Landscape Ecol Eng (2015) 11:227–233
DOI 10.1007/s11355-014-0254-y

REPORT

Creation of paddy levees to enhance the ecosystem service of weed seed predation by crickets

Minoru Ichihara · Kazuo Matsuno · Hidehiro Inagaki · Chieko Saiki · Shunsuke Mizumoto · Shou Yamaguchi · Masayuki Yamashita · Hitoshi Sawada

Received: 27 October 2013 / Revised: 7 February 2014 / Accepted: 9 March 2014 / Published online: 7 May 2014

Abstract The influence of ground cover plants on the ecosystem service of weed seed predation by crickets (Orthoptera: Gryllidae) was evaluated on paddy field levees in Japan in 2010 and 2011. We compared the activity density of crickets and invertebrate seed predation on *Lolium multiflorum*, a non-native grass weed, among five vegetation types grown on paddy levees: the ground covers *Eremochloa ophiuroides*, *Phyla canescens*, *Phlox subulata*, and *Zoysia japonica*, and weedy vegetation dominated by *Digitaria ciliaris*. Camera recordings showed that crickets were the predominant invertebrate seed predators. Cricket density tended to be higher on levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* [5.8–7.2 individuals/trap/day (individuals/trap/d) (2010); 5.4–7.6 individuals/trap/d (2011)] than in those with *Z. japonica* and weedy vegetation [1.0–2.2 individuals/trap/d (2010); 2.2–3.2 individuals/trap/d (2011)]. Invertebrate seed predation on levees with *Phyla canescens* and *Phlox subulata* tended to be relatively high in both years. These results suggest that *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* can increase cricket density, and that *Phyla canescens* and *Phlox subulata*, in particular, can stably enhance weed seed predation on paddy field levees.

Keywords Biological weed control · Post-dispersal seed predation · Insect seed predator · Rice paddy field · Ground cover plant

M. Ichihara (✉) · K. Matsuno · H. Inagaki · C. Saiki
Shizuoka Prefectural Research Institute of Agriculture and Forestry, 678-1 Tomigaoka, Iwata-shi, Shizuoka 438-0803, Japan
e-mail: minoru1_ichihara@pref.shizuoka.lg.jp

S. Mizumoto · S. Yamaguchi · M. Yamashita · H. Sawada
Faculty of Agriculture, Shizuoka University, 836 Ohya, Suruga-ku, Shizuoka-shi, Shizuoka 422-8529, Japan

Present Address:
H. Inagaki
Faculty of Agriculture, Shizuoka University, 836 Ohya, Suruga-ku, Shizuoka-shi, Shizuoka 422-8529, Japan

Introduction

Post-dispersal seed predation is one of the main causes of weed seed mortality, and this could contribute to biological weed control in farmlands (Zhang et al. 1997; Westerman et al. 2003a, b, 2005; Heggenstaller et al. 2006; O'Rourke et al. 2006; Ichihara et al. 2011, 2012, 2014). To maintain or enhance the ecosystem service of weed seed predation, it is important to manage the habitats for seed predators in an appropriate manner. Non-crop areas such as field margins are considered valuable habitats for seed predators, and they play an important role in supporting seed predators in farmlands (Menalled et al. 2000; Saska et al. 2007; Chauhan et al. 2010; Ichihara et al. 2014). The seed predation is possibly enhanced by developing vegetation management in non-crop areas that increase seed predators.

Although studies of the effects of non-crop area management on seed predators have increased in upland fields, mainly in Europe and the United States (Povey et al. 1993; Carmona and Landis 1999; Thomas and Marshall 1999; Lee et al. 2001; Gaines and Gratton 2010; Hof and Bright 2010; Woodcock et al. 2010), there have been no investigations into the management of paddy field margins in Asia for enhancing seed predation. In monsoon Asia, much of the farmland is occupied by paddy fields for rice cultivation. Paddy fields are surrounded by levees to retain water and are important habitats for seed predators because field interiors are flooded with irrigation water during the summer crop-growing season (Chauhan et al. 2010; Ichihara et al. 2014). The levees can act as a source of seed predators in the paddy fields after irrigation is stopped and the water recedes in the rice harvest season (Chauhan et al. 2010; Ichihara et al. 2014). To enhance the ecosystem service of seed predation in paddy areas, an appropriate system of paddy levee management must be developed to conserve the seed predators.

Crickets and carabid beetles are important seed predators in paddy areas in Japan (Ichihara et al. 2011, 2012, 2014). In particular, crickets show a greater ability to feed on seeds than that by ground beetles (Carmona et al. 1999; Lundgren and Rosentrater 2007; White et al. 2007), and large numbers of crickets inhabiting farmlands could contribute to biological weed control (Davis and Liebman 2003; Heggenstaller et al. 2006; O'Rourke et al. 2006; Ichihara et al. 2012). Ichihara et al. (2012), indicated that seed predation by *Teleogryllus emma* (Ohmachi and Matsuura), a field cricket native to Japan, can strongly suppress seedling emergence of grass weeds in environments with a high cricket density. Therefore, crickets are expected to be efficient biological control agents for weeds in paddy areas in Japan.

Grass weeds, including *Lolium multiflorum* Lam., a non-native annual plant, often invade paddy field levees and seriously affect rice production in Japan. Grass weeds are host plants for rice bugs that cause pecky rice by sucking on the developing kernels and reducing rice quality (Higuchi 2010). To reduce the occurrence of pecky rice grains, grass weeds on paddy levees must be suppressed. Crickets can contribute substantially to the depletion of grass weed seed banks (Ichihara et al. 2009, 2011, 2012), and thus invasion and infestation by these weeds could be suppressed by conserving crickets on paddy levees. Furthermore, crickets can contribute to weed suppression in paddy field interiors because they penetrate into the paddy fields after the irrigation water recedes, and consume the seeds of weeds such as *Echinochloa crus-galli* (L.) P. Beauv. var. *crus-galli*, a noxious paddy weed in Japan (Ichihara et al. 2014).

The aging of farmers has become a serious problem in Japan, and management of paddy field levees is becoming difficult, mainly in the hilly and mountainous areas where the paddy fields are often surrounded by relatively large-sized levees. Ground cover plants, including *Eremochloa ophiuroides* (Munro) Hack. (Poaceae) (Islam and Hirata 2005; Otani et al. 2007, 2009; Kawaguchi et al. 2012), *Phyla canescens* (Kunth) Greene (Verbenaceae) (Otani et al. 2007, 2009; Kawaguchi et al. 2012), *Phlox subulata* L. (Polemoniaceae) (Kawasaki et al. 1997; Tomosho 2000; Kaku et al. 2007; Otani et al. 2007), and *Zoysia japonica* Steud. (Poaceae) (Tomosho 2000; Otani et al. 2007; Fushimi and Naganuma 2009; Fushimi and Otani 2010), are useful for weed suppression, prevent soil erosion on paddy levees, and can help reduce farm work. Therefore, it is predicted that the introduction of cover plants on paddy levees will increase, mainly in the hilly and mountainous areas, and paddy levees should be managed in a manner that reconciles the delivery of ecosystem services with reduced farm work to accommodate the aging of farmers. However, the influence of cover plants on the ecosystem service of seed predation has not yet been determined. The contribution of seed predation to biological weed control might be enhanced on the levees and interiors of paddy fields if the population density of crickets is increased by cover plants. The goals of this study were to determine whether cover plants increase cricket population density and enhance predation on *L. multiflorum* seeds on paddy levees.

Materials and methods

Experimental site

Experiments were conducted in demonstration paddy fields for ground cover plants in Gotemba City, Shizuoka Prefecture, Japan (35°19′N, 138°55′E; 505 m above sea level) in 2010 and 2011. On part of the levees of three paddy fields (each field size 1600–3700 m^2), *E. ophiuroides*, *Phyla canescens*, *Phlox subulata*, and *Z. japonica* existed before the experiments began. These cover plants had been transplanted to the levees in 2008 by the local government to demonstrate and promote their practical application, and these were successfully established. All cover plants are perennials and reproduce mainly by vegetative propagation. This experimental site is appropriate for evaluating the influence of cover plants on cricket density and seed predation in working paddy fields under the same climatic and geographical conditions. These paddy fields were located within a radius of 200 m. Although it was impossible to replicate the cover plants, there are few sites similar to this in Japan, and this investigation will be a valuable case study in working paddy fields under the same environmental conditions. The activity density of crickets and invertebrate seed predation were investigated mainly in September, when many adult crickets emerge (Fig. 1) on the paddy levees with cover plants and weedy vegetation. The cricket species dominant at this experimental site are univoltine. These cricket species develop to the adult stage and oviposit from summer to autumn. The investigation period in September was before the rice harvest and after irrigation water recedes from the paddy field interiors. Rice in the

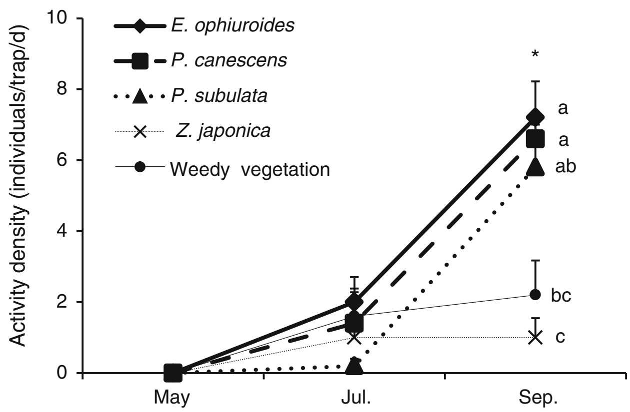

Fig. 1 Seasonal changes in the activity density of crickets in five vegetation types on paddy levees in 2010. The *asterisk* indicates a significant difference on that date ($^{*}P < 0.05$). The means that are significantly different at $P < 0.05$ based on Tukey's honestly significant difference test are identified by *different letters*. *Vertical bars* represent the standard errors of the means

paddy fields is planted in May and harvested in late September or early October.

The lengths of the levees with *E. ophiuroides*, *Phyla canescens*, *Phlox subulata*, *Z. japonica*, and weedy vegetation were 95, 65, 30, 40, and 95 m, respectively, and the width of all levees was 2 m. The levee gradient (ca. 40°) was similar among these vegetation types. The levees were mowed with a weed cutter 1–3 times during summer. Weeds on the levees with cover plants were mowed to a height above the cover plants, leaving these plants intact, whereas weeds on the levees with weedy vegetation were mowed to the soil surface. No herbicides or insecticides were applied to the levees. In September, the levee with weedy vegetation was dominated by *Digitaria ciliaris* (Retz.) Koeler and the remaining levees were respectively dominated by *E. ophiuroides*, *Phyla canescens*, *Phlox subulata*, and *Z. japonica*. During this period, the total vegetation coverage of the levee with weedy vegetation was 50–75 % in 2010 and 75–100 % in 2011, and that of the levees with cover plants was almost 100 % in both years, as estimated by a vegetation survey using the quadrat method.

Cricket density and seed predation

We first investigated seasonal changes in the activity density of crickets on the levees with each vegetation type during summer (from May 19–20, July 21–22, and September 21–22, 2010). Crickets were the most abundant in September (Fig. 1), and both cricket density and invertebrate seed predation were investigated on the levees with each vegetation type from September 21–22, 2010 and September 12–13, 2011. During these periods, many crickets were in their adult stage. The activity density of crickets and invertebrate seed predation were investigated using adhesive traps (cockroach traps: 10 cm × 16 cm; Earth Chemical Co., Ltd., Tokyo, Japan) and seed cards (Westerman et al. 2003a, b), respectively. Each experimental period was determined as 1 day based on the preliminary experiment, which indicated that cricket density and seed predation were very high at this experimental site, particularly in September. The adhesive traps and seed cards were placed from 14:00 on the first day to 10:00 the next day, because the crickets were observed to feed on seeds mainly at night (Ichihara, unpublished data).

The seed cards were prepared using sand cloth (6 cm × 7 cm; grain size 60; Bell Star Abrasive Mfg. Co., Ltd., Nara, Japan) sprayed with repositionable glue (Spray Adhesive 55; Sumitomo 3 M Limited, Tokyo, Japan), to which 50 seeds of *L. multiflorum* were applied. The same number of seeds was used on the seed cards placed on the levees with each vegetation type to determine the relative difference in seed predation intensity among the vegetation types. It is known that crickets readily consume the seeds of *L. multiflorum* (Ichihara et al. 2011, 2012, 2014), and the relative difference in seed predation intensity among the vegetation types can be appropriately evaluated by using the seeds of this weed species. The remaining glue on the seed cards was covered using fine sand. To estimate the proportion of seed predation by invertebrates, including crickets, we used exclosures to prevent vertebrate seed predators, such as birds and rodents, from accessing the seeds. An area with a radius of 10 cm around each seed card was surrounded using metal wire mesh (size 2.6 cm^2, height 10 cm), and the upper part of the mesh was covered using a plastic sieve (mesh size 0.03 cm^2). The adhesive traps and seed cards were placed alternately in a line at least 0.5 m away from the field edge (five cards and five traps per vegetation type). Each adhesive trap and seed card were at least 1 m apart.

A control seed card was placed on the levees with *Phlox subulata* and weedy vegetation during both the years to assess seed loss by rain, wind, or loss of adhesive power. Each card was placed at the bottom of a cubic cage (side length 15 cm) of metal wire mesh (mesh size 0.25 cm^2), and the cage was supported at approximately 10 cm above the ground by four metal poles (Ichihara et al. 2011). The upper part of each pole was lined using double-sided adhesive tape to keep seed predators out of the cage.

Identification of seed predators using digital time-lapse cameras

A digital time-lapse camera (GardenWatchCam; Brinno Incorporated, Palm City, FL, USA) was set up above one seed card in each vegetation type throughout each experimental period to identify the invertebrate seed predators. The image-acquisition interval was set to 10 s. An 8-cm-diameter hole was cut in the upper part of the sieve covering the seed card under each camera so that photographs of the seed predators could be taken through the sieve. To allow nighttime photography, each camera was set for low-light recording and the seed card under each camera was illuminated using constant red light, by using a red cellophane filter and a light-emitting diode (LED) flashlight (BF-158BF-W; Panasonic Corporation, Osaka, Japan).

Data analysis

The number of seeds remaining on the seed cards was converted into the proportion of seed predation relative to the number of seeds remaining on the control cards using Abbott's correction formula $M = (C - R)/C$, where M is the proportion of seed predation, R is the number of seeds remaining on the cards for each treatment, and C is the number of seeds remaining on the control cards (Abbott 1925). The captured crickets were identified to the species level, and the number of individuals was recorded.

The differences in seed predation and number of captured crickets among treatments were tested using Tukey's honestly significant difference test for multiple comparisons using R (R Development Core Team 2008). Five seed cards and five traps in each treatment were used as pseudoreplicates for the statistical analysis, because it was impossible to replicate the vegetation types in the working paddy fields. Pseudoreplication is an approach often used to overcome the lack of exact replication in on-farm studies (Blanco-Canqui and Lal 2008). Arcsine transformation and log transformation were used to normalize the percentage data and count data, respectively, before performing statistical analyses.

Results

The abundance of crickets increased with time and was greatest in September (Fig. 1). Seven cricket species were recorded (Fig. 2). *T. emma* (Ohmachi and Matsuura) (body length 29.6–34.4 mm); *Velarifictorus micado* (Saussure) (body length 15.5–16.2 mm); *Mitius minor* (Shiraki) (body length 11.6–12.2 mm); *Loxoblemmus* sp., including *L. campestris* (Matsuura) (body length 12.4–14.9 mm); *Dianemobius nigrofasciatus* (Matsumura) (body length 6.2–7.7 mm); *Polionemobius mikado* (Shiraki) (body length 6.1–6.6 mm); and *Pteronemobius ohmachii* (Shiraki) (body length 6.2–9.0 mm) were captured. In September 2010, the activity density of crickets was higher on

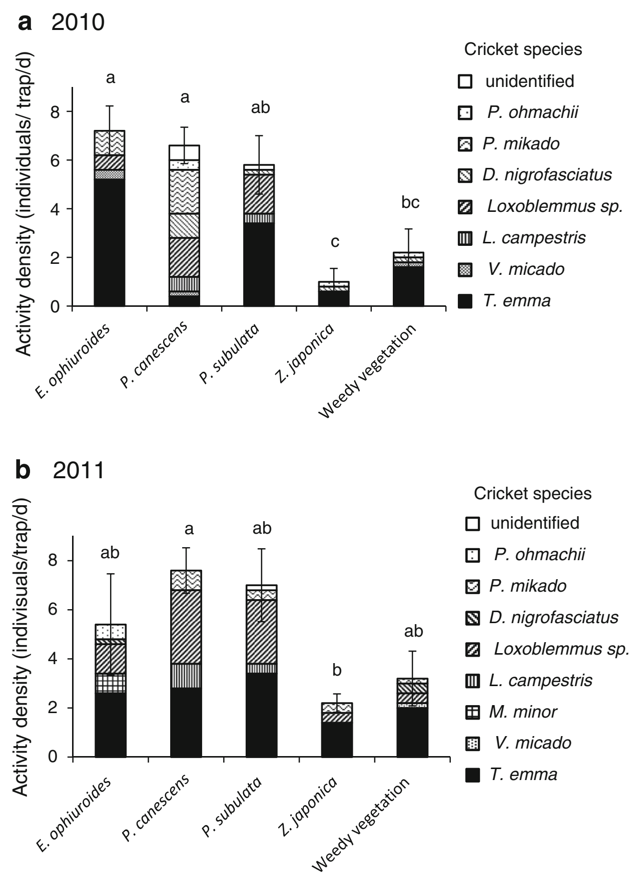

Fig. 2 Activity density of crickets in five vegetation types on paddy levees in September **a** 2010 and **b** 2011. The means that are significantly different at $P < 0.05$ based on Tukey's honestly significant difference test are identified by *different letters*. *Vertical bars* represent the standard errors of the means

the levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* [5.8–7.2 individuals/trap/day (individuals/trap/d)] than on the levee with weedy vegetation (2.2 individuals/trap/d) (Fig. 2a). In addition, in September 2011, the activity density tended to be higher on the levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* (5.4–7.6 individuals/trap/d) than on the levee with weedy vegetation (3.2 individuals/trap/d), although the differences were not significant (Fig. 2b). On the levee with *Z. japonica*, the activity density was the lowest (1.0–2.2 individuals/trap/d) in both the years.

Invertebrate seed predation on the levees varied between the years (Fig. 3). The proportion of seed predation on the levees with *Phyla canescens* and *Phlox subulata* tended to be relatively high in both the years, while that on the levees with *Z. japonica* and weedy vegetation was extremely low in 2010. Camera recordings showed that crickets such as *T. emma* were the predominant invertebrate seed predators on the levees (Fig. 4). Seed predation by invertebrates other than crickets was not observed.

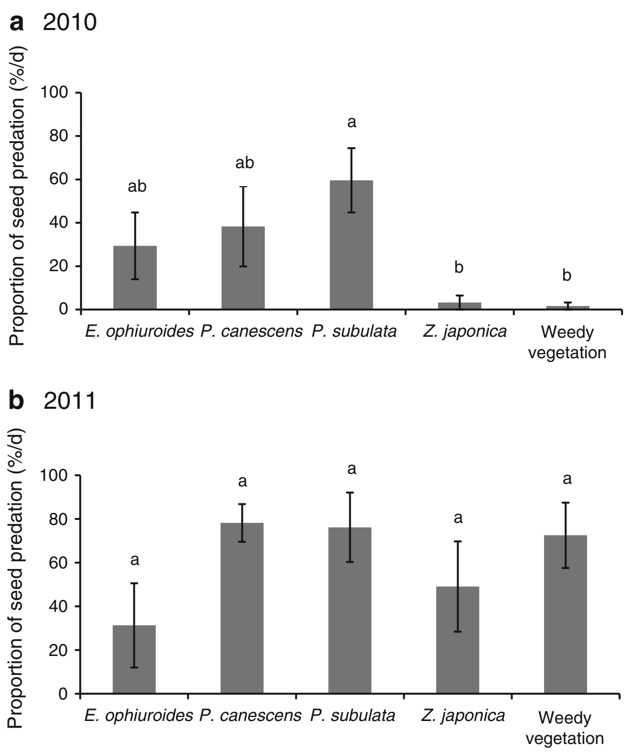

Fig. 3 Proportion of seed predation by invertebrates in five vegetation types on paddy levees in September **a** 2010 and **b** 2011. The means that are significantly different at $P < 0.05$ based on Tukey's honestly significant difference test are identified by *different letters*. *Vertical bars* represent the standard errors of the means

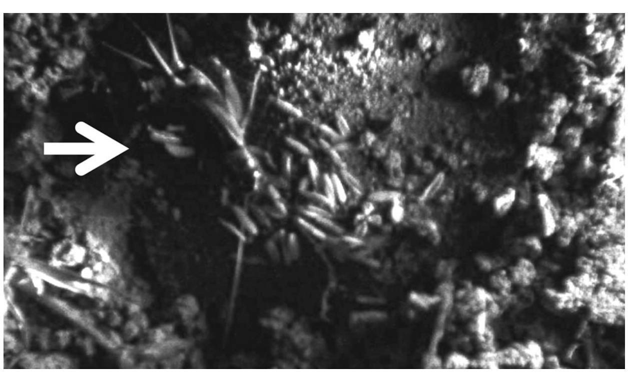

Fig. 4 *Teleogryllus emma* feeding on the seeds of *Lolium multiflorum*

Discussion

This study indicated the influence of ground cover plants on the ecosystem service of weed seed predation by crickets on the levees of working paddy fields. Crickets were the predominant invertebrate seed predators on the paddy levees in Japan, and tended to be abundant on the levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* (Figs. 1, 2). Therefore, the levees with these cover plants are considered suitable habitats for crickets. In addition, on the levees with *Phyla canescens* and *Phlox subulata*, in particular, seed predation tended to be relatively high in both the years (Fig. 3). These results suggest that *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* can increase the abundance of crickets, and in particular, *Phyla canescens* and *Phlox subulata* can stably enhance weed seed predation on paddy field levees.

In grassland, seedling emergence is considered to be reduced by the combined effect of ground cover and seed predation (Reader 1993). Although *Phyla canescens* and *Phlox subulata* reportedly suppress the seedling emergence of other plants through shading (Kawasaki et al. 1997; Eom et al. 2005; Otani et al. 2007) and allelopathy (Shiraishi et al. 2002; Daley et al. 2005), seed predation by crickets may also be an important factor for controlling seedling emergence on paddy levees with these cover plants in Japan. Seed predation by crickets can strongly suppress weed seedling emergence in environments with a high density of crickets (Ichihara et al. 2012). Ichihara et al. (2012) indicated that *L. multiflorum* seedling emergence decreased with an increase in the density of *T. emma*. Furthermore, the crickets may contribute to the suppression of weed invasion (Ichihara et al. 2012). Crickets are omnivores, feeding on insects (Monteith 1971; Barney et al. 1979; Bechinski et al. 1983; Burgess and Hinks 1987) and the seeds of various plant species (Carmona et al. 1999; Lundgren and Rosentrater 2007; White et al. 2007). Crickets may be sustained by alternative prey if weed seeds are unavailable, and can thus effectively suppress the invasion of weeds. Therefore, crickets can function as biological control agents to suppress the invasion and emergence of weeds on paddy levees, particularly those with *Phyla canescens* and *Phlox subulata*.

The abundance of crickets might have increased on the levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* for the following two reasons. First, the entire surface of the levees was covered by these perennial plants throughout the year. The total vegetation coverage of these levees was almost 100 %. Crickets are thought to preferentially inhabit areas covered by dense vegetation. Davis and Liebman (2003) reported that the activity density of *Gryllus pennsylvanicus* Burmeister, a field cricket widely distributed in North America, and seed predation were higher in plots of wheat underseeded with red clover (*Trifolium pratense* L.) than those in plots with wheat as the sole crop. Second, the crickets can hide and move freely in spaces among the leaves and stems of *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata*, and the soil surface. We observed many crickets inhabiting these spaces, which might provide them with a means by which to escape from predators. Meanwhile, on the levee with *Z. japonica*, cricket density tended to be lower than that on the levees with *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* despite the same vegetation coverage. This might be because it is difficult for the crickets to hide in the vegetation of *Z. japonica*, where there are few spaces among the stems and soil surface.

Cricket density tended to be relatively low on the levees with *Z. japonica* and weedy vegetation in both 2010 and 2011, whereas seed predation on these levees varied between years. Although the reason is unknown, the abundance of alternative prey might influence seed predation on the levees. It is necessary to investigate in detail the factors that influence the relationship between the abundance of crickets and seed predation in future studies.

In Japan, it is predicted that the introduction of ground cover plants on paddy levees will increase, mainly in hilly and mountainous areas. The use of *E. ophiuroides*, *Phyla canescens*, and *Phlox subulata* on paddy levees might increase the abundance of crickets. Furthermore, these plantings might also enhance seed predation in paddy field interiors because the levees can serve as a source of cricket populations for field colonization (Ichihara et al. 2014). Therefore, the use of these cover plants on paddy levees might contribute to the enhancement of the ecosystem service of weed seed predation.

Paddy levees planted with cover plants provide various ecosystem services, including weed suppression, esthetic values, and weed seed predation. *Phyla canescens* is known to be visited by many pollinators, such as honeybees (Gross et al. 2010), and can thus enhance the ecosystem service of pollination on farmlands. In future studies, the trade-offs and synergies among these services must be evaluated. In addition, most cover plants used in Japan are non-native species, and future studies must assess their ecological impacts, as well as consider the feasibility of using native plant species as cover plants.

Acknowledgments We gratefully acknowledge Civil Engineering and Eco-Technology Consultants Co., Ltd., and SEIKAN Co., Ltd., for identifying the crickets. Further, we thank the farmers who allowed us to use their fields for this study. The experiments comply with the current laws of the country in which they were performed. There are no ethical problems for this study or conflicts of interest regarding this manuscript.

References

Abbott WS (1925) A method of computing the effectiveness of an insecticide. Econ Entomol 18:265–267

Barney RJ, Roberts SJ, Pausch RD, Armbrust EJ (1979) Insect predators of the alfalfa weevil and clover root curculio (Coleoptera: Curculionidae) during fall field reentry. Gt Lakes Entomol 12:153–155

Bechinski EJ, Bechinski JF, Pedigo LP (1983) Survivorship of experimental green cloverworm (Lepidoptera: Noctuidae) pupal cohorts in soybeans. Environ Entomol 12:662–668

Blanco-Canqui H, Lal R (2008) No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72:693–701

Burgess L, Hinks CF (1987) Predation on adults of the crucifer flea beetle, *Phyllotreta cruciferae* (Goeze), by the northern fall field cricket, *Gryllus pennsylvanicus* Burmeister (Orthoptera: Gryllidae). Can Entomol 119:495–496

Carmona DM, Landis DA (1999) Influence of refuge habitats and cover crops on seasonal activity-density of ground beetles (Coleoptera: Carabidae) in field crops. Environ Entomol 28:1145–1153

Carmona DM, Menalled FD, Landis DA (1999) *Gryllus pennsylvanicus* (Orthoptera: Gryllidae): laboratory weed seed predation and within field activity-density. J Econ Entomol 92:825–829

Chauhan BS, Migo T, Westerman PR, Johnson DE (2010) Post-dispersal predation of weed seeds in rice fields. Weed Res 50:553–560

Daley AT, Tan DKY, Wu H (2005) Phytotoxic effects of lippia (*Phyla canescens*) on germinating seeds. In: Proc 4th World Congress on Allelopathy, pp 233–236

Davis AS, Liebman M (2003) Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. green manure and tillage timing. Weed Sci 51:919–929

Eom SH, Senesac AF, Tsontakis-Bradley I, Weston LA (2005) Evaluation of herbaceous perennials as weed suppressive groundcovers for use along roadsides or in landscapes. J Environ Hort 23:198–203

Fushimi A, Naganuma K (2009) Ground cover ability of *Zoysia japonica* in a new levee and introduction of double net planting method. J Agric Sci 64:165–168 (in Japanese)

Fushimi A, Otani I (2010) Vegetation analysis of *Zoysia japonica* Steud. establishment on a new, rural levee. Jpn J Grassl Sci 56:126–130 (in Japanese with English summary)

Gaines HR, Gratton C (2010) Seed predation increases with ground beetle diversity in a Wisconsin (USA) potato agroecosystem. Agric Ecosyst Environ 137:329–336

Gross CL, Gorrell L, MacDonald MJ, Fatemi M (2010) Honeybees facilitate the invasion of *Phyla canescens* (Verbenaceae) in Australia—no bees, no seed! Weed Res 50:364–372

Heggenstaller AH, Menalled FD, Liebman M, Westerman PR (2006) Seasonal patterns in post-dispersal seed predation of *Abutilon theophrasti* and *Setaria faberi* in three cropping systems. J Appl Ecol 43:999–1010

Higuchi H (2010) Ecology and management of rice bugs causing pecky rice. Jpn J Appl Entomol Zool 54:171–188 (in Japanese)

Hof AR, Bright PW (2010) The impact of grassy field margins on macro-invertebrate abundance in adjacent arable fields. Agric Ecosyst Environ 139:280–283

Ichihara M, Yamashita M, Sawada H, Kida Y, Asai M (2009) Influence of after-ripening environments on the germination characteristics and seed fate of Italian ryegrass (*Lolium multiflorum*). Weed Biol Manag 9:217–224

Ichihara M, Maruyama K, Yamashita M, Sawada H, Inagaki H, Ishida Y, Asai M (2011) Quantifying the ecosystem service of non-native weed seed predation provided by invertebrates and vertebrates in upland wheat fields converted from paddy fields. Agric Ecosyst Environ 140:191–198

Ichihara M, Inagaki H, Matsuno K, Saiki C, Yamashita M, Sawada H (2012) Postdispersal seed predation by *Teleogryllus emma* (Orthoptera: Gryllidae) reduces the seedling emergence of a non-native grass weed, Italian ryegrass (*Lolium multiflorum* Lam.). Weed Biol Manage 12:131–135

Ichihara M, Inagaki H, Matsuno K, Saiki C, Mizumoto S, Yamaguchi S, Yamashita M, Sawada H (2014) Postdispersal weed seed predation by crickets in a rice paddy field after irrigation water recedes. JARQ 48:63–69

Islam MA, Hirata M (2005) Centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.): growth behavior and multipurpose usages. Grassl Sci 51:183–190

Kaku T, Ito M, Ito K (2007) Weed management issues and dynamics during establishment of Phlox (*Phlox Subulata* L.) ground cover using geotextile mulch. J Weed Sci Technol 52:57–65 (in Japanese with English summary)

Kawaguchi Y, Inoue T, Oki Y (2012) The present state of weed emergence on levees planted with centipedegrass and lippia in Shiga Prefecture. J Weed Sci Technol 57:9–13 (in Japanese)

Kawasaki T, Sugiyama E, Kawauchi H, Sato K (1997) Light condition and weed development on the ground covering with vegetation. J Agric Eng Soc Jpn 65:165–170 (in Japanese)

Lee JC, Menalled FD, Landis DA (2001) Refuge habitats modify impact of insecticide disturbance on carabid beetle communities. J Appl Ecol 38:472–483

Lundgren JG, Rosentrater KA (2007) The strength of seeds and their destruction by granivorous insects. Arthropod Plant Interact 1:93–99

Menalled FD, Marino PC, Renner KA, Landis DA (2000) Post-dispersal weed seed predation in Michigan crop fields as a function of agricultural landscape structure. Agric Ecosyst Environ 77:193–202

Monteith LG (1971) Crickets as predators of the apple maggot, *Rhagoletis pomonella* (Diptera: Tephritidae). Can Entomol 103:52–58

O'Rourke ME, Heggenstaller AH, Liebman M, Rice ME (2006) Post-dispersal weed seed predation by invertebrates in conventional and low-external-input crop rotation systems. Agric Ecosyst Environ 116:280–288

Otani I, Watanabe O, Fushimi A (2007) Effect of slope aspects on the growth of ground cover plants and their soil conservation abilities. Bull Natl Agric Res Cent West Reg 6:39–53 (in Japanese with English summary)

Otani I, Watanabe O, Fushimi A (2009) Effect of mulching of plant materials on the growth of ground cover plants and emergence of weeds on levee slope. J Weed Sci Technol 54:129–138 (in Japanese with English summary)

Povey FD, Smith H, Watt TA (1993) Predation of annual grass weed seeds in arable field margins. Ann Appl Biol 122:323–328

R Development Core Team (2008) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.r-project.org

Reader RJ (1993) Control of seedling emergence by ground cover and seed predation in relation to seed size for some old-field species. J Ecol 81:169–175

Saska P, Vodde M, Heijerman T, Westerman P, van der Werf W (2007) The significance of a grassy field boundary for the spatial distribution of carabids within two cereal fields. Agric Ecosyst Environ 122:427–434

Shiraishi S, Watanabe I, Kuno K, Fujii Y (2002) Allelopathic activity of leaching from dry leaves and exudate from roots of ground cover plants assayed on agar. Weed Biol Manage 2:133–142

Thomas CFG, Marshall EJP (1999) Arthropod abundance and diversity in differently vegetated margins of arable fields. Agric Ecosyst Environ 72:131–144

Tomosho T (2000) Ground cover plants. J Rural Plan Assoc 18:320 (in Japanese)

Westerman PR, Wes JS, Kropff MJ, van der Werf W (2003a) Annual losses of weed seeds due to predation in organic cereal fields. J Appl Ecol 40:824–836

Westerman PR, Hofman A, Vet LEM, van der Werf W (2003b) Relative importance of vertebrates and invertebrates in epigaeic weed seed predation in organic cereal fields. Agric Ecosyst Environ 95:417–425

Westerman PR, Liebman M, Menalled FD, Heggenstaller AH, Hartzler RG, Dixon PM (2005) Are many little hammers effective? Velvetleaf (*Abutilon theophrasti*) population dynamics in two- and four-year crop rotation systems. Weed Sci 53:382–392

White SS, Renner KA, Menalled FD, Landis DA (2007) Feeding preferences of weed seed predators and effect on weed emergence. Weed Sci 55:606–612

Woodcock BA, Redhead J, Vanbergen AJ, Hulmes L, Hulmes S, Peyton J, Nowakowski M, Pywell RF, Heard MS (2010) Impact of habitat type and landscape structure on biomass, species richness and functional diversity of ground beetles. Agric Ecosyst Environ 139:181–186

Zhang J, Drummond FA, Liebman M, Hartke A (1997) Insect predation of seeds and plant population dynamics. MAFES Tech Bull 163:5–32