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Ground beetle (Coleoptera: Carabidae) assemblages associated with a satoyama landscape in Japan: the effects of soil moisture, weed height, and distance from woodlands.

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Abstract

Agricultural landscapes generally include not only crop fields but also semi-natural habitats (non-crop vegetation), such as woodlands, hedgerows, or grasslands. In Japan, such a mixed rural landscape is called "satoyama." Although ground beetles are potential predators of farmland pest insects, the environmental factors that determine their distribution in Japanese rural landscapes have not been fully elucidated. To understand the effects of distance from woodland edges, soil moisture, and weed height on assemblages of carabid beetles, we examined the number of adult beetles in pitfall traps placed in the mixed landscape of paddy fields, orchards, bamboo groves, and woodlands in the lowlands of western Honshu, Japan. Our results show that the carabid species in satoyama landscapes could be largely differentiated into woodland species, intermediate species, and open-land species, along the geographical gradient from woodlands to open lands. While the woodland and open-land groups of species are primarily habitat specialists, the "intermediate species" group includes species that depend on woodland or woodland edges for at least part of their life cycles. Intermediate species include beetles such as *Carabus yaconinus*. Soil moisture had a marked effect upon the distribution and abundance of ground carabid species, supporting previous studies conducted in Europe. Paddy fields must have long provided semi-natural habitats that complement those in natural grasslands and wetland for open-land beetles that prefer wet conditions. Weeds can also increase the abundance of some intermediate and woodland species, which is further enhanced by the conservation of woodlands in agricultural landscapes and leaving beetle banks that consist of weeds and connect forest edges to farmland. The arrangement of such landscape elements, woodlands, and paddies, should determine the species richness and abundance of ground beetles in agricultural fields.

Keywords

Agroecosystem・conservation biological control・ecotone・forest edge・natural enemy・paddy・*Carabus*

Introduction

Agricultural landscapes can be described as heterogeneous and shifting mosaics of crop fields and semi-natural vegetation, such as woodlands, hedgerows, or grasslands. Maintaining a heterogeneous habitat mosaic may contribute to the overall diversity of farmland natural enemies (Landis et al. 2000; Altieri and Nicholls 2004; Tscharntke et al. 2007) because many predatory invertebrates require a variety of habitats to complete their life cycles (e.g., Tucker 1997; Delettre et al. 1998; Kagawa and Maeto 2009). In Japan, such mixed rural landscapes are called "satoyama" (Yamamoto 2001; Takeuchi 2003). Semi-natural habitats are particularly important because they serve as temporal refuges for the natural enemies of pests (Lyngby and Nielsen 1981; Gravesen and Toft 1987; Desender and Alderweireldt 1988; Bedford and Usher, 1994).

However, while much work has been undertaken to investigate the spatial distribution and dynamics of the natural enemies of farmland pests in European heterogeneous landscapes (Gravesen and Toft, 1987; Desender and Alderweireldt 1988; Altieri and Nicholls 2004), few studies have investigated the environmental factors that affect the habitat preferences of these animals in the mixed agricultural landscapes, including paddy fields, of Japan.

Ground beetles (Coleoptera: Carabidae) are considered to be beneficial arthropods, as they are usually generalist predators of various agricultural insect pests. For this reason, they have been studied intensively in Europe and North America (Thiele 1977; Luff 1987; Luff et al. 1992; Sunderland 2002). Understanding the environmental factors that affect beetle distribution is important for the conservation of carabid assemblages for biological control (Maudsley et al. 2002). Previous studies have supposed that a few microhabitat factors, such as humidity, temperature, pH of soil, or the quantity and quality of organic matter (weeds, fallen leaves) affect habitat preference of ground beetles (e.g., Thiele 1977; Petit et al. 1998; Ings et al. 1999; Holland 2004; Fahy and Gormally 1998), as do landscape factors, such as the distance from, and the size of, neighboring semi-natural habitats (Niemelä 2001; Niemelä et al. 1988, 1993, 2001; Altieri and Nicholls 2004). However, most of these studies were conducted in Europe and North America. Therefore, the environmental factors that determine the distribution of ground beetles in East Asian agricultural fields, such as in Japanese traditional rural “satoyama” landscapes, particularly those that include paddy fields, have not been fully investigated (but see Kagawa and Maeto, 2008).

The aim of this study was to clarify the effects of soil moisture, weed height, and distance from woodland edges on the assemblages of ground beetles in a satoyama landscape. We examined the number of adult beetles in pitfall traps that were placed in a mixed landscape of paddy fields, orchards, and woodlands in the lowlands of western Japan.

Materials and Methods

Study site

The study was conducted at the Food Resources Education and Research Centre of Kobe University (34°52' N, 134°51' E; 55–58 m a.s.l.) and its neighboring woodlands in Kasai, Hyogo Prefecture, Japan. The study site landscape consisted of paddy fields, meadows, farm ponds, orchards (pear and vines), and woodlands that were dominated by deciduous oak trees or bamboo (Fig. 1).

Plot design and sampling

Figure 1 shows 3 transects across the farmland mosaic. Two transects (A, B) were arranged from paddy fields (A-1–3, B-1–3), through the edge of a woodland (A-4, B-4), a bamboo-dominated woodland (A-5–6, B-5–6), an oak-dominated woodland (A-7, B-7), an orchard (A-8–10, B-8–10), to an oak-dominated woodland (A-11, B-11). A third transect (C) crossed oak-dominated woodland (C-1) and an orchard (C-2, 3). Sampling plots were placed at 20–100 m intervals along each transect, for 25 plots (Fig. 1). Three pitfall traps (plastic cups of 80-mm diameter and 95-mm depth) were set at each sampling plot. Traps were set along a straight line at 5 m intervals. In paddy fields, the traps were set up on ridges, but not within the rice paddies. Each trap had 2 or 3 drainage holes at the bottom; a plywood roof (12 × 12 cm) was placed above the trap to exclude sunlight and rainwater. The traps were operated dry and without bait. Adult ground beetles were collected from the traps every week from March 2004 to January 2005 and were identified to species in the laboratory. Voucher specimens were deposited in the Graduate School of Agricultural Science, Kobe University, Kobe, Japan.

Environmental variables

The distance from the woodland edge was defined as a straight-line distance between the center of each plot and the nearest woodland edge, as measured on an aerial photograph. Soil moisture and weed height were measured at each sampling plot on April 28, June 8, and

September 1, 2004, and the mean values of the 3 seasonal measurements were used for analysis. Soil samples were collected from each plot using a shovel. The soil was sampled to a depth of 5 cm, weighed, dried in the oven at 80 °C for 24 h, and reweighed in order to calculate soil moisture. The following equation was used to calculate soil moisture: soil moisture (%) = 100 × (MW - DW)/MW, where MW is the fresh soil sample weight and DW is the dry soil sample weight. The height of the tallest herbaceous plant in a 1 × 1 m quadrat that included the central pitfall trap at each plot was measured and recorded as the weed height. Table 1 shows the summary of these 3 environmental variables and correlations among them.

Statistical analyses

We pooled the carabid catches at each plot (i.e., in the 3 pitfall traps) over the entire trapping period. Those species that were captured at 3 or more plots were included in analyses. The species composition of carabid assemblages was analyzed using canonical correspondence analysis (CCA; ter Braak 1986), based on the root-transformed number of adults collected from each plot and the 3 environmental variables. Axis scores were centered and standardized to unit variance. Axes were scaled to compromise representation of species and plots, and the scores used in figures were linear combinations of variables. A Monte Carlo test was performed to test the null hypothesis that there is no relationship between species abundance and environmental variables. Two-way cluster analysis (TWCA; Madeira and Oliveira 2004) was also conducted on the root-transformed number of adults, using Ward's method of clustering based on Chi-square distance measures (McCune *et al.*, 2002). All of these analyses were performed using PC-ORD Version 5.10 for Windows (McCune and Mefford 2006).

Carabus yaconinus, which was the most abundant carabid beetle, were collected at more than 3/4 of the plots. A generalized linear model (GLM) was used to analyze the effects of environmental variables on the number of these beetles that were captured. The raw data was evaluated using a Poisson distribution model with log link function, the number of *C. yaconinus* as a dependent variable, and the 3 environmental variables as covariates. In the final analysis, significant interactions ($P < 0.05$) as well 3 main factors were treated. Analyses were performed using IBM SPSS Statistics version 19.

Results

A total of 1268 individuals of 36 carabid species were collected across 25 plots during the sampling period (Table 2). The 5 most abundantly collected species represented 62.1% of the total catch. These species were *C. yaconinus, Synuchus dulcigradus, Amara macronota, Synuchus nitidus*, and *Harpalus chalcentus*. A large number of species and individuals were collected at the plots located on paddy ridges (A-1–3, B-1, and B-3), at woodland edges (A-4 and B-4), in oak-dominated woodland (A-7, A-11, B-7, and B-11), and in the orchard (A-9 and B-8). The collection was poor (< 3 species) at plots in bamboo-dominated woodland (A-5, A-6, B-5, and B-6) and orchard (B-9, B-10, and C-3).

Table 3 summarizes the results of CCA for the 23 carabid species that were captured at 3 or more plots. The first and second axes explained 32.9% of the total variance, while the third axis explained little variance (3.1%) and should be ignored. The eigenvalue of the first axis (0.532) was significant ($P = 0.001$, Monte Carlo test with 999 permutations). Thus, the null hypothesis of no relationship between species and environmental variables was rejected. The first axis was most strongly and negatively affected by distance from the woodland edges, whereas the second axis was negatively affected by soil moisture. On both the first and second axes, weed height showed a small, but opposite effect to that of distance from the woodland edge.

The species ordination in Fig. 2 shows that *Synuchus* spp. (ee–hh) were mainly found in habitats that were very close to, or were within, woodlands. These species were also associated with relatively high soil moisture and tall weeds. *C. yaconinus* (g), *Dolichus halensis* (n), and many *Chlaenius* spp. (i–m) were found in habitats that were not far from woodlands and had relatively low soil moisture. *Amara* spp. (a–c), *Anisodactylus* (d), *Harpalus* spp. (o–t), *Platynus* (w), and *Pterostichus* (y–aa) were found in habitats that were relatively far from woodlands and had varied soil moisture. *Harpalus* spp., exhibited the following relative soil moisture preferences (from wettest to driest): *H. tinctulus* (s), *H. chalcentus* (o), *H. sinicus sinicus* (r), *H. tridens* (t), and *H. griceus* (q).

Figure 3 shows the result of TWCA for the 23 carabid species, which could be clustered into 3 groups, with the exception of *D. halensis* (n). The right cluster included 2 *Chlaenius* spp. (k, l) and all of the *Synuchus* spp. (ee–hh). These beetles were collected in oak-dominated woodland (A7, A-11, B7, and B-11) or at the woodland edge (A-4 and B-4). The left cluster included many species of *Amara* (a–c), *Anisodactylus* (d), *Harpalus* (o, q–s), *Platynus* (w), and *Pterostichus* (y–aa). These species were primarily collected from paddy ridge plots (A-1–4 and B-1–3) or orchard plots (A-8 and A-9). The middle cluster included *C. yaconinus* (g), collected at almost all plots, except for paddy ridges, and 2 *Chlaenius* spp. (i, m) and *H. tridens* (t), which were collected from woodland (C-1), woodland edge (A-4 and B-4), and orchard plots (A-9, B-8, and C-2).

Figure 4 shows scatter plots of the number of *C. yaconinus* captured *versus* distance from woodland edge (a), soil moisture (b), and weed height (c). In the final GLM analysis, there was a significant negative interaction between distance from woodland edge and soil moisture. There was also a significant positive effect of weed height (Table 4). This indicates that the number of *C. yaconinus* adults decreases with distance from the woodland edge, but the effect is weakened in areas with relatively low soil moisture. Weed height was independently associated with the number of *C. yaconinus* collected.

Discussion

Our results show that the carabid species in a satoyama landscape can be largely differentiated into woodland species (e.g., *Synuchus*), intermediate species (e.g., *C. yaconinus*, many *Chlaenius,* and *D. halensis*), and open-land species (e.g., *Amara,* many *Harpalus,* and *Pterostichus*), along the geographical gradient from woodlands to open-lands. While the first and third groups are habitat specialists of woodlands and open grasslands, respectively, the second group of "intermediate species" includes those that depend on woodland or woodland edges for at least part of their life cycles, such as *C. yaconinus* (Kagawa and Maeto 2009). Although the open-land species were mainly found on paddy ridges, these species were also rich and abundant in the center of the orchard (A-9). This indicates that the relatively sparse litter and under growth in orchards is appropriate habitat for these beetles, as are manicured paddy ridges and low-height grassland.

As mentioned in previous reports (Niemela et al. 1988; Niemela, 2001; Hori 2003; Boulton et al. 2008; Fujita et al. 2008), woodland size and location markedly affect the distribution of woodland and generalist species of carabids. In the satoyama landscapes of Japan, paddy ridges must have long provided semi-natural habitats for open-land species, on behalf of natural grasslands and wetlands. The arrangement of such landscape elements, woodlands, and paddies, should determine the species richness and abundance of ground beetles in agricultural fields.

Soil moisture had a marked effect upon the distribution and abundance of carabid species, supporting previous studies conducted in Europe and woodland specialists generally prefer wet soil conditions, while intermediate species tend to prefer dry conditions (Thiele 1977;

Petit et al. 1998; Fahy and Gormally 1998). We had first supposed that the open-land species inhabiting paddy ridges prefer wet soil conditions, but this is not the case. These species show a wide variety of moisture preferences and were occasionally found in orchards or, rarely, in woodlands. Wetland specialists were often found together with dry-land species in paddy fields.

Weed height also affects carabid distribution. It might seem as though the effect of weed height is simply related to that of distance from woodland edges (Fig. 2). However, our analysis of *C. yaconinus* abundance showed that these effects are independent of each other. As indicated by Matsumoto (2008), some intermediate species, such as *Chlaenius naeviger*, prefer thick vegetation. Forest edges provide such carabids with food resources as well as refuge from their natural enemies (Lewis 1969; Fagan et al. 1999; Holland et al. 2000). Weedy covering in open-land areas likely improve conditions for the movement and rest of those species that favor woodlands or woodland edges.

Some promising biocontrol agents against vegetable pests have been suggested by Tanaka (1956), Suenaga and Hamamura (2001), Kagawa and Maeto (2007), and Masuda (2011). These species include *Chlaenius* spp., *D. helensis*, and *C. yaconinus*, were all classed as intermediate species in the present study. For one of these species, *C. yaconinus*, we showed that adult abundance increased with weed height and proximity to woodlands. Our study indicates that intermediate species, which are natural enemies of crop pests, can be enriched by the connection of woodland edges and farmland with weed belts, such as the "beetle banks" found in Europe (Frampton et al. 1995; Kromp 1999). Further studies that focus on estimating the effects of woodland location and weed condition on important target species will be necessary for appropriate management of the satoyama landscapes and improve biocontrol of crop pests by native natural enemies.

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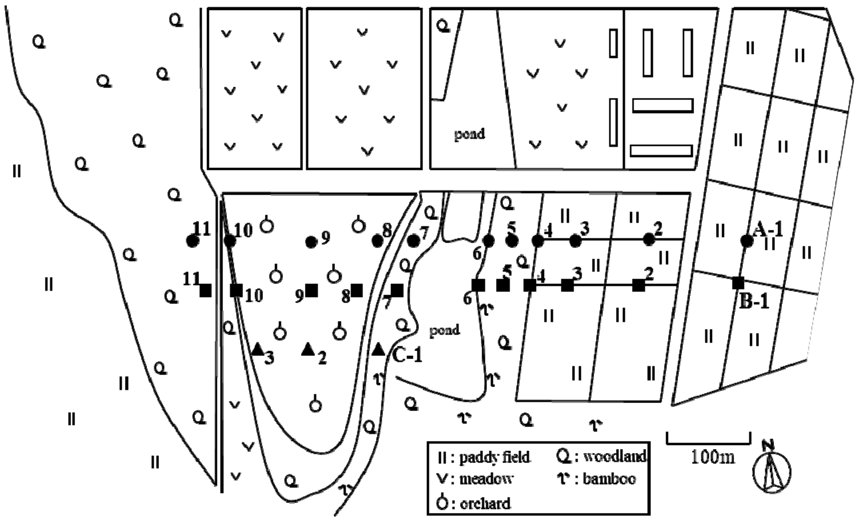

Figure 1. Map of the study site and trapping plots in the Food Resources Education and Research Center of Kobe University, Kasai, Hyogo. This map shows three transects crossing the farmland. Two transects (A,●; B,■) cross paddy fields, a bamboo, a woodland, an orchard and another woodland. One transect (C,▲) crosses a woodland, an orchard and another woodland. Along each transect, sampling plots were established (indicated by closed circles, squares, and triangles). At each sampling plot, three pitfall traps were set

Table 1. Summary of environmental variables and correlations among them.

				Correlaton coefficients, r	
Environmental variables	Mean	SD	Range	Soil moisture	Weed height
Distance from woodland edge (m)	39.2	81.2	-50 - 250	0.397	-0.371
Soil moisture (%)	10.9	3.5	1.2 - 18.1		0.072
Weed height (cm)	27.2	20.7	6.0 - 81.1		

Table 2. Number of carabid adults collected in each sample plot.

		Sample plot																									
Species	Code	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10	B-11	C-1	C-2	C-3	Total
Amara chalsites	a	10	1	1					1	1			6														20
Amara congrua	b	2							2	14			1														19
Amara macronota	c	1	1	14	13					2		1	12		38				1								83
Anisodactylus punctatipennis	d	26	1	4	11							1	9										1				53
Anisodactylus sadoensis	e	2										1															3
Campalita chinense	f				1																						1
Carabus yaconinus	g				25		3	47	3	15	8	71	2		9	64	12	35	13	23	5	20	49	20	14	20	458
Chlaenius abstersus	h				1										1												2
Chlaenius micans	i				2					2					2	2		2		2				6			18
Chlaenius naeviger	j				10											6											16
Chlaenius pallipes	k													2					2				2				6
Chlaenius sericimicans	l											18				4							4				26
Chlaenius virgulifer	m								1				1		1									1			4
Dolichus halensis	n			1							1				5												7
Harpalus chalcentus	o	8	28	13	6					3			5	1	2												66
Harpalus eous	p							1																		1	2
Harpalus griceus	q		1		1					1			6	9	1				1					1			21
Harpalus sinicus sinicus	r		8	3	1				1	5			1	3											1		23
Harpalus tinctulus	s	28	1										23														52
Harpalus tridens	t	2		1	2			2		4			8		2					16				1	1		39
Lestichus magnus	u				1					3																	4
Platynus chalcoms	v	14		1																							15
Platynus magnus	w	6	5	7	4								7		1												30
Platynus puncticeps	x							1																			1
Pterostichus hapteroides	y	13	9		1					1			14		1					1							40
Pterostichus longiguus	z	3								1			1										1				6
Pterostichus microcephalus	aa	1			1					1			1														4
Pterostichus planicoiis	bb												1														1
Pterostichus sulcitarsis	cc				2																						2
Scarites acutidens	dd									1																	1
Synuchus arcuaticollis	ee			3	8	5		1				7				1			9				11				45
Synuchus cycloderus	ff				1			1				4							8				17				31
Synuchus dulcigradus	gg				29			3			1	14			1				5				43				96
Synuchus nitidus	hh				3			8				18							3				39				71
Trechus ephippiatus	ii			1																							1
Trigonotoma lewisii	jj	1																									1
Total		117	55	49	123	5	3	64	8	54	10	135	98	15	64	77	12	37	42	42	5	20	167	29	16	21	1268

Table 3. Results of canonical correspondence analysis (CCA) of carabid data.

	Axis 1	Axis 2	Axis 3
Eigenvalue	0.532	0.215	0.07
Variance explained in species data (%)	23.4	9.5	3.1
Standardized canonical coefficients			
Distance from woodland edge	-0.592	0.268	0.618
Soil moisture	-0.248	-0.681	-0.200
Weed height	0.189	-0.226	0.652
Biplot scores			
Distance from woodland edge	-0.817	0.132	0.122
Soil moisture	-0.524	-0.534	-0.050
Weed height	0.613	-0.289	0.285

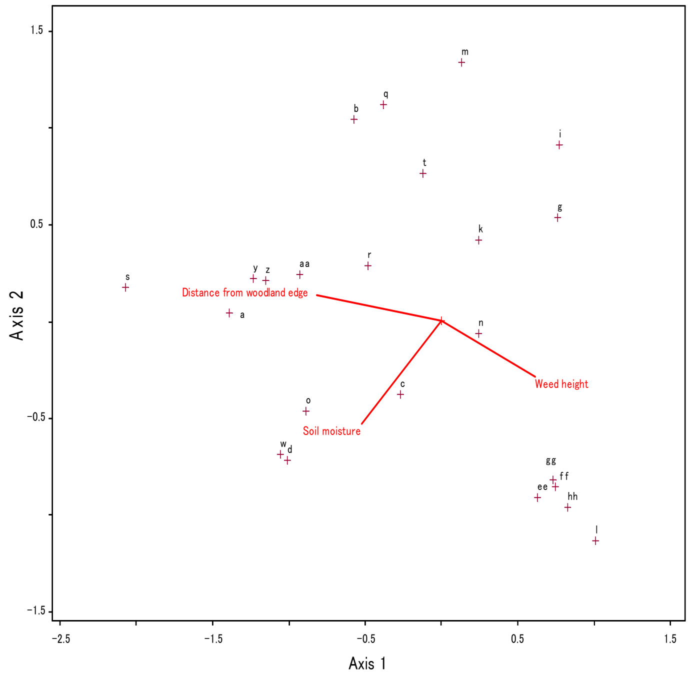

Figure 2. CCA ordination of the carabid species shown in Table 2. The biplot overlay shows vectors related to the three environmental variables. Axes are scaled by standard deviates.

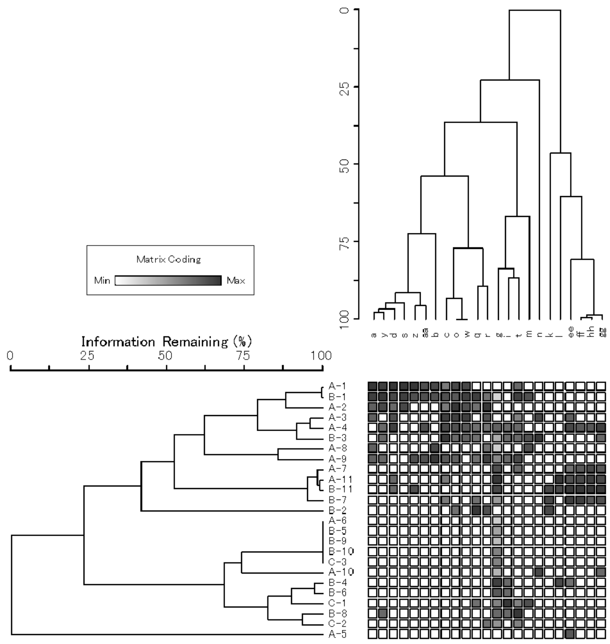

Figure 3. Two-way dendrogram of sample plots (A–C) and carabid species (a–gg). The relative abundance of each species is shown in a matrix.

Table 4. Generalized linear model (GLM) of the effects the number of *Carabus yaconinus* collected on the environmental variables.

Parameter	B	95% confidence interval Lowe	Upper	Wald chi-square	df	P
Intercept	2.389	1.978	2.800	129.65	1	0.001
Distance from woodland edge (A)	0.011	-0.002	0.024	2.75	1	0.098
Soil moisture (B)	-0.029	-0.071	0.013	1.84	1	0.175
Weed height	0.027	0.023	0.031	165.63	1	0.001
A * B	-0.002	-0.003	-0.001	8.37	1	0.004

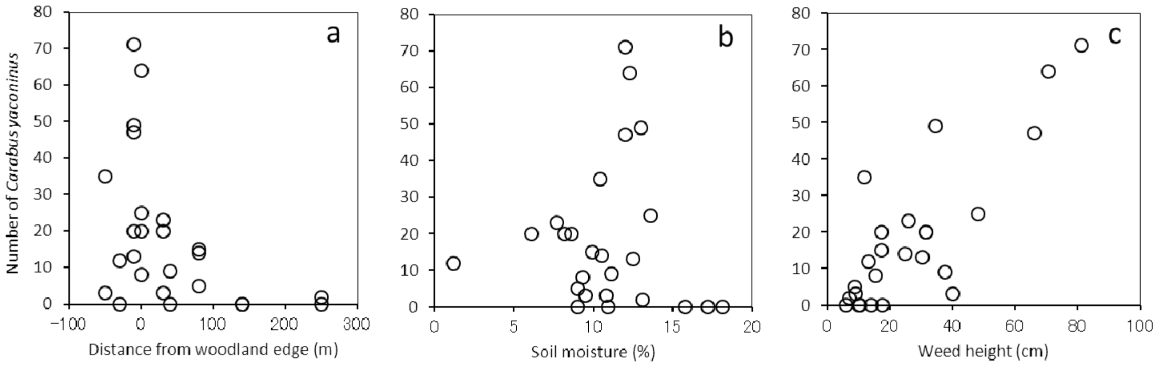

Figure 4. Scatter plots of the number of *Carabus yaconinus* collected and distance from woodland edge (a), soil moisture (b), and weed height (c).