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The habitat requirement of the Genji-firefly *Luciola cruciata* (Coleoptera : Lampyridae), a representative endemic species of Japanese rural landscapes

MARI TAKEDA[1], TATSUYA AMANO[1,*], KAZUHIRO KATOH[2] and HIROYOSHI HIGUCHI[1]

*[1]Laboratory of Biodiversity Science, School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan; [2]Laboratory of Agricultural Field Ecology, School of Agricultural and Life Sciences, The University of Tokyo, 1051 Hata-machi, Hanamigawa-ku, Chiba City, Chiba 262-0018, Japan; *Author for correspondence (e-mail: tatsu@es.a.u-tokyo.ac.jp; phone: +81-3-5841-7542; fax: +81-3-5841-7542)*

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Abstract. Raising public interest in nature through conserving species of high social interest is crucial in achieving effective conservation of biodiversity. In Japan, the Genji-firefly *Luciola cruciata* (Coleoptera Lampyridae) in biodiversity rich agricultural landscapes called the satoyama has always attracted exceptional public interest. This study provides rare information on environmental factors associated with the abundance of the Genji-firefly. Stepwise backward multiple regression revealed that firefly abundance increased with increasing pH, DO and prey abundance while decreasing with water depth and the proportion of artificially modified ditch length. These factors are thought to be influential mainly to the larval and pre-pupal periods of the firefly. The implications of the results for the conservation of the Genji-firefly are discussed, with reference to the relationship between Genji-firefly conservation and extensive biodiversity conservation in the satoyama.

Introduction

Today, with increasing interests for the conservation of wild fauna and flora, people have become aware not only of the importance of natural environments but also of semi-natural environments (Buckley et al. 1997; Endels et al. 2002). Typical examples of such semi-natural environments are agricultural landscapes found in rural areas worldwide (Burel 1996; Elphick 2000). Hedgerows in Europe for instance, have been studied intensively for their roles as refuges or corridors for the conservation of biodiversity in rural areas (Burel 1996; Burel et al. 1998).

In Japan, agricultural landscapes called the satoyama provide a variety of habitat types for wildlife, helping to maintain rich biodiversity in the Japanese countryside (Kobori and Primack 2003). The satoyama consists of a mosaic of forests, grasslands, rice-fields, ponds, creeks and irrigation ditches that have historically provided resources for agricultural life (Kobori and Primack 2003).

Today, however, the reduced rice production policy by the government (Moore 1990), together with modernized agricultural schemes, urban developments and changes in forestry, have altered the rural landscapes drastically (Fukamachi et al. 2001), causing a corresponding decline in aquatic plants [e.g., *Sparganium japonicum* (Typhales : Sparganiaceae), Kato 2001], birds [e.g., *Butastur indicus* (Falconiformes : Accipitridae), Fujioka and Yoshida 2001], and insects [e.g., *Japonica saepestriata* (Lepidopter : Lycaenidae) and *Antigius attilia* (Lepidopter : Lycaenidae), Kato 2001, *Oligoaeschna pryeri* (Odonata : Aeshnidae) and *Rhyothemis fuliginosa* (Odonata : Libellulidae), Washitani 2001].

The Genji-firefly, with its unique luminescence, has been a representative insect of Japanese satoyama. Japanese people's admiration for the insect is exceptional to the extent that it has had a prominent influence on the Japanese culture (Kobori and Primack 2003). Nevertheless, the Genji is no exception to today's general trend and its population has declined in many areas of Japan (Ohba 1988). There are various reasons to believe that the conservation of the Genji-firefly is significant for the conservation of satoyama as a whole. Firstly, the Genji-firefly is an object of exceptionally high social interest mainly due to its aesthetic value. It has demonstrated to date that it can attract a large number of people to be involved in its conservation (Ohba 1988). Many authors have argued that raising public interest in nature through conserving such species of high interest is a crucial feature in successful conservation projects (e.g., Harrison and Burgess 2000; Primack et al. 2000; Suh and Samways 2001). Secondly, throughout its life cycle, the Genji utilises the diverse spatial environment typical to the satoyama; in the larval period, it uses water in the irrigation ditches; in the pupal period, it uses the soil surrounding the ditches; and finally in the adult phase, it makes use of the vegetation and space around and above the ditches (Ohba 1988). Therefore, it can be said that they are relatively sensitive to environmental changes in the habitat (Yuma 2000).

Due to their popularity, a considerable amount of conservation efforts has already been dedicated to this species. The Genji is a designated national natural treasure in at least 10 districts, and conservation activities are found in almost all prefectures of Japan, where various environmental conditions are typically used as general guidelines to distinguish favourable habitats from non-favourable ones (Ohba 1988). However, for the coexistence of human activities and the effective conservation of the Genji-firefly, accurate understanding of the abundance and distribution of this species is indispensable. Surprisingly, the number of scientific data on the habitat requirement of the Genji-firefly that are likely to lead to practical conservation measures is minimal. In the only study on the habitat requirement of the Genji-firefly thus far, Shibue et al. (1995) do not take into account a number of potentially important factors, such as prey abundance, water quality and artificial alteration conditions of irrigation ditches. Thus, the aim of this study was to identify the habitat characteristics associated with the abundance and distributional pattern of the Genji-firefly in the study area, based on which a more robust predictive model can be constructed and applied to practical conservation activities.

Material and methods

Study material

After hatching from eggs laid on mosses and vegetation on the walls of irrigation ditches, the Genji larvae drop into the irrigation ditches where they sink to the bottom. They remain under water for the majority of the life cycle (usually approximately 10 months), preying on pleurocerid snails (Kato 2001), most commonly Kawanina snails, *Semisulcospira libertina*, to which it is highly specific (Ohba 1988). Around April, fully-grown larvae emerge from the water by climbing up the ditch walls to reach suitable soil. They burrow underground and develop into pupae; emergence of the luminous adults occurs in June. They then fly above the rice fields and irrigation ditches before mating on suitable nearby lower vegetation, after which the females oviposit on mosses and lower vegetation. The adults only consume water in the form of dew on leaves (Yuma 2000).

Study sites

Study sites were in Ichikai-town (36°33′ N, 140°07′ E), Tochigi prefecture in the North Kanto region of Japan. In Ichikai, where many satoyama landscapes remain, anthropogenic developments are causing changes to the long used habitat of the Genji firefly.

Within the study area, 44 yatos with various environmental conditions were selected as study sites. Yatos are defined as networks of valleys with flat bottoms where rice fields are typically developed, surrounded by coppice (Washitani 2001). Today, in Ichikai, there are some yatos with relatively high firefly abundance, while a decline in abundance has been observed at others (M. Komori, personal communication).

The 44 yatos had rice field components of at least 200 m in length (on Digital Map 25,000 of Mito by the Geographic Survey Institute, Japan) to ensure independence of each study site. Here, the average migration distance of adult Genji-fireflies, known to be approximately 100 m (Ohba 1988) was taken into consideration. Yatos unsuitable for adult Genji observation due to unfavourable conditions such as strong artificial illumination, and/or the presence of vision hindering obstacles were eliminated. Both the firefly abundance survey and the environmental factors survey were carried out at each of the 44 sites.

Abundance survey of the Genji-firefly

Past observations have shown that the number of adult fireflies in the study area reaches its peak at the end of June on average. Since the weather condition in the survey year was an average one, the abundance survey of adult Genji-firefly was conducted on 17th, 19th, and 21st June 2002. The number of illuminating adult fireflies was recorded from a fixed observation point between the generally accepted peak hours of 8 pm to 8:30 pm (Ohba 1988) by over 120 pre-trained local volunteers. Pairs of volunteers were allocated to each study site, for which they were responsible for all three survey dates. The observation point at each site was selected so that viewing conditions were as similar as possible among sites, and observations were made for a uniform duration of 1 min within a uniform 180° field of view, divided into three directions, right, centre, and left, for practical means. In the study area, it was not difficult to distinguish individual fireflies flying in near proximity, such that double counts were unlikely. Thus, it seems plausible to assume that overestimation of firefly abundance has been avoided. On the other hand, to avoid underestimation, the maximum number of Genji-fireflies observed over the three survey dates was used for analysis.

Environmental factors survey

Based on the life cycle of the Genji firefly, aquatic and terrestrial environmental factors in and around the irrigation ditches that are likely to be relevant to firefly abundance were selected and investigated (Tables 1 and 2). Generally, for each of the irrigation ditches surveyed, the structural and ecological features were uniform throughout the length of the ditch, and drainage openings that could potentially affect water qualities were not found in any of the surveyed ditches. Those environmental factors that were assumed to be consistent throughout the entire length of a single ditch were measured at a fixed point. Other factors were surveyed every 10 m for 200 m along each irrigation ditch. All environmental factors were surveyed four times in total unless when data were not available. The four study periods were: February 2002, March–April 2002, end of May–July 2002, September–October 2002, which almost covers the entirety of a single life-cycle of the Genji-firefly. Since seasonal variations observed were minimal, the mean of four seasonal measurements were used for statistical analysis.

Statistical analyses

A multiple regression analysis was performed for the dependent variable, firefly abundance, with surveyed environmental factors as potential explanatory variables using SYSTAT 8.0 (SPSS 1998). The firefly abundance data, as well

Table 1. Environmental factors investigated and incorporated into the analysis, with definitions, survey methods, and survey style.

Variable	Definition	Survey method	Survey style
Ditch modification% [a]	proportion of ditch length modified artificially	observation	5 m interval along ditch length
Ditch base material [b]	prevalent material forming base of ditch	observation	single fixed point
Silt% [a]	proportion of silt in sediment	observation	along 1 m ditch length upstream of single fixed point
Litter% [a]	proportion of litter in sediment	observation	along 1 m ditch length upstream of single fixed point
Flow continuity [a]	proportion of ditch length with flowing water	observation	5 m interval along ditch length
Ditch width (cm) [c]	width of ditch	measured by measure	single fixed point
Water depth (cm) [c]	depth from water surface to base of ditch	measured by measure	single fixed point[e]
Base current velocity (cm/s) [c]	water current velocity at base of ditch	measured by electric meter	single fixed point[e]
Vegetation height (cm) [c]	Height of vegetation adjacent to ditch	measured by measure	single fixed point
Vegetation cover [a]	proportion of vegetation cover adjacent to ditch	observation	single fixed point
PH	pH	measured by pH meter	single fixed point[f]
DO (ppm)	DO (dissolved oxygen)	measured by Oxymeter	single fixed point[f]
EC (mS/m)	EC (electric conductivity)	measured by electric meter	single fixed point[f]
Water temperature (°C)	water temperature	measured by thermometer	single fixed point
S. libertina [c]	abundance of *S. libertine*	soil samples taken from ditch bases using a sieve	mean of five samples taken within 1.5 m of single fixed point
Alternative land use % [a]	proportion of ditch length in alternative land use	observation	5 m interval along ditch length
Ditch coverage [d]	whether vegetation covers only water edges or water surface as well	observation	5 m interval along ditch length

[a] Arcsin transformed.
[b] Included in analysis as three dummy variables: unexposed base material (1) or not (0), exposed natural material (1) or not (0), and concrete (1) or not (0).
[c] Log transformed.
[d] Dummy variable coding: 0 = no vegetation cover, 1 = vegetation covers only water edges, 2 = vegetation also covers water surface.
[e] Mean of 3 points; left, centre and right for ditch width above 1 m.
[f] Mean of data for ripple and pool when both existed within 1 m of single fixed point.

Table 2. Environmental elements expected to affect the abundance of the Genji-firefly, specific environmental factors relevant to each element, how each affect firefly abundance, and the life stage it affects.

Environmental elements	Variables	Role/effect	Relevant life stage
Artificial ditch alteration conditions	ditch modification %	availability of climbable & burrowable ditch wall	pre-pupae
Ditch hydrological conditions	ditch base material	larval habitat	larvae
	Silt %	larval habitat	larvae
	litter %	larval habitat	larvae
	flow continuity	stability of habitat	larvae
	ditch width	water quantity/velocity	larvae
	Water depth	water quantity/velocity	larvae
	base current velocity	water quantity/velocity	larvae
Water quality	canal coverage	availability of source of shade	larvae
	vegetation height	source of shade	larvae
	vegetation cover	source of shade	larvae
	pH	water quality	larvae
	DO (dissolved oxygen)	water quality	larvae
	EC (electric conductivity)	water quality	larvae
	water temperature	water quality	larvae
Prey abundance	*S. libertina*	prey abundance for larvae	larvae
	litter %	prey food	larvae
	vegetation height	prey food	larvae
	vegetation cover	prey food	larvae
Environment surrounding ditch	alternative land use %	continuity of habitat	adult
	canal coverage	disturbance of flight	adult
	vegetation height	resting site	adult
	vegetation cover	resting site	adult

as those explanatory variables that showed non-normal distributions were log transformed, and data expressed as proportions were arcsin transformed prior to the analysis. Intercorrelations of explanatory variables were examined prior to the regression analysis and strongly correlated variables (defined as Pearson correlation $r > 0.8$) were eliminated from the analysis to avoid multicollinearity. Explanatory variables were selected based on the stepwise backward elimination method and p(elimination) > 0.05.

Results

Correlations between variables were low to moderate in most cases (Table 3), though five combinations of the variables showed correlations of 0.50 to 0.76. However, since correlations above 0.8 were not found between any of the variables, all variables were included as explanatory variables in the regression analysis.

Table 3. Pearson correlations between each explanatory variable surveyed.

	Ditch modification %	Unexposed base material	Exposed natural base material	Concrete base	Silt %	Litter %	Flow continuity	Ditch width	Water depth	Base current velocity
Ditch modification %	1									
Unexposed base material [a]	−0.425	1								
Exposed natural base material [a]	−0.049	−0.478	1							
Concrete base [a]	0.507	−0.736	−0.243	1						
Silt%	0.122	−0.024	−0.203	0.184	1					
Litter%	−0.332	0.212	−0.002	−0.232	0.193	1				
Flow continuity	0.070	0.040	0.087	−0.111	0.204	0.172	1			
Ditch width	0.193	−0.079	0.309	−0.151	−0.272	−0.252	−0.227	1		
Water depth	0.078	−0.011	0.109	−0.071	−0.317	−0.203	0.047	0.512	1	
Base current velocity	0.130	0.045	0.002	−0.050	−0.368	−0.488	−0.035	0.241	0.590	1
Vegetation height	−0.512	0.395	0.082	−0.499	−0.190	0.150	−0.119	0.198	−0.005	0.062
Vegetation cover	−0.765	0.395	0.030	−0.459	0.008	0.292	0.027	−0.176	0.042	0.003
PH	0.217	−0.149	0.240	−0.020	−0.144	−0.124	−0.076	0.383	−0.074	−0.152
DO	0.120	−0.177	0.288	−0.026	−0.165	0.066	0.224	−0.009	0.145	0.219
EC	0.259	−0.238	0.106	0.181	−0.005	−0.035	−0.002	0.307	0.142	−0.117
Water temperature	0.332	−0.379	0.006	0.414	0.068	−0.270	−0.130	0.278	−0.001	−0.010
S. libertina	−0.399	0.235	−0.101	−0.181	0.092	0.130	0.078	−0.464	−0.142	0.018
Alternative land use %	−0.189	0.220	−0.062	−0.195	0.149	0.261	0.054	−0.239	−0.322	−0.440
Ditch coverage [a]	−0.009	−0.023	0.011	0.017	−0.063	−0.026	0.125	−0.022	0.124	0.041

Table 3. Continued.

	Vegetation height	Vegetation cover	PH	DO	EC	Water temperature	*S. libertina*	Alternative land use %	Ditch coverage
	Vegetation height	Vegetation cover	PH	DO	EC	Water temperature	*S. libertina*	Alternative land use %	Ditch coverage
Vegetation height	1								
Vegetation cover	0.497	1							
PH	−0.008	−0.291	1						
DO	0.107	−0.034	−0.043	1					
EC	−0.159	−0.238	0.434	−0.146	1				
Water temperature	−0.220	−0.352	0.395	−0.238	0.220	1			
S. libertina	0.029	0.447	−0.154	−0.093	−0.436	−0.040	1		
Alternative land use %	0.075	0.164	−0.036	−0.107	−0.007	−0.199	0.008	1	
Ditch coverage [a]	−0.133	−0.064	−0.252	0.028	−0.053	0.131	0.071	0.202	1

[a] Dummy variables.

Table 4. Results of backward stepwise multiple regression analysis on Genji-firefly abundance.

Explanatory variables adopted	Partial regression coefficients	Standard error	Standardized partial regression coefficients	Tolerance	t	p
Constant	−2.593	0.750				
PH	0.269	0.082	0.329	0.934	3.286	0.002
DO	0.251	0.055	0.454	0.962	4.602	< 0.001
Water depth	−0.422	0.140	−0.299	0.953	−3.022	0.004
S. libertina	0.316	0.083	0.405	0.821	3.790	0.001
Ditch modification %	−0.245	0.078	−0.339	0.807	−3.146	0.003

Shown are only significant variables. $F_{5,\ 38} = 13.762$, $p < 0.001$, $R^2 = 0.644$, $R^2_{adj} = 0.597$.

The number of Genji-fireflies in a yato varied from 0 to 71 and the mean was 17.34 ± 2.49 (± SE). According to the regression analysis, five variables, PH, DO, water depth, *S. libertina* abundance, and the proportion of artificially modified ditch length were found to be significantly affecting firefly abundance; 60% of the variation in firefly abundance was explained by these variables (Table 4). PH, DO, and *S. libertina* abundance showed positive relationships with firefly abundance, while the number of fireflies decreased with increasing water depth and modified ditch%. All of the five variables selected as significant variables had tolerance values above 0.8, indicating the absence of strong collinearity among those variables.

Discussion

It has been reported that not only aquatic conditions, but also terrestrial conditions, especially bank-side structure and vegetation, have an impact on the abundance of aquatic insects with terrestrial adult phases, such as caddisflies and dragonflies (Samways and Steytler 1996; Collier et al. 1997; Harrison and Harris 2002; Iwata et al. 2003). The results of this study clearly supported this idea by showing that the abundance of Genji-fireflies was also affected by both aquatic (e.g., pH, DO) and terrestrial factors (e.g., the proportion of artificially modified ditch length).

The negative impact of increased proportions of artificially modified ditch length on fireflies is understandable since it is crucial for the firefly larvae to be able to find ditch walls suited for pre-pupal landing after emergence from the water, followed by underground burrowing (Ohba 1988; The Japanese Firefly Society 1996). Further, the relatively high correlation of the proportion of artificially modified ditch length to vegetation height ($r = -0.512$) and vegetation cover ($r = -0.765$, Table 3) indicated the possibility that bank side vegetation positively affects firefly abundance through its role in resting, mating and oviposition, as has been reported in other species of aquatic insects (Ormerod et al. 1990; Samways and Steytler 1996).

Water quality is thought to affect firefly abundance as the direct determinant of larval habitat quality. Though many studies have found that the sensitivity to acid varies among aquatic insects (Ward 1992), from highly tolerant dragonflies (e.g., Pollard and Berrill 1992) to particularly sensitive mayflies (e.g., Courtney and Clements 1998), the positive influence of relatively high pH (range: 6.07–8.46) on firefly abundance indicated that the Genji-firefly larvae were relatively sensitive to water acidification. The positive relationship between DO (range: 6.26–9.12) and firefly abundance is consistent with the generally accepted knowledge that DO is an environmental variable of considerable importance to many aquatic insects (Ward 1992; Williams and Feltmate 1992).

Prey abundance has often been considered as one of the most powerful determinants of firefly abundance (Ohba 1988; The Japanese Firefly Society 1996). Indeed, *S. libertina* abundance was found to affect the Genji-firefly's abundance significantly. However, when compared with the other selected explanatory variables, the standardized partial regression coefficient of prey abundance indicated that its impact on firefly abundance was not much stronger, or even weaker. Since *S. libertina* abundance was not highly correlated to pH or DO (Table 3), while those variables strongly affected firefly abundance, *S. libertina* in the study area is thought to be more tolerant with regard to water quality than the firefly. That is, in the study area, the two species differ in their habitat requirements, with the prey being more tolerant than the predator, causing factors other than prey abundance to have a stronger impact on the abundance of the Genji-firefly.

The results of this study also appeared to suggest water depth (a maximum of 21 cm) to have a significantly negative impact on firefly abundance. However, Genji-fireflies have been found to inhabit streams as deep as 2 m (Ohba 1988). Thus, it is more likely that the apparent negative impact of water depth on firefly abundance is an indirect one through other factors not investigated in this study. Indeed, the three deepest ditches were characterised by the presence of heavy traffic roads running along the yato, together with street lights, as well as relatively large numbers of houses, which are all indicative of increased human activities. These surrounding environmental conditions are expected to affect the behaviour of adult fireflies, especially their mating behaviour. Investigating the influence of such factors on firefly abundance will be needed in future studies. In fact, for other aquatic insects, it has been argued that the adult terrestrial stage can be critical in regulating population size (Werneke and Zwick 1992; Enders and Wagner 1996).

Conservation recommendations

The present regression model represents a basic model explaining Genji-firefly abundance distribution, upon which a more extensive and robust predictive model can be developed. Based on this fundamental model, the following potential conservation recommendations are provided. When development programmes and other human activities with potential impacts on the environment are considered in the study area, special attention needs to be paid to the artificial ditch alteration conditions, water quality and prey abundance. As much change is in progress in Ichikai town, including a ditch modification programme in planning, the information provided by this study is thought to become of immediate use.

Though much care should be taken when the results of this study is applied to other habitats of the Genji-firefly, the biological basis for most of the variables selected in this study is likely to confirm, at least, the qualitative generality of the conclusion. Therefore, when considering the recovery of the Genji-firefly abundance at other habitats, the determinants identified here could serve as practical guidelines. For example, increasing the abundance of *S. libertina*, which had previously been regarded as a factor of highest and sometimes sole priority in firefly abundance recovery, may be insufficient on its own unless other environmental factors are improved.

Although the model needs to be further improved, this study represents the first extensive attempt to examine the habitat requirements of the Genji-firefly and provide reliable information about the key habitat variables for this insect of high public interest. Further, habitat requirements of the Genji-firefly identified here also apply to a wide range of organisms in agricultural landscapes. Water quality, for instance, is known to have a marked impact on the abundance of many aquatic insects (e.g., Ward 1992; Courtney and Clements 1998; Suh and Samways 2001), while ditch modification in Japanese rice fields has been reported to affect negatively the abundance of various frogs and fishes, through which the distribution of predatory birds, such as egrets and herons, is also changed (Fujioka and Lane 1997; Lane and Fujioka 1998). Therefore, we believe that raising public interest towards the conservation of the Genji-firefly in the satoyama would be a crucial first step for the extensive conservation of biodiversity in the satoyama.

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