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

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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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Abstract

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

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

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

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

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

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

Materials & Methods

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

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

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

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

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

Data analysis. We estimated the period during which the temperature or precipitation impacted the skin counts. The response variable was the cumulative number of skins during one season (which was $\ln(y+1)$ transformed to improve normality). The explanatory variable was the effective accumulated temperature or precipitation, which was calculated using daily mean temperature (°C) or daily total precipitation (mm). The effective accumulated temperature or 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 effective accumulated temperature or precipitation E represents the sum of the precipitation or 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 ($df1$ = no. of parameters – 1, and $df2$ = 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).

Results

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

Climatic effects on phenology. The accumulated temperatures >17.9°C and >18.9°C over the previous 101 and 109 days best fit the observed patterns for the cumulative skin counts of *C. facialis* and *G. nigrofuscata* within a season, respectively (parameters t_0 and th , respectively: Table 1). The points until which temperature was accumulated, t_1 , were approximately 38 and 44 days in the two respective species (Table 1). The accumulated temperature explained 47% and 64% of the total variation in the cumulative skin counts of *C. facialis* and *G. nigrofuscata*, respectively (Table 1; Fig. 3). Temperature was also analyzed using daily maxima, but similar 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. facialis* and *G. nigrofuscata*, respectively). Regarding the sexes of the two cicada species, t_0 was estimated at 88 and 92 days, while the threshold temperatures were 17.4°C and 21.3°C, respectively (Table 1). The parameter t_1 ranged from 28 to 37 days among the sexes and species.

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

Discussion

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

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

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

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

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

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

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

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Table 1 Effects of daily mean temperature (°C) on cumulative skin counts of *Cryptotympana facialis* and *Graptopsaltria 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

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

Table 2 Effects of daily precipitation (mm) on cumulative skin counts of *Cryptotympana facialis* and *Graptopsaltria 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

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

Figure legends

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

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

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

437 Figure 1

450 Figure 2

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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
553
554
555
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/0B8lD2dRmBfQdb3RmWGxXMzhhUkU/view?usp=sharing>)

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