

Title	Spring Temperature Predicts the Long-term Molting Phenology of Two Cicadas, <i>Cryptotympana facialis</i> and <i>Graptopsaltria nigrofuscata</i> (Hemiptera: Cicadidae)
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Citation	Annals of the Entomological Society of America (2015), 108(4): 494-500
Issue Date	2015-05-16
URL	http://hdl.handle.net/2433/201636
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Type	Journal Article
Textversion	author

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20 **Spring Temperature Predicts the Long-term Molting Phenology of Two Cicadas,**
21 ***Cryptotympana facialis* and *Graptopsaltria nigrofuscata* (Hemiptera: Cicadidae)**
22

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35 **Abstract**

36 To investigate how seasonal insects respond to changing environments, nymphal skins of the two
37 cicadas *Cryptotympana facialis* (Walker) and *Graptopsaltria nigrofuscata* (Motschulsky)
38 (Hemiptera: Cicadidae) were monitored weekly from late July to August over 12 years in a
39 suburban habitat of central Japan. Based on over 8,000 skins collected from 1995 to 2006, we
40 estimated the period during which temperature or precipitation impacted skin abundance and
41 phenology. Adults of *C. facialis* tended to emerge earlier than those of *G. nigrofuscata*, for which
42 total skin counts fluctuated up to sevenfold among years. The effective accumulated temperature
43 from the previous 3.0–3.5 months to the most recent 1.0–1.5 months at a threshold of
44 approximately $>18^{\circ}\text{C}$ showed the best fit to the cumulative skin counts within a season.
45 Temperature explained 47% and 64% of the total variation in the skin counts for *C. facialis* and *G.*
46 *nigrofuscata*, respectively. The point at which temperature had this effect was consistent between
47 male and female cicadas. Conversely, accumulated precipitation accounted for $<16\%$ of the
48 variation in the skin counts for both species. In summary, our long-term study revealed that
49 late-spring temperature plays a key role in predicting the molting phenology of *C. facialis* and *G.*
50 *nigrofuscata* but does not necessarily explain a large amount of the abundance fluctuation.

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52 **Keywords:** *Cryptotympana facialis*, Effective accumulated temperature, *Graptopsaltria*
53 *nigrofuscata*, Phenology, Population fluctuation

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60 **Introduction**

61 Understanding the responses of organisms to changing environments is important for
62 predicting how climate change threatens biodiversity and the ecosystem services provided by
63 particular species. Evidence has accumulated to suggest that recent climate warming has shifted
64 the phenology (Roy and Sparks 2000, Bale et al. 2002), distribution (Bale et al. 2002, Hagen et al.
65 2007, Harsch et al. 2009), and population dynamics (Jilliard et al. 2004, Kiritani 2006, Chaves et
66 al. 2012) of species based on their physiological constraints. Seasonal outbreaks are known to
67 occur in several insect taxa, such as mayflies (Harper and Peckarsky 2006), bush crickets
68 (Hochkirch and Damerau 2009), and winter moths (Hagen et al. 2007). The phenology of seasonal
69 organisms is considered an indicator of climatic impacts on local biodiversity (Roy and Sparks
70 2000, Gibbs and Breisch 2002, Ogawa-Onishi and Berry 2012). However, both snapshot
71 abundance measurements and long-term presence/absence records are unable to disentangle the
72 seasonality and increase/decrease of population size. Thus, a long-term survey considering both
73 phenology and abundance is necessary to combine the physiological response of a species to the
74 changing environment with its population fluctuation.

75 Cicadas (Hemiptera: Cicadidae) provide an important ecosystem function, as they
76 transfer a significant flux of nutrients from belowground to aboveground (Karban 1982,
77 Menninger et al. 2008). The black cicada, *Cryptotympana facialis* (Walker), and the large brown
78 cicada, *Graptopsaltria nigrofuscata* (Motschulsky), are common species distributed across
79 western Japan. Unlike periodical cicadas, these Japanese cicadas emerge every summer (Dunn
80 2000). *Cryptotympana facialis*, is distributed more southerly and occurs intensively in urbanized
81 habitats. Conversely, *G. nigrofuscata* is usually observed in suburban and rural areas covered by
82 trees. Because of the gradual habitat partitioning between *C. facialis* and *G. nigrofuscata*, these
83 two cicadas are regarded as index species of urbanization (Shiyake 2008). Recently, *C. facialis*
84 has been shown to be increasing as *G. nigrofuscata* decreases across the most urbanized area of

85 western Japan, Osaka City (Kitamoto 1997, Shiyake 2012). Several previous studies have
86 attributed this compositional shift of the cicada community to the heat island phenomenon
87 (Moriyama and Numata 2011) or to habitat fragmentation combined with avian predation
88 (Takakura and Yamazaki 2007).

89 The physiological responses of *C. facialis* and *G. nigrofuscata* have been well-studied in
90 terms of local climate change in urbanized areas. For example, temperature determines the timing
91 and rate of egg hatching, and the eggs of both *C. facialis* and *G. nigrofuscata* exhibit some degree
92 of cold tolerance (Moriyama and Numata 2008, 2009). In the field, adults of *C. facialis* are known
93 to emerge earlier as temperature increases (Shiyake 2012). Humidity is also important for the
94 hatching rate of *C. facialis* and *G. nigrofuscata* (Moriyama and Numata 2010). Thus, in
95 conjunction with the desiccation dependence of egg hatching, warming influences cicada fitness
96 by synchronizing the hatching phenology of *C. facialis* (Moriyama and Numata 2011). However,
97 the extent to which these climate variables explain long-term phenology and population
98 fluctuation remains insufficiently understood.

99 In this study, we employed a 12-year field survey and statistical modeling to estimate
100 how abiotic factors influence the molting phenology and abundance of the two species of
101 Japanese cicada. Specifically, three questions were addressed in this study: Which abiotic factor,
102 temperature or precipitation, influences the molting phenology of *C. facialis* and *G. nigrofuscata*
103 to a greater degree? Do the duration and degree of change for this factor necessary to influence
104 molting phenology differ between *C. facialis* or *G. nigrofuscata*? Finally, to what extent do these
105 environmental factors explain the variation in cicada abundance? Based on the present results and
106 other previously documented evidence, we discuss the factors responsible for long-term variation
107 in the phenology and abundance of cicada populations.

108

109 **Materials & Methods**

110 **Study site.** We conducted the study at a suburban site located in Hokusei-cho, Mie
111 Prefecture, central Japan (34°09'N, 136°31'E, approximately 100 m in altitude). The study site
112 consisted of 208 m² of shady area near a small park surrounded by residential houses. The ground
113 was covered with gravel in which a few weeds grew. Twenty-one trees of ten species were planted
114 sparsely within the study area. These trees consisted of the evergreen magnolia *Magnolia*
115 *grandiflora* L. (*n* = 1, diameter at breast height = 18 cm), the empress tree *Paulownia tomentosa*
116 (Thunb.) Steud. (*n* = 1, DBH = 32 cm), the chinaberry *Melia azedarach* L. (*n* = 1, DBH = 51 cm),
117 *Acer palmatum* Thunb. (*n* = 1, DBH = 51 cm), the hemp palm *Trachycarpus fortunei* (Hook.)
118 H. Wendl. (*n* = 1, DBH = 11 cm), the Japanese cypress *Chamaecyparis obtusa* (Siebold et Zucc.)
119 Endl. (*n* = 1, DBH = 46 cm), the Japanese persimmon tree *Diospyros kaki* Thunb. (*n* = 1, DBH =
120 51 cm), the wild cherry tree *Cerasus jamasakura* (Siebold ex Koidz.) H. Ohba (*n* = 2, DBH = 50,
121 50 m), *Camellia* sp. (*n* = 2, DBH = 13, 22 cm), and *Podocarpus macrophyllus* (Thunb.) Sweet (*n*
122 = 10, DBH = 10 cm for all individuals). The Japanese persimmon tree died in 1999, and the
123 magnolia and empress tree were cut in 2006 due to the development of the nearby area.

124 **Collection of cicada skins.** *Cryptotympana facialis* and *Graptopsaltria nigrofuscata*
125 individuals spend a nymphal period of several years on tree roots belowground. When the final
126 instar is ready to molt, it emerges from the ground and sheds its skin on a nearby tree or artificial
127 structure. The adult cicada flies away after molting, while its exuvia remains for several weeks.
128 The two species in this study can be distinguished by these skins based on the width, darkness,
129 and color pattern of the abdomen. Thus, skin number is an excellent predictor of cicada
130 abundance within a site.

131 We visited the site and collected all cicada skins at least weekly from late July to the
132 end of August for 12 years, from 1995 to 2006. The cicada skins were collected by hand from the
133 ground, tree surfaces, and artificial structures (such as fences and poles) within the site. We also
134 used an insect net (4 m in length) to collect skins attached to elevated places (up to approximately

135 6 m in height). The skins were taken to the laboratory and counted. From 2001 to 2006, sexes
136 were also identified from the cicada skins based on the presence/absence of an ovipositor on the
137 tip of the abdomen. From 1997 to 2000, the number of holes on the ground was also counted; the
138 holes were buried after each survey to avoid counting them repeatedly. The surveys were
139 conducted on sunny or cloudy days. Skins were collected during the morning, because the
140 nymphal cicadas emerged during the evening and molted during the night. Detailed survey dates
141 and skin counts are available in the supplementary material (Supp. Table S1).

142 **Weather data.** Data were downloaded from the website of the Japan Meteorological
143 Agency (<http://www.data.jma.go.jp/gmd/risk/obsdl/index.php>). The weather stations nearest to the
144 study site were selected for temperature (Kuwana, Mie Prefecture: 35°03'N, 136°41'E, 3 m in
145 altitude) and precipitation data (Hokusei-cho, Mie Prefecture: 35°08'N, 136°32'E, 125 m in
146 altitude). Daily mean and maximum temperatures, as well as daily total precipitation, were
147 compiled from 1994 to 2006. Several time points were not available (one point for temperature
148 and three points for precipitation) from the database; these values were estimated using the
149 average of the neighboring two days. To improve the presentation of data in the figure, the daily
150 temperature was smoothed using a spline method. We used the `smooth.spline` function
151 implemented in R version 3.0.1 (R Core Team 2013).

152 **Data analysis.** We estimated the period during which the temperature or precipitation
153 impacted the skin counts. The response variable was the cumulative number of skins during one
154 season (which was $\ln(y+1)$ transformed to improve normality). The explanatory variable was the
155 effective accumulated temperature or precipitation, which was calculated using daily mean
156 temperature (°C) or daily total precipitation (mm). The effective accumulated temperature or
157 precipitation was modeled as follows: $E = \sum_{t = t_0 \rightarrow t_1} (x_t - th) \{ \text{if } (x_t - th) > 0, \text{ otherwise } 0 \}$. The
158 effective accumulated temperature or precipitation E represents the sum of the precipitation or
159 temperature x at day t , higher than the threshold value th , from the past t_0 to the most recent t_1

160 days. The effect of E was analyzed using the linear regression $\ln(y+1) = a \times \ln(E) + b$. We then
161 determined the unknown parameters a , b , t_0 , t_1 , and th that minimized the ordinary least-squares of
162 the cumulative skin counts. The coefficient a and slope b were estimated on an exponential scale
163 to obtain positive values (i.e., $a = \exp(a)$, $b = \exp(b)$). For the least-square optimization, we used
164 the simulated-annealing method (Belisle 1992) and the Nelder-Mead method (Nelder and Mead
165 1965) because of their applicability to nondifferentiable functions (implemented in the `optim`
166 function in the R software). To avoid local optima, we first applied the simulated-annealing
167 method (which is robust for the initial parameters but requires a long calculation time) with the
168 following initial parameters: $t_0 = 90$; $t_1 = 30$; $th = 15$ (for temperature) and 5 (for precipitation); $a =$
169 $\exp(0) = 1$; and $b = \exp(0) = 1$. We then utilized the Nelder-Mead method (which requires less
170 calculation time than the simulated-annealing method) after the parameters obtained from the
171 previous calculation were set as the initial parameters. This Nelder-Mead optimization was
172 repeated until the algorithm converged. Model fitting was evaluated by the proportion of the
173 explained sum of squares (representing the coefficient of determination, R^2 : Kvålseth 1985), and
174 statistical significances were examined by F -tests for the mean squares of the explained and
175 residual sums of squares ($df1 = \text{no. of parameters} - 1$, and $df2 = \text{sample size} - df1$). These
176 analyses were performed for the two cicada species and two climate variables (temperature and
177 precipitation). Temperature and precipitation were separately fitted to avoid multicollinearity. The
178 best-fitted temperature and precipitation were further analyzed using multiple regressions to test
179 their combined effects on the skin counts. Two additional analyses were also conducted to confirm
180 the robustness of the parameter estimation. First, we repeated the temperature analysis using the
181 daily maxima instead of the means. Second, for the data from 2001 to 2006, we separately
182 analyzed male and female skins for *C. facialis* and *G. nigrofuscata*. The R code and input data
183 files are provided as supplementary materials (Supp. Appendix 1 and 2 for the code and input data
184 files, respectively).

185

186 **Results**

187 **Patterns of molting phenology.** Skins of *C. facialis* were observed earlier than those of
188 *G. nigrofuscata* (Fig. 1). Total skin counts fluctuated up to sevenfold among the study years. The
189 yearly total counts fluctuated at a similar level between *C. facialis* and *G. nigrofuscata* (coefficient
190 of variation = SD/Mean = 0.55 and 0.60, respectively). The total number of ground holes roughly
191 corresponded with the total skin count for each year (1349, 960, 683, and 550 holes for 1997,
192 1998, 1999, and 2000, respectively). From 2001 to 2006, male cicadas emerged earlier than
193 females for both *C. facialis* and *G. nigrofuscata* (Fig. 1). Two other cicada species, *Platypleura*
194 *kaempferi* (Fabricius) and *Meimuna opalifera* (Walker), were also observed at the site, but their
195 abundances were much lower than those of *C. facialis* and *G. nigrofuscata* (at most, eight skins
196 per day; see Supp. Table S1). In total, 8,216 skins of the four species were collected across 12
197 years. During the study years, daily mean temperature ranged from approximately 0°C to 30°C
198 near the study site (Fig. 2). Daily precipitation tended to increase with temperature (Fig. 2).

199 **Climatic effects on phenology.** The accumulated temperatures >17.9°C and >18.9°C
200 over the previous 101 and 109 days best fit the observed patterns for the cumulative skin counts of
201 *C. facialis* and *G. nigrofuscata* within a season, respectively (parameters t_0 and th , respectively:
202 Table 1). The points until which temperature was accumulated, t_1 , were approximately 38 and 44
203 days in the two respective species (Table 1). The accumulated temperature explained 47% and
204 64% of the total variation in the cumulative skin counts of *C. facialis* and *G. nigrofuscata*,
205 respectively (Table 1; Fig. 3). Temperature was also analyzed using daily maxima, but similar
206 results were obtained ($t_0 = 102$ and 107 , $t_1 = 37$ and 29 , $th = 23$ and 23 , $R^2 = 0.40$ and 0.51 for *C.*
207 *facialis* and *G. nigrofuscata*, respectively). Regarding the sexes of the two cicada species, t_0 was
208 estimated at 88 and 92 days, while the threshold temperatures were 17.4°C and 21.3°C,
209 respectively (Table 1). The parameter t_1 ranged from 28 to 37 days among the sexes and species.

210 R^2 varied from 30% to 74% (Table 1). In contrast, the effective accumulated precipitation
211 explained at most 16% of the variation in the cumulative skin counts of *C. facialis* and *G.*
212 *nigrofuscata* (Table 2). The variation explained by precipitation was at most 8% for male and
213 female cicada skin counts (Table 2). We also performed multiple regressions using the best-fitted
214 temperature and precipitation. However, the models including the temperature, precipitation, and
215 interaction term did not considerably improve the variation explained (*C. facialis*, $R^2 = 0.48$; *G.*
216 *nigrofuscata*, $R^2 = 0.69$), indicating weak combined effects of the two climatic factors.

217

218

219 **Discussion**

220 Our long-term survey and quantitative analysis uncovered several characteristics of the
221 molting phenology of *C. facialis* and *G. nigrofuscata*. First, the effective accumulated temperature
222 explained significantly more of the variation in the cumulative skin counts than did precipitation.
223 Second, the time over which past temperature had an effect was consistent from the past 3.0–3.5
224 months to the most recent 1.0–1.5 months. Conversely, the threshold temperature ranged from
225 18°C to 23°C depending on the species, temperature criterion (daily mean or maximum), and sex.
226 These results indicate that the accumulated temperature during late spring is a key predictor for
227 the molting phenology of both cicada species, whereas the current year’s precipitation is likely a
228 less influential factor. Third, temperature accounted for 17% more of the variation of the
229 cumulative skin counts in *G. nigrofuscata* compared to *C. facialis*. Physiological and other
230 possible factors are therefore discussed in to the following section regarding the temporal
231 fluctuation of skin counts within and among years.

232 Several previous studies have suggested that warming can shift the first singing day or
233 date of peak abundance in Japanese cicadas (Shiyake 2008, Kamitani 2010, Ogawa-Onishi and
234 Berry 2012). Our quantitative results support the potential impact of temperature on molting

235 phenology. In addition, the physiological evidence reported to date has shown that temperatures
236 ranging from 10°C to 30°C strongly affect the timing and rate of egg hatching (Moriyama and
237 Numata 2008), whereas low temperature has a relatively weak impact on the egg mortality of *C.*
238 *facialis* and *G. nigrofuscata* (Moriyama and Numata 2009). Thus, the nymphs of the two cicadas
239 are likely more sensitive to moderate temperatures during late spring than to winter coldness. In
240 contrast, we found limited evidence regarding the impact of precipitation on the molting
241 phenology of *C. facialis* and *G. nigrofuscata*, although rainfall is known to be critical for egg
242 hatching in Japanese cicadas (Hirose 1977; Moriyama and Numata 2010, 2011). As the rainy
243 season often ends in mid-July (known as the “Baiu” period in Japan), the limited effect of
244 precipitation may be due to the emergence of final-instar nymphs of *C. facialis* and *G.*
245 *nigrofuscata* in late July or early August, allowing them to avoid the direct impacts of the rainy
246 period. Additionally, we sampled the nymphal skins on days with no rain, which may have
247 prevented us from detecting the influence of precipitation on skin counts. Further investigations
248 are required to evaluate the relative importance of temperature and precipitation throughout the
249 cicada life cycle, including egg hatching and adult emergence.

250 Our results should be interpreted carefully regarding the confounding effects of the
251 distribution of peak abundance within the study season. The proportion of explained variation
252 tended to increase as the time point of peak abundance became later in the season (i.e., descending
253 order of male *C. facialis*, female *C. facialis*, male *G. nigrofuscata*, and female *G. nigrofuscata*:
254 Table 1; Fig. 1). In addition to these sexual differences, the start dates of our survey were too late
255 to follow the phenology of *C. facialis*, particularly when abundance peaked earlier than usual (e.g.,
256 1998 and 2004: Fig. 1). Therefore, the differences in predictability between the species and sexes
257 might reflect the differences of the observed abundance peaks. To deal with these potential
258 limitations, multiple populations should be compared in the future.

259 In Japanese cicadas, an abundance fluctuation of approximately threefold is considered

260 moderate, as documented for *Platypleura kaempferi* (Hirose 1977). Despite the significant
261 predictability of temperature for the phenological pattern, the actual variations in yearly
262 abundance (up to sevenfold) were often larger or smaller than those predicted by the temperature.
263 Thus, we believe that temperature is unlikely a regulator of cicada abundance among years.
264 Regarding factors other than climate that regulate cicada populations, predation and intraspecific
265 competition can be hypothesized as ecological mechanisms. While resource competition has
266 rarely been reported for cicadas, several studies have suggested the importance of predation in
267 their population fluctuations (e.g., Karban 1982, Williams and Simon 1995, Koenig and Liebhold
268 2005). For example, Takakura and Yamazaki (2007) revealed that avian predation on *G*
269 *nigrofuscata* was moderate in a dense plantation because adult cicadas were able to hide from
270 predators. As the suburban habitat in the present study was covered with secondary forest, the
271 higher predictability of *G. nigrofuscata* abundance could be explained by this relatively moderate
272 avian predation. Furthermore, the total number of ground holes was similar to the yearly skin
273 count, suggesting that predation (such as ant predation on aboveground nymphs) was unlikely
274 pivotal during molting. If predation were involved, we hypothesize that the population fluctuation
275 of skin abundance may be attributed to avian predation or other belowground agents.

276 In summary, our study revealed that late spring temperature is a key predictor for the
277 summer outbreaks of two Japanese cicadas. We also found that the duration over which
278 temperature was influential was consistent between the species and their sexes. These quantitative
279 results provide critical insight into how seasonal insects respond to changing environments.
280 Furthermore, the long-term abundance data posed a further question regarding the population
281 stability of seasonal insects, i.e., what factors regulate yearly abundance? Another factor, such as
282 predation, must be evaluated carefully to obtain a comprehensive understanding of the fluctuation
283 of *C. facialis* and *G. nigrofuscata* populations.

284

285 *Acknowledgements* – The authors thank all members of the Inabe River Association of Natural
286 History for their fieldwork advice; Satomi Sato for assistance with inputting the data; and
287 Masuhisa Sato for help with counting cicadas. Thanks are also given to two anonymous reviewers
288 for their comments on the manuscript.

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376 **Table 1** Effects of daily mean temperature (°C) on cumulative skin counts of *Cryptotympana*
 377 *facialis* and *Graptosaltria nigrofuscata* within a season.

Species	Parameters estimated					SS	R^2
	a	b	t_0	t_1	th		
<i>C. facialis</i>	1.26	0.14	101	38	17.9	97.9	0.47
<i>G. nigrofuscata</i>	1.29	0.01	109	44	18.9	112.0	0.64
<i>C. facialis</i> M	1.09	0.12	92	28	17.4	54.1	0.30
<i>C. facialis</i> F	0.98	1.24	88	35	21.3	57.6	0.53
<i>G. nigrofuscata</i> M	0.98	0.91	91	37	21.2	28.7	0.68
<i>G. nigrofuscata</i> F	1.16	0.00	91	35	21.3	39.6	0.74

378 Shown are the estimated parameters for the time over which daily mean temperature had an effect
 379 (from the past t_0 days to the most recent t_1 days), the threshold (th) of effective accumulated
 380 temperature, and the slope coefficient (a) and intercept (b) of the linear regression for temperature.
 381 Sum of squares (SS) and coefficient of determination (R^2) values are listed to the right of the
 382 parameters. The estimated results for male (M) and female (F) skins of the two species (from
 383 2001 to 2006) are also listed below the table. Bold values of R^2 indicate <5% significance
 384 according to the F -test.

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394 **Table 2** Effects of daily precipitation (mm) on cumulative skin counts of *Cryptotympana facialis*
 395 and *Graptosaltria nigrofuscata* within a season.

Species	Parameters estimated					SS	R^2
	a	b	t_0	t_1	th		
<i>C. facialis</i>	0.88	0.34	71	33	0.0	163.7	0.12
<i>G. nigrofuscata</i>	0.85	0.00	70	34	9.4	258.5	0.16
<i>C. facialis</i> M	0.10	4.37	82	27	20.0	75.8	0.02
<i>C. facialis</i> F	0.64	0.43	88	49	0.0	117.0	0.05
<i>G. nigrofuscata</i> M	0.34	2.42	74	49	36.3	83.1	0.08
<i>G. nigrofuscata</i> F	0.00	3.13	98	27	3.0	151.5	0.00

396 Shown are the estimated parameters for the time over which daily mean temperature had an effect
 397 (from the past t_0 days to the most recent t_1 days), the threshold (th) of effective accumulated
 398 precipitation, and the slope coefficient (a) and intercept (b) of the linear regression. Bold values of
 399 R^2 indicate <5% significance according to the F -test. The interpretation follows that of Table 1.

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412 **Figure legends**

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414 **Figure 1** Molting phenology of *Cryptotympana facialis* (black line) and *Graptopsaltria*
415 *nigrofuscata* (grey line) over 12 years at the study site. The upper figure shows the skin counts of
416 the two species at each survey date over the entire study period, while the lower two figures
417 present the number of male (solid line) and female (dashed line) skins collected from 2001 to
418 2006 for the two species.

419

420 **Figure 2** Temporal variation in daily mean temperature (°C: solid line) and daily precipitation
421 (mm: vertical bars) from 1994 to 2006 around the study site (northern Mie Prefecture, central
422 Japan). Daily mean temperature was smoothed using a spline method for legibility.

423

424 **Figure 3** Observed (circles) and predicted (vertical bars) values of the cumulative skin counts of
425 *Cryptotympana facialis* (closed: upper figure) and *Graptopsaltria nigrofuscata* (open: lower
426 figure). Predictions were made based on the effective accumulated temperature according to the
427 estimated parameters in Table 1. Dashed lines indicate intervals between the study years. The skin
428 counts are shown on a ln-scale.

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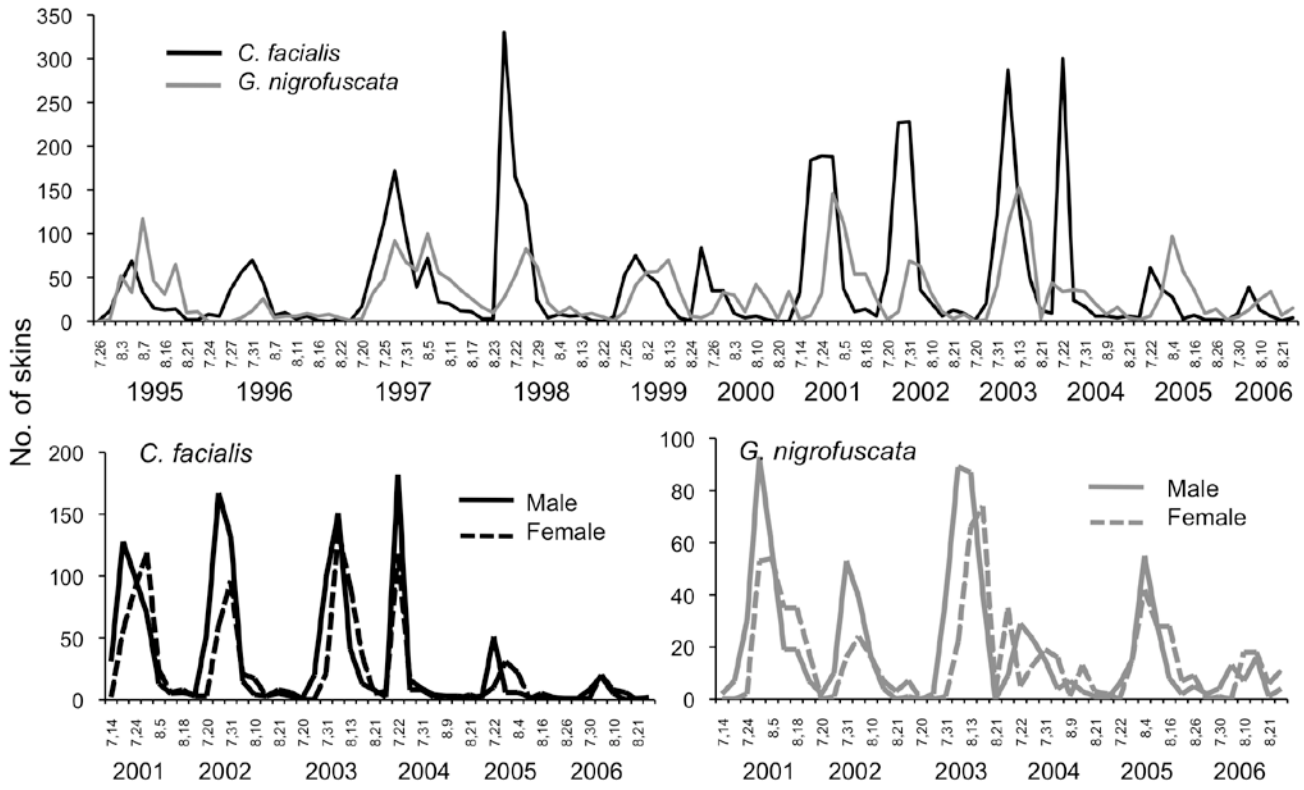
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437 Figure 1



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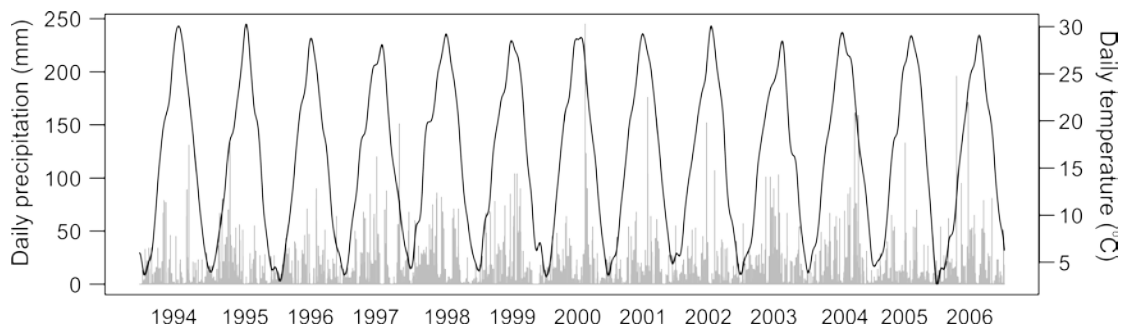
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450 Figure 2



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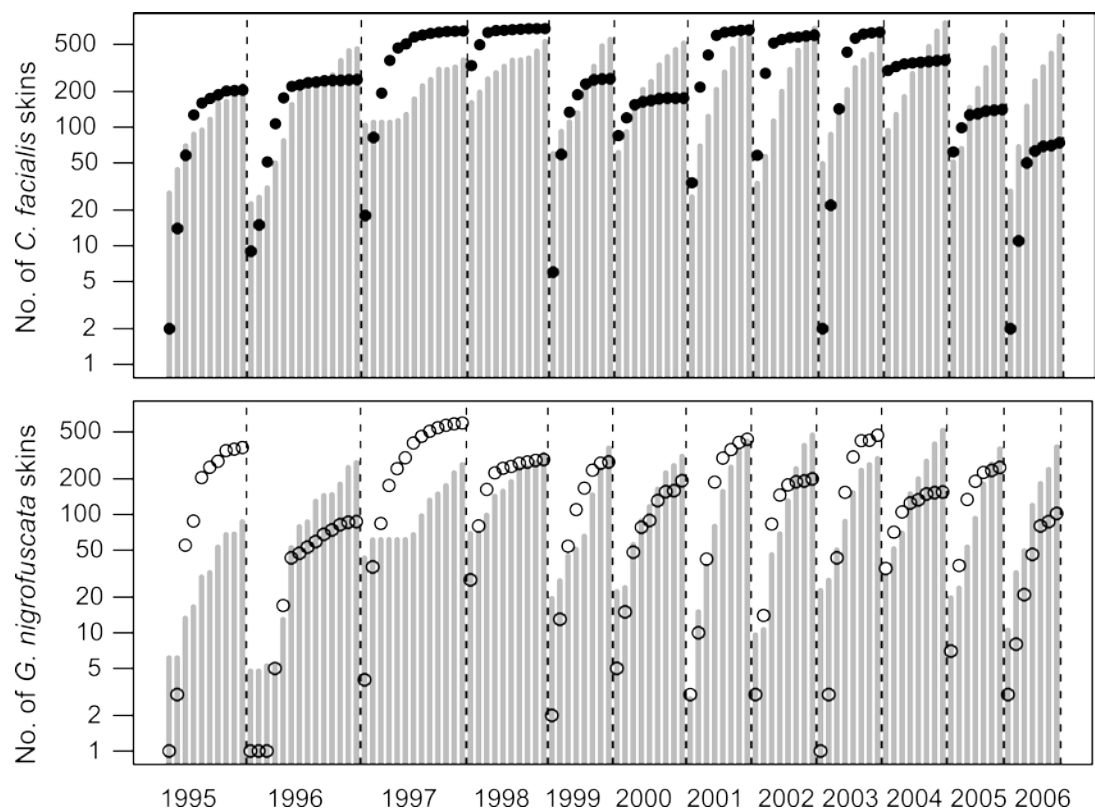
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469 Figure 3



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482 **Supplemental Table S1.** Detailed survey dates and numbers of skins collected for four cicada
 483 species. Cf, *Cryptotympana facialis*; Gn, *Graptopsaltria nigrofuscata*; Pk, *Platypleura kaempferi*;
 484 Mo, *Meimuna opalifera*. Sex information (M, Male; F, Female) are not available from 1995 to
 485 2000 (indicated by “NA”).

Year	Month	Date	Cf	Cf_M	Cf_F	Gn	Gn_M	Gn_F	Pk	Pk_M	Pk_F	Mo	Mo_M	Mo_F
1995	7	26	1	NA	NA	0	NA	NA	0	NA	NA	0	NA	NA
1995	7	29	12	NA	NA	2	NA	NA	1	NA	NA	0	NA	NA
1995	8	3	44	NA	NA	52	NA	NA	0	NA	NA	0	NA	NA
1995	8	5	69	NA	NA	33	NA	NA	0	NA	NA	1	NA	NA
1995	8	7	33	NA	NA	117	NA	NA	0	NA	NA	0	NA	NA
1995	8	10	15	NA	NA	46	NA	NA	0	NA	NA	0	NA	NA
1995	8	16	13	NA	NA	31	NA	NA	0	NA	NA	2	NA	NA
1995	8	18	14	NA	NA	65	NA	NA	0	NA	NA	3	NA	NA
1995	8	21	2	NA	NA	10	NA	NA	0	NA	NA	3	NA	NA
1995	8	23	2	NA	NA	11	NA	NA	0	NA	NA	0	NA	NA
1996	7	24	8	NA	NA	0	NA	NA	0	NA	NA	0	NA	NA
1996	7	26	6	NA	NA	0	NA	NA	1	NA	NA	0	NA	NA
1996	7	27	36	NA	NA	0	NA	NA	2	NA	NA	0	NA	NA
1996	7	29	56	NA	NA	4	NA	NA	0	NA	NA	1	NA	NA
1996	7	31	70	NA	NA	12	NA	NA	0	NA	NA	0	NA	NA
1996	8	5	44	NA	NA	26	NA	NA	0	NA	NA	1	NA	NA
1996	8	7	7	NA	NA	4	NA	NA	0	NA	NA	2	NA	NA
1996	8	8	10	NA	NA	6	NA	NA	0	NA	NA	1	NA	NA
1996	8	11	3	NA	NA	6	NA	NA	0	NA	NA	0	NA	NA
1996	8	13	6	NA	NA	9	NA	NA	0	NA	NA	2	NA	NA
1996	8	16	1	NA	NA	6	NA	NA	0	NA	NA	0	NA	NA
1996	8	19	0	NA	NA	8	NA	NA	0	NA	NA	0	NA	NA
1996	8	22	3	NA	NA	4	NA	NA	0	NA	NA	3	NA	NA
1996	8	23	1	NA	NA	1	NA	NA	0	NA	NA	2	NA	NA
1997	7	20	17	NA	NA	3	NA	NA	0	NA	NA	0	NA	NA
1997	7	23	64	NA	NA	32	NA	NA	0	NA	NA	0	NA	NA

1997	7	25	112	NA	NA	48	NA	NA	0	NA	NA	1	NA	NA
1997	7	28	172	NA	NA	92	NA	NA	0	NA	NA	0	NA	NA
1997	7	31	100	NA	NA	68	NA	NA	2	NA	NA	0	NA	NA
1997	8	2	39	NA	NA	58	NA	NA	0	NA	NA	0	NA	NA
1997	8	5	72	NA	NA	100	NA	NA	4	NA	NA	0	NA	NA
1997	8	8	22	NA	NA	56	NA	NA	4	NA	NA	0	NA	NA
1997	8	11	20	NA	NA	48	NA	NA	3	NA	NA	0	NA	NA
1997	8	15	12	NA	NA	36	NA	NA	6	NA	NA	0	NA	NA
1997	8	17	11	NA	NA	26	NA	NA	6	NA	NA	0	NA	NA
1997	8	20	3	NA	NA	16	NA	NA	8	NA	NA	0	NA	NA
1997	8	23	3	NA	NA	10	NA	NA	6	NA	NA	0	NA	NA
1998	7	19	330	NA	NA	27	NA	NA	0	NA	NA	0	NA	NA
1998	7	22	165	NA	NA	52	NA	NA	0	NA	NA	0	NA	NA
1998	7	26	133	NA	NA	83	NA	NA	0	NA	NA	1	NA	NA
1998	7	29	24	NA	NA	62	NA	NA	0	NA	NA	0	NA	NA
1998	7	31	4	NA	NA	21	NA	NA	0	NA	NA	0	NA	NA
1998	8	4	8	NA	NA	9	NA	NA	0	NA	NA	0	NA	NA
1998	8	8	6	NA	NA	16	NA	NA	0	NA	NA	0	NA	NA
1998	8	13	7	NA	NA	7	NA	NA	0	NA	NA	0	NA	NA
1998	8	16	1	NA	NA	9	NA	NA	0	NA	NA	0	NA	NA
1998	8	22	0	NA	NA	5	NA	NA	0	NA	NA	0	NA	NA
1999	7	20	5	NA	NA	1	NA	NA	0	NA	NA	0	NA	NA
1999	7	25	53	NA	NA	11	NA	NA	0	NA	NA	2	NA	NA
1999	7	29	75	NA	NA	41	NA	NA	0	NA	NA	2	NA	NA
1999	8	2	54	NA	NA	56	NA	NA	0	NA	NA	1	NA	NA
1999	8	7	44	NA	NA	57	NA	NA	0	NA	NA	0	NA	NA
1999	8	13	19	NA	NA	70	NA	NA	3	NA	NA	0	NA	NA
1999	8	19	4	NA	NA	35	NA	NA	5	NA	NA	0	NA	NA
1999	8	24	1	NA	NA	6	NA	NA	3	NA	NA	0	NA	NA
2000	7	22	84	NA	NA	4	NA	NA	0	NA	NA	3	NA	NA
2000	7	26	35	NA	NA	10	NA	NA	0	NA	NA	1	NA	NA
2000	7	30	35	NA	NA	33	NA	NA	0	NA	NA	1	NA	NA

2000	8	3	9	NA	NA	30	NA	NA	0	NA	NA	0	NA	NA
2000	8	5	4	NA	NA	11	NA	NA	0	NA	NA	1	NA	NA
2000	8	10	6	NA	NA	42	NA	NA	1	NA	NA	0	NA	NA
2000	8	14	2	NA	NA	25	NA	NA	3	NA	NA	0	NA	NA
2000	8	20	0	NA	NA	3	NA	NA	1	NA	NA	0	NA	NA
2000	8	23	0	NA	NA	34	NA	NA	0	NA	NA	0	NA	NA
2001	7	14	33	31	2	2	2	0	0	0	0	0	0	0
2001	7	20	184	128	56	7	7	0	0	0	0	1	1	0
2001	7	24	189	99	90	32	30	2	0	0	0	0	0	0
2001	7	30	188	69	119	146	93	53	0	0	0	2	2	0
2001	8	5	37	13	24	112	58	54	0	0	0	0	0	0
2001	8	13	11	5	6	54	19	35	0	0	0	0	0	0
2001	8	18	14	6	8	54	19	35	0	0	0	0	0	0
2001	8	23	6	3	3	25	7	18	4	3	1	0	0	0
2002	7	20	57	54	3	2	2	0	0	0	0	0	0	0
2002	7	25	227	167	60	11	10	1	1	1	0	0	0	0
2002	7	31	228	132	96	69	53	16	1	1	0	0	0	0
2002	8	6	36	15	21	63	39	24	4	3	1	0	0	0
2002	8	10	21	4	17	32	16	16	1	1	0	0	0	0
2002	8	15	6	3	3	11	4	7	1	0	1	0	0	0
2002	8	21	13	8	5	3	0	3	1	1	0	0	0	0
2002	8	25	9	6	3	8	1	7	0	0	0	0	0	0
2003	7	20	1	1	0	0	0	0	0	0	0	1	1	0
2003	7	26	20	20	0	2	2	0	0	0	0	0	0	0
2003	7	31	121	99	22	40	39	1	0	0	0	0	0	0
2003	8	6	287	151	136	111	89	22	0	0	0	0	0	0
2003	8	13	133	41	92	153	87	66	0	0	0	0	0	0
2003	8	19	49	13	36	114	40	74	3	1	2	0	0	0
2003	8	21	13	8	5	3	0	3	1	1	0	0	0	0
2003	8	25	9	2	7	44	9	35	1	1	0	0	0	0
2004	7	22	300	182	118	34	29	5	0	0	0	1	1	0
2004	7	27	24	8	16	36	23	13	0	0	0	0	0	0

2004	7	31	17	8	9	34	15	19	0	0	0	0	0	0
2004	8	5	6	2	4	20	4	16	0	0	0	0	0	0
2004	8	9	6	3	3	8	7	1	0	0	0	0	0	0
2004	8	15	4	1	3	16	3	13	0	0	0	0	0	0
2004	8	21	6	4	2	4	1	3	1	0	1	0	0	0
2004	8	25	4	1	3	2	0	2	0	0	0	0	0	0
2005	7	22	61	51	10	6	6	0	0	0	0	0	0	0
2005	7	26	37	6	31	30	15	15	0	0	0	0	0	0
2005	8	4	28	6	22	97	55	42	0	0	0	0	0	0
2005	8	10	3	2	1	57	29	28	0	0	0	0	0	0
2005	8	16	7	2	5	36	8	28	1	1	0	0	0	0
2005	8	22	2	0	2	9	2	7	0	0	0	0	0	0
2005	8	26	2	1	1	14	5	9	2	1	1	0	0	0
2006	7	23	1	1	0	2	2	0	0	0	0	1	0	1
2006	7	30	9	8	1	5	4	1	0	0	0	0	0	0
2006	8	4	39	19	20	13	13	0	0	0	0	1	0	1
2006	8	10	13	5	8	25	7	18	0	0	0	0	0	0
2006	8	16	6	0	6	34	16	18	0	0	0	0	0	0
2006	8	21	1	1	0	7	1	6	0	0	0	0	0	0
2006	8	26	4	2	2	15	4	11	3	1	2	0	0	0

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495 Appendix 1 R code for the parameter estimation
496 #####
497 #Sato&Sato: Cicada Phenology, R code##
498 #####
499
500 #Note: This is an example for the temperature analysis of C. facialis skins
501 #For the other response variables, please change "Cf.Cum" into "Gn.Cum", "Cf.CumM", "Cf.CumF",
502 "Gn.CumM", or "Gn.CumF".
503
504 #Load data
505 #CicadaMie = read.csv("cicadaSkinMF.csv", header=T) # for Male-Female data
506 CicadaMie = read.csv("cicadaSkin.csv", header=T)
507 ClimateData = read.csv("MieClimate.csv", header=T)
508
509 #ClimateData[,4]:Daily Mean Temp; [,5]: Daily Max Temp; [,6]: Precip
510 calc.CumTemp = function(t0, t1, th) {
511   CumTemp = c()
512   for (k in 1:nrow(CicadaMie)) {
513     t.point = subset(ClimateData, Year==CicadaMie[k,1]&DaysFromNewYear==CicadaMie[k,4])$rowID
514     ThH = (ClimateData[,4][(t.point-t0):(t.point-t0+t1)]>th) #Change [,4] or [,5] or [,6]
515     CumTemp = c(CumTemp, sum((((ClimateData[,4][(t.point-t0):(t.point-t0+t1)]-th)*ThH))) #Note: ThH
516 is a TRUE or FALSE vector
517   }
518   return(CumTemp+1) #+1 to prevent log(0)
519 }
520
521 #Define a target function
522 SS = function(x) {
523   a = exp(x[1]);b = exp(x[2]);t0 = x[3];t1 = x[4];th = x[5] #a and b are exponential to range >0
524   Temp = calc.CumTemp(t0, t1, th)
525   SS = sum((log(CicadaMie$CfCum+1)-(a*log(Temp)+b))^2)
526   return(SS)

```

```

527 }
528
529 #Parameter optimization
530 par = c(0,0,90,30,15) #Initial values
531
532 #First step: Simulated-annealing
533 res = optim(par,SS, method="SANN")
534
535 #Second step: Nelder-Mead method, repeat until convergence as "res3 = optim(res2$par[1:5], SS...)"
536 res2 = optim(res$par[1:5],SS, method="Nelder-Mead")
537
538 #Calculating R2 value
539 SSnull = sum((log(CicadaMie$CfCum+1)-mean(log(CicadaMie$CfCum+1)))^2)
540 print(1-(res2$value/SSnull))
541
542 #F-test
543 df.param = length(res2$par)-1; MSg = ((SSnull-res2$value)/df.param)
544 df.resi = length(CicadaMie$CfCum)-df.param; MSr = (SSnull/df.resi)
545 Fval = MSg/MSr; pf(Fval,df.param,df.resi,lower.tail=F)
546
547 #Observed vs. Prediction plot
548 plot(exp(exp(res2$par[1])*log(calc.CumTemp(res2$par[3],res2$par[4],res2$par[5]))+exp(res2$par[2])),ty
549 pe="h",lwd=3,col="grey",las=1,ylab="Cumulative shell no.",log="y")
550 points(CicadaMie$CfCum+1,pch=1)
551 abline(v=cumsum(c(10,14,13,10,8,9,8,8,8,8,7,7))+0.5,lty=2,col="grey")
552
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554
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556

```

557 **Appendix 2** Input data files for R analyses (SatoSato_Appendix2_inputFiles.xls)

558

559 Download URL

560 →(<https://drive.google.com/file/d/0B8ID2dRmBfQdb3RmWGxXMzhhUkU/view?usp=sharing>)

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