Entomological Science (2007) **10**, 237–244 doi:10.1111/j.1479-8298.2007.00219.x

ORIGINAL ARTICLE

Effect of rainfall on the long-term population dynamics of the aquatic firefly *Luciola cruciata*

Masahide YUMA

Department of Environmental Solution Technology, Faculty of Science and Technology, Ryukoku University, Otsu, Japan

Abstract

Long-term observations of adult populations of the aquatic Genji firefly, *Luciola cruciata* (Coleoptera: Lampyridae), were conducted using a simple flash counting method from 1975 to 2006 at four locations in Kyoto City, Japan. The relative population sizes of adult *L. cruciata* at these sites fluctuated almost synchronously, indicating the influence of large-scale environmental phenomena such as weather conditions on population dynamics. Rainfall in September and the latter half of July caused a significant decrease in the population size. The frequent rainfall during these months may have caused considerable drift in the emergence of early instars of firefly larvae and a decrease in their foraging activity.

Key words: Genji firefly, long-term population dynamics, *Luciola cruciata*, rainfall.

INTRODUCTION

Long-term observations are important for understanding long-term ecological processes and their relationship with temporal and spatial variability (e.g. Stork & Nakashizuka 2002; Kratz *et al*. 2003). Population dynamics has been a central component of ecological theory since the science first emerged, and numerous long-term observations of population fluctuations have been conducted for animals and plants within the context of the effects of environmental factors and intra- and inter-specific interactions. The discharge regimes of lotic environments, particularly seasonal and aperiodic floods and droughts, are generally considered the most prominent disturbance mechanisms affecting the population dynamics of organisms in these environments (Resh *et al*. 1988; Ward 1992; Williams & Feltmate 1992).

The Genji firefly, *Luciola cruciata* (Coleoptera: Lampyridae), is an aquatic species that inhabits streams in Japan. Population levels of this species have declined since the mid 20th century, possibly owing to the development of land and rivers, as well as eutrophication and pollution of river environments (Ohba 1988; Mitsuishi 1990; Yuma *et al*. 1999). However, the species appears to have recovered since local populations of *L. cruciata* were afforded legal protection by both national and local governments, and improvement of stream environments generally has also contributed.

Given that estimation of population size is generally difficult for animals, long-term observations of populations are necessary to assess species conservation. Fortunately, since fireflies emit light at night, population counts are relatively straightforward and do not require any special equipment or techniques. In the present paper, I demonstrate the usefulness of the flash counting method for evaluating population fluctuations based on observations of adult *L. cruciata* over a quarter of a century, and I also analyze the observed fluctuations in population size in relation to rainfall.

MATERIALS AND METHODS

Long-term observations of adult populations of the aquatic firefly *L. cruciata* were conducted using a simple flash counting method (Yuma & Ono 1985; Yuma 1993) between 1975 and 2006 in rivers within Kyoto City, Japan (Fig. 1): Kiyotaki River (Seiryuu and Kinrei Bridges in Saga-Kiyotaki-cho, 35°02′03′N, 135°39′37′E

Correspondence: Masahide Yuma, Department of Environmental Solution Technology, Faculty of Science and Technology, Ryukoku University, 1-5 Yokotani, Seta-Oe, Otsu, 520-2194 Japan. Email: yuhma@rins.ryukoku.ac.jp
Received 14 December 2006; accepted 7 March 2007.

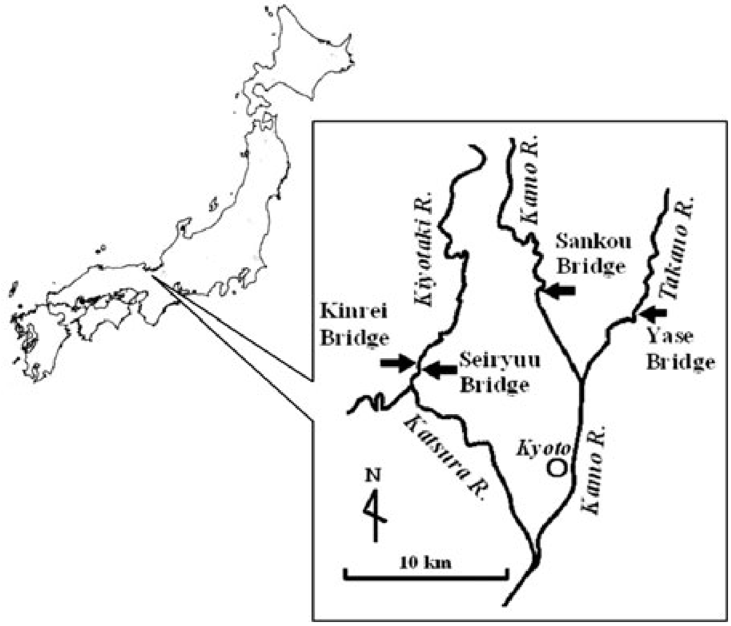

Figure 1 Locations of the study sites in Kyoto City.

and 35°02′11′N, 135°39′39′E, respectively), Kamo River (Sankou Bridge in Simo-Shouda-cho, 35°04′36′N, 135°44′37′E) and Takano River (Yase Bridge in Yase-Nose-cho, 35°04′59′N, 135°44′42′E). Flashes emitted by flying and stationary fireflies were counted at the study sites, taking care not to duplicate counts from individual fireflies. A slow flying pattern and constant flashing contributes to the ease and accuracy with which fireflies can be counted. Observations were conducted at sites upstream and downstream from the bridges: approximately 90 m and 210 m in the upstream and downstream directions from Seiryuu Bridge, 210 m and 160 m from Kinrei Bridge, 120 m and 100 m from Sankou Bridge, and 70 m and 90 m from Yase Bridge, respectively.

Flashes from adult *L. cruciata* at these sites were counted by the author throughout the observation period using the same method, generally once or twice per week during the adult season from late May to mid-July (Fig. 2). Flash counting was performed three times a night (usually from 21.00 to 24.00 hours) with the average of these counts used for analysis. Estimates of the adult population at Seiryuu Bridge using the mark-and-recapture method (Hori *et al.* 1978) closely reflected estimates of the adult population in the same area on the same day using the flash count method, with the flash counts of adult fireflies being approximately one-third of the population size estimated using the mark-and-recapture technique.

The landscapes of the areas surrounding the observation sites at the Kiyotaki- and Yase River bridges remained unchanged throughout the observation period, although the riverbank near Sankou Bridge was repaired in 1998. In Saga-Kiyotaki-cho, *L. cruciata* has been designated as a National Natural Monument since 1979, and is thus protected.

The relative size of the adult *L. cruciata* population can be expressed as a function of three parameters acting on the adult population: discovery rate, number of emerged adults for the season, and average longevity (survival rate; Yuma & Ono 1985; Yuma 1993). Here, the relative size of the adult *L. cruciata* population for each year, which was assumed to be correlated with the number of adults that emerged that season, was estimated using the cumulative observed flash count (individuals · days), which was calculated considering seasonal observations (Table 1). When data for the start and end of the period of adult emergence were not available, based on average yearly data, these dates were assumed to be 1 June and 20 July, respectively, for the two observation sites in Kiyotaki-cho. For the Sankou and Yase Bridges, these dates were taken as 10 June and 20 July. This procedure was unlikely to have any marked effect on annual estimates of population size, as insect abundance around these dates was always low. The change rate of the adult *L. cruciata* population (CRP) was calculated as the log-converted ratio of the relative population size to the value obtained for the previous year.

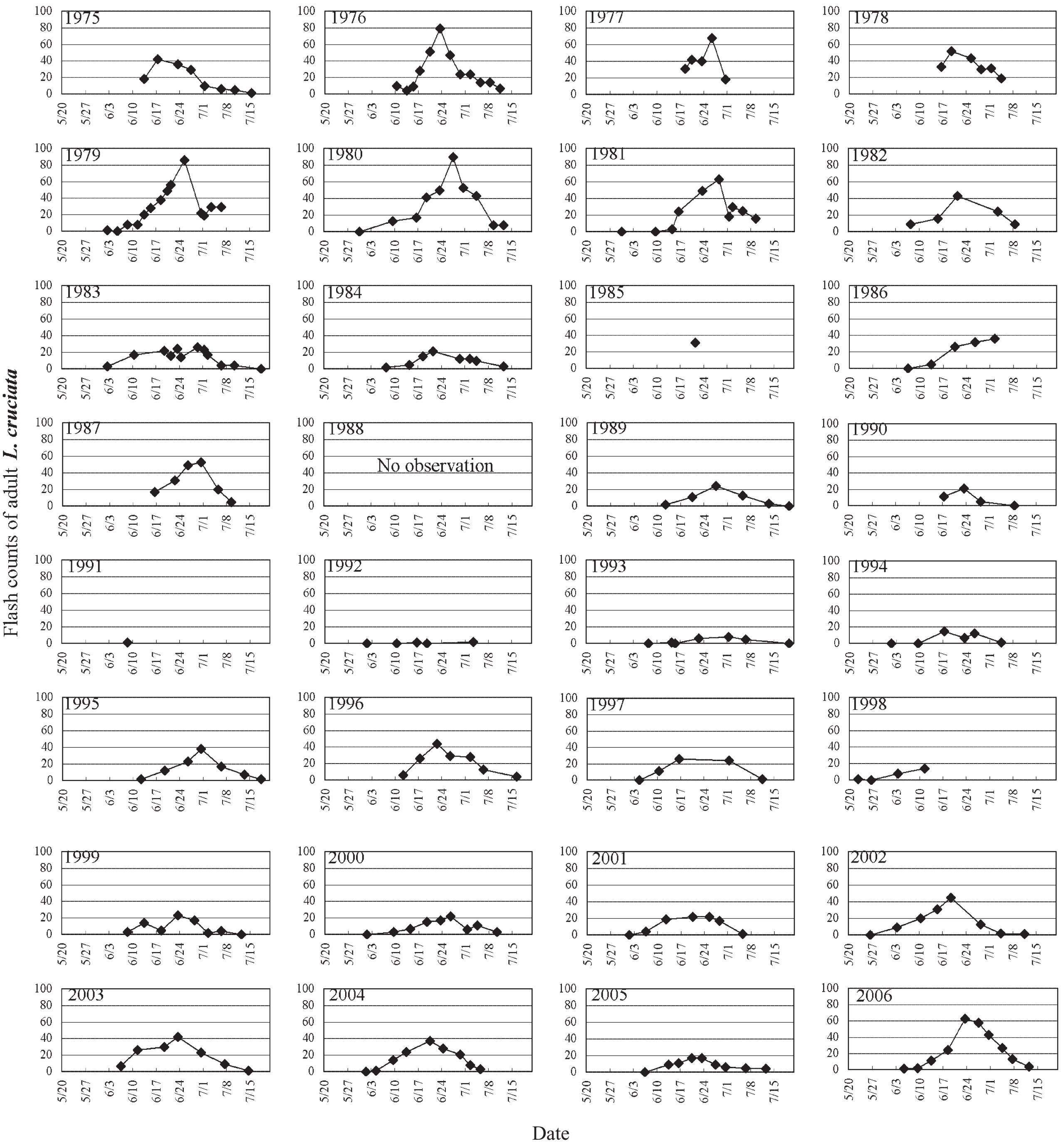

Figure 2 Seasonal flash counts of adult *Luciola cruciata* at Seiryuu Bridge on the Kiyotaki River between 1975 and 2006.

Precipitation data were obtained from the Kyoto Meteorological Observatory (35°00′44′N, 135°44′09′E; run by the Japan Meteorological Agency), which was located close to the center of the distribution of the four observation sites. Adult *L. cruciata* in Kyoto appeared primarily in June, with eggs laid from mid-June to early July, larvae in the river from late July to April, and pupae existing from April to May (Yuma 1981, 1993;

Table 1 Relative adult *Luciola cruciata* population sizes per 100 m stream stretch between 1975 and 2006 at four observation sites in Kyoto City

Year	Kiyotaki River Seiryuu Bridge	Kiyotaki River Kinrei Bridge	Kamo River Sankou Bridge	Takano River Yase Bridge
1975	250	–	–	–
1976	320	–	–	–
1977	325	–	–	–
1978	363	–	–	–
1979	422	–	–	–
1980	436	–	–	–
1981	323	–	367	–
1982	281	177	–	–
1983	199	85	124	–
1984	126	38	105	206
1985	–	–	–	–
1986	276	165	138	–
1987	299	107	216	149
1988	–	–	–	–
1989	136	68	120	256
1990	91	35	46	–
1991	–	–	–	–
1992	12	46	159	91
1993	51	43	236	173
1994	72	58	322	284
1995	193	107	425	330
1996	260	131	210	258
1997	216	140	113	208
1998	132	78	–	212
1999	111	60	86	78
2000	122	64	89	122
2001	161	92	59	–
2002	246	137	234	226
2003	281	199	331	243
2004	215	96	207	121
2005	103	61	57	58
2006	327	195	153	181

Yuma & Hori 1990). Precipitation events that had an effect on the CRP of the adult population occurred between January and May of a given year, and June and December of the previous year. For analysis, since hatching of larvae (i.e. dropping into the river) mainly occurred in the latter half of July (Yuma 1984), the precipitation in July was separated into the first and second halves of the month.

Stepwise multiple regression analysis was performed by including and excluding variables from analyses to assess their relative contributions to the relationship between CRP (year n to year $n-1$) and log-transformed precipitation events (from June in year $n-1$ to May of year n) using SYSTAT 11 (Systat Software, Richmond, USA).

RESULTS AND DISCUSSION

Long-term population dynamics of adult fireflies

Although observations for some populations are missing for some years (Fig. 2), the relative sizes of adult *L. cruciata* populations observed at the four locations between 1975 and 2006 appeared to fluctuate according to a 7–9 year cycle (Fig. 3). Despite the populations being more than 7 km apart (Fig. 1), the fluctuations in the

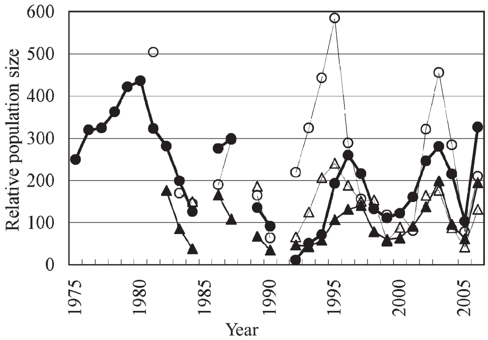

Figure 3 Fluctuations in adult *Luciola cruciata* populations presented as cumulative observed flash counts (individuals · days per 100 m stream stretch) between 1975 and 2006 at the four study sites in Kyoto City. (●), Seiryuu Bridge, Kiyotaki River; (▲), Kinrei Bridge, Kiyotaki River; (○), Sankou Bridge, Kamo River; (△), Yase Bridge, Takano River.

populations at the study sites were almost synchronous in the three rivers (four sites) observed (Kendall rank correlation between CRPs at Seiryuu Bridge and Kinrei Bridge, $n = 18$, $\tau = 0.511$, $P < 0.01$; Seiryuu Bridge and Sankou Bridge, $n = 15$, $\tau = 0.600$, $P < 0.01$; Seiryuu Bridge and Yase Bridge, $n = 12$, $\tau = 0.689$, $P < 0.01$; Sankou Bridge and Yase Bridge, $n = 10$, $\tau = 0733$, $P < 0.01$). Consequently, it seems that the fluctuations in these populations occurred in response to large-scale environmental phenomena such as weather conditions, and not characteristics specific to observation sites or rivers.

Floods are considered to be the most important events affecting the population dynamics of aquatic insects in rivers (Resh *et al*. 1988; Williams & Feltmate 1992), and recovery due to succession of insect fauna in rivers therefore proceeds quicker when there are few such flooding events in a given year (Ward 1992). Consequently, rainfall patterns are likely to have an important effect on the population dynamics of *L. cruciata*.

Effect of rainfall on population dynamics

Given that fluctuations in the populations of *L. cruciata* at the four study sites were almost synchronous, long-term fluctuations were analyzed using the dataset for the Seiryuu Bridge site on the Kiyotaki River, because it was most comprehensive for the period from 1975 to 2006.

Simple correlation analysis between the CRP of the adult *L. cruciata* population and precipitation (log-transformed) revealed that rainfall was responsible for the majority of the negative effects on the population size of the species (Table 2, Fig. 4). Among the precipitation events analyzed, total monthly precipitation in September had the most marked effect on CRP. These findings suggested a strong negative effect of large precipitation events on the number of early larval instars of this species.

Since the total monthly precipitation (total precipitation for a given month) was highly correlated with the maximum monthly precipitation (maximum daily precipitation for a given month; $P < 0.01$ for all months), whichever of these two factors showed a stronger correlation with CRP, by month, was adopted for the multiple regression analysis. Stepwise multiple regression analysis showed a significant negative correlation between CRP and total monthly precipitation in the latter halves of July and September (Table 3, $R^2 = 0.374$, $F = 6.585$, $P < 0.01$, Durbin-Watson's D statistic = 1.496, no autocorrelation at $P = 0.01$). The same results were obtained when the dataset was analyzed by including and excluding variables. While anomalous correlations between the precipitation events between October (total) and the first half of July (maximum), October (total) and November (total), October (total) and January (total), and April (maximum) and the first half of July (maximum) may lead to misinterpretation of the results, the results of the stepwise multiple regression analysis were the same as those obtained when the precipitation data for October (total) and April (maximum) were omitted from the analysis.

The rainy season in Japan occurs in June and July, with frequent heavy rains often occurring later in the season. In addition, the typhoons that frequently hit Japan in September and October also result in heavy rains and floods.

Given that the newly hatched larvae begin to appear in the river from the latter half of July (Yuma 1984, 1993), the negative effect on CRP may be due to the increased total monthly precipitation in the latter half of July, which might be responsible for the increased drift of newly hatched larvae due to the strong river currents associated with the increased runoff during this period. However, the eggs of *L. cruciata* are strongly attached to mosses on the riverbank, usually located 1 m or more above the average water level (Yuma & Hori 1981), and are thus generally safe from heavy rains and floods. The heavy rains in September cause another period of increased runoff in rivers, and further serious loss of early larval instars to drift is likely to occur. The increased river flows during these periods of heavy rain may also restrict the foraging activities of small firefly larvae on the river bottom.

These results show that the negative effects of heavy rains on populations of *L. cruciata* are possibly caused by

Table 2 Simple correlations between the change rate of the adult *Luciola cruciata* population (CRP) at Seiryuu Bridge and total monthly precipitation (mm) and maximum monthly precipitation (mm) between 1975 and 2006 ($n = 25$)

	CRP *vs* total monthly precipitation	CRP *vs* maximum monthly precipitation
June†	–0.242	–0.301
July,† first half	–0.030	–0.088
July,† latter half	–0.357*	–0.315
August†	–0.356*	–0.306
September†	–0.447**	–0.276
October†	0.070	0.035
November†	–0.095	–0.002
December†	–0.027	0.060
January	0.143	0.187
February	0.028	0.073
March	–0.111	0.068
April	–0.005	0.103
May	0.027	0.020

*$P < 0.10$, **$P < 0.05$. †Months of the previous year. Precipitation events were log-transformed for analysis.

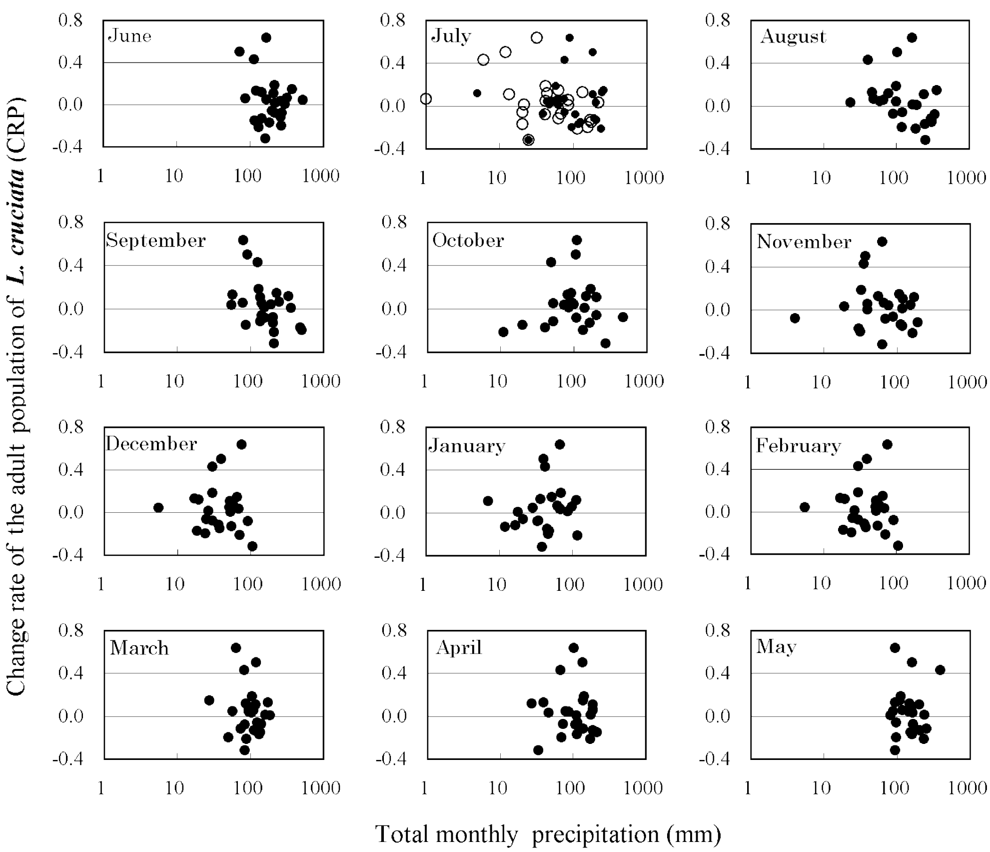

Figure 4 Relationship between the change rate of the adult *Luciola cruciata* population (CRP) at Seiryuu Bridge and total monthly precipitation between 1975 and 2006. Precipitation for July was divided into that falling in the first (solid circles) and second (open circles) halves of the month.

Table 3 Stepwise multiple regression analysis of the change rate of the adult *Luciola cruciata* population (CRP) by precipitation events ($n = 25$)

Effect	Partial coefficient	Standard error	Standard coefficient	Tolerance	t-value	P (two-tailed)
Constant	1.296	0.363	0.000		3.567	<0.01
September (monthly total)	–0.180	0.072	–0.422	0.983	–2.480	<0.01
Latter half of July (monthly total)	–0.437	0.148	–0.501	0.983	–2.949	0.02

larval drift during flooding. These findings corroborate the conclusions of previous studies, in which flash floods were found to have serious effects on populations of benthic macro invertebrates in streams (Resh *et al*. 1988; Hendricks *et al*. 1995; Gayraud *et al*. 2000; Thomson *et al*. 2002). Heavy rains may also adversely affect populations of these invertebrates' prey species, such as freshwater *Semisulcospira* snails (Holomuzki & Biggs 1999).

The simple flash counting method adopted here to count adult fireflies was effective for long-term monitoring of aquatic firefly populations. This is important given that to date very few long-term studies have been conducted on the macroinvertebrates of lotic systems (Bradt *et al*. 1999). Since rainfall patterns may affect the population dynamics of both predatory *L. cruciata* larvae and their freshwater-snail prey, the long-term prey–predator relationships (Thomson *et al*. 2002) between freshwater snails and firefly larvae, as well as the population dynamics of freshwater snails, should be studied in greater detail.

ACKNOWLEDGMENTS

The author thanks the staff of the Firefly Conservation Committee in Kiyotaki-cho, Kyoto City, for their assistance during the field survey. This research was partly supported by a MEXT Grant-in-Aid for the 21st Century COE Program at Kyoto University (A2), the Open Research Center Project of Ryukoku University 2004–2006 for Scientific Research (A1), no. 14506039 (2002–2005), Scientific Research (A1), no. 18201008 (2006) and Scientific Research (A2), no. 15206058 (2003–2005).

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