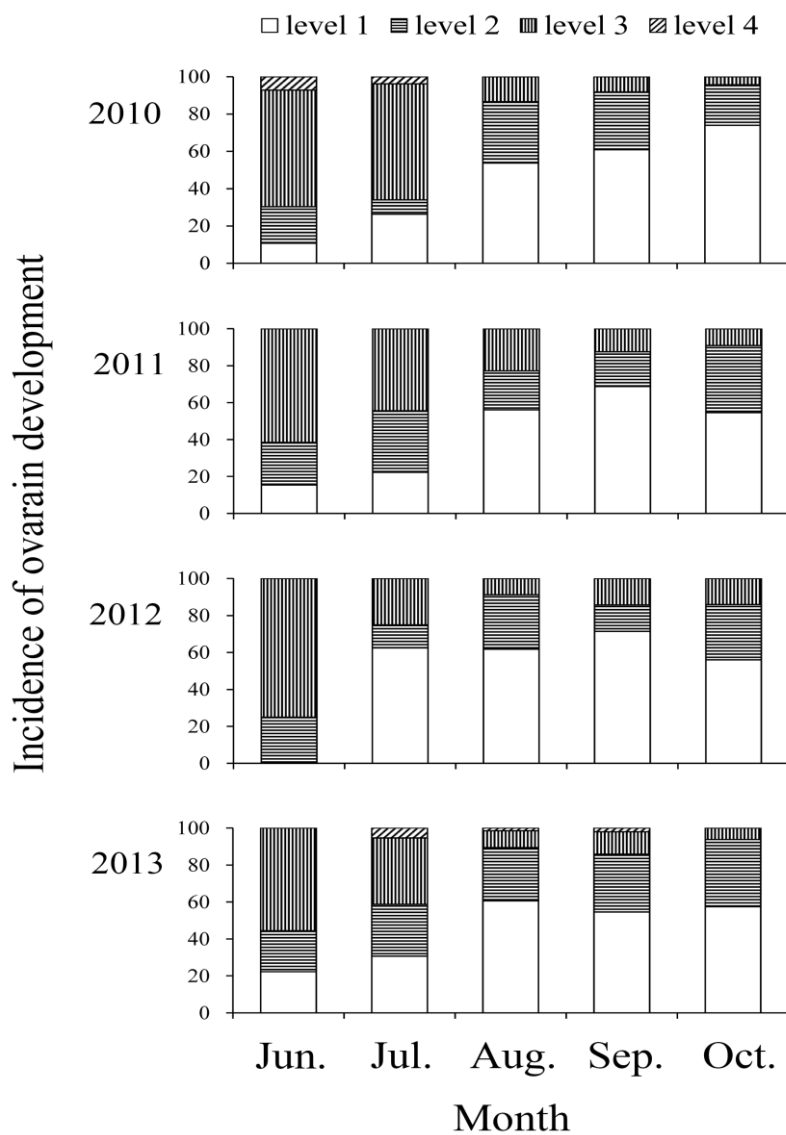
508 Single asterisk (*) or double asterisks (**) above a bar indicates the proportion of

509 females was significantly greater than that of males in that month at the 5% or

510 1% level as determined by a chi-squared test.

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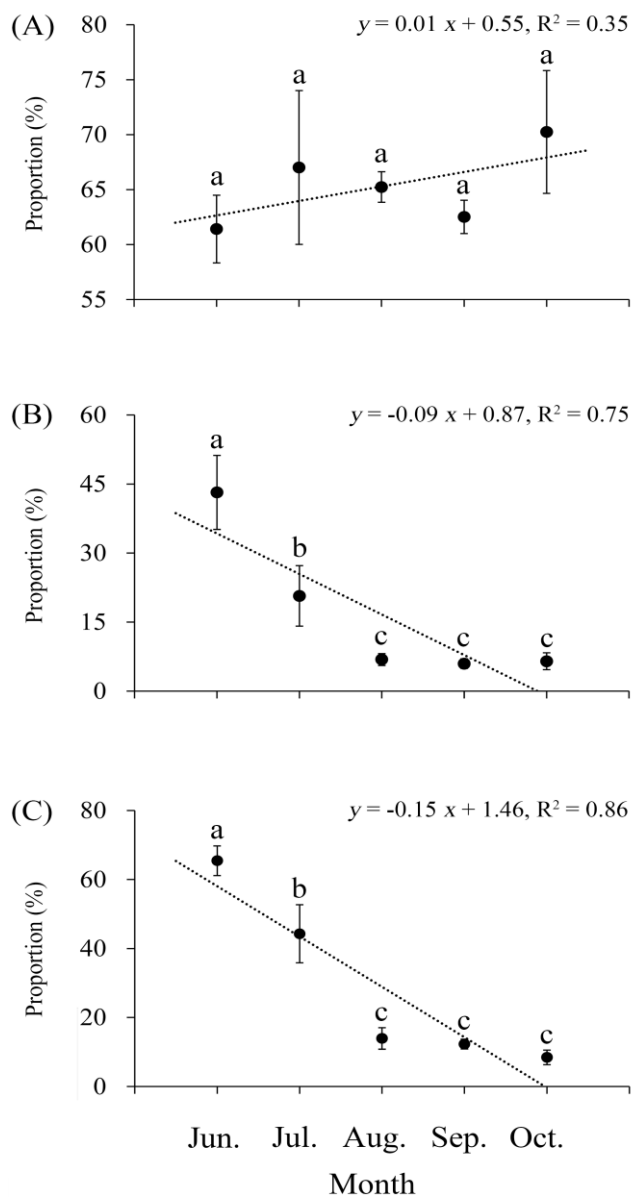
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515 Fig. 5. Incidence of ovarian development in *C. medinalis* females captured in the

516 searchlight trap on BH during 2010-2013.

517



518

519 Fig. 6. Seasonal variation of the proportion of *C. medinalis* females (A), mated
520 females (B), and sexually mature females (C) captured in the searchlight trap on
521 BH during 2010-2013. The dots indicate mean proportions that were calculated
522 by averaging the yearly numbers in each of the months, and the bars represent
523 standard errors between years in that month. Dots sharing the same letter mean
524 there were no significant inter-month differences at the 5% level by Tukey's
525 HSD tests.