

# Impact of predatory carabids on below- and above-ground pests and yield in strawberry

Jana C. Lee · David L. Edwards

Received: 23 June 2011 / Accepted: 10 November 2011  
© International Organization for Biological Control (outside the USA) 2011

**Abstract** The impact of adult carabid beetles on below- and above-ground pests and fruit yield was examined in the laboratory and a two-year strawberry field study. In the laboratory, adults of *Carabus nemoralis* Muller, *Nebria brevicollis* (F.), *Pterostichus algidus* LeConte, *Pterostichus melanarius* (Illiger), and *Scaphinotus marginatus* Fischer (Coleoptera: Carabidae) consumed black vine weevil, *Otiorhynchus sulcatus* (F.) (Coleoptera: Curculionidae) eggs, larvae and/or pupae placed on the surface. The same five carabid species showed no impact or low removal rates of *O. sulcatus* larvae that had burrowed into the root of potted strawberry plants. In an assay with only *P. melanarius*, adults consumed *O. sulcatus* larvae placed on the soil surface more frequently than larvae buried 1.3 or 5 cm below. In a field study, the density of adult carabids, predominantly *P. melanarius*, was manipulated with augmented, exclusion, and open control plots (2 × 2 m). Manipulating carabid density had no impact on the removal of sentinel *O. sulcatus* larvae and pupae that were buried belowground which is consistent with laboratory observations. Increasing carabid density within augmented plots led to greater removal of red clover seeds, *Trifolium pratense* L.,

placed on the soil surface in the first year. Decreasing carabid density within exclusion plots resulted in fewer marketable fruits compared to control plots in both years. These results suggest that certain adult carabids may have limited impact belowground, and some beneficial impacts above-ground with pest control and crop protection.

**Keywords** Carabidae · Density-manipulation plots · *Otiorhynchus sulcatus* · *Pterostichus melanarius* · Weed seed predation

## Introduction

Carabid beetles are common polyphagous predators, and a review of 241 species of adult carabids from 110 studies reveals that pest Lepidoptera were killed by 43% of carabid species, Diptera by 20%, Coleoptera by 12% and Homoptera by 12% of species examined (Sunderland 2002). Also, ten genera of carabids are known seed predators in North America (Tooley and Brust 2002). Adult carabids frequently burrow beneath the soil during parts of the day and could potentially suppress pests belowground. While a wealth of studies exist on carabid predation, fewer studies have focused on belowground predation by adult carabids. Numerous predation studies of dipteran and coleopteran pests focus on the egg or larval pest stages that occur on the soil surface or above, or the

---

Handling Editor: Patrick De Clercq

---

J. C. Lee (✉) · D. L. Edwards  
USDA ARS, Horticultural Crops Research Laboratory,  
3420 NW Orchard Avenue, Corvallis, OR 97330, USA  
e-mail: jana.lee@ars.usda.gov

removal of sentinel pests placed on the surface (Sunderland 2002).

Potential evidence of belowground predation by carabid adults includes studies that use belowground sentinel prey, predator gut content analysis, or manipulating predator densities. Two carabid species have been shown to substantially remove sentinel weed seeds buried 0.5 or 1.0 cm below in greenhouse experiments (White et al. 2007). DNA analysis of adult carabids collected from citrus orchards (Monzó et al. 2011), and immuno-analysis of carabids from wheat fields (Floate et al. 1990) indicated that carabids were consuming a fruit fly and midge pest, respectively. When carabids were excluded from oilseed rape plots, the number of emerging adult weevils from the soil was higher than from plots accessible to carabids (Zaller et al. 2009). Conversely, when carabids were augmented to plots, the number of emerging adult pollen beetles from the soil was marginally reduced (Zaller et al. 2009). It is important to consider that the examples cited (Floate et al. 1990, Zaller et al. 2009, Monzó et al. 2011) may also reflect carabids encountering pest larvae at the soil surface as the pest moves from the plant into the soil to pupate.

Strawberries are a high-value crop grown worldwide in temperate areas, and plagued by aphids, mites, root weevils, slugs and weeds. A review of biological control in strawberries describes carabids contributing to vine weevil and slug control (Cross et al. 2001). Root weevils including black vine weevil, *Otiorhynchus sulcatus* (F.) (Coleoptera: Curculionidae), are very damaging because the larval stage feeds on strawberry roots and diminishes plant growth. Management of weevils in strawberries often relies on chemical treatments with limited biological control options (DeFrancesco et al. 2002). Trench barriers have shown to protect strawberries from immigrating weevils but can also stop the immigration of beneficial carabids and can be costly to implement (Bomford and Vernon 2005).

The effectiveness of carabids in controlling *O. sulcatus* requires further study. Carabids of unknown species were described to consume *O. sulcatus* eggs and larvae in the laboratory (Evenhuis 1983; Garth and Shanks 1978). Evidence of *O. sulcatus* predation in the field was anecdotal. Insecticide-treated plots had more *O. sulcatus* and fewer carabids suggesting that the lack of carabids and predation activity led to higher pest abundance (Evenhuis 1982). The objectives of this

study were: (1) to confirm predation of adult carabids on *O. sulcatus* in the laboratory, and (2) to evaluate the impacts carabid adults have on belowground *O. sulcatus* larvae and pupae, above-ground weed seeds, and fruit harvest in strawberry fields. Red clover, *Trifolium pratense* L., is a common perennial weed and the seeds were used in this study because they might be encountered by carabids foraging in strawberry fields in the Pacific Northwest.

## Methods

### Laboratory experiments

Potential predation was monitored in a simple arena using field-collected carabids of five species: *Carabus nemoralis* Muller, *Nebria brevicollis* (F.), *Pterostichus algidus* LeConte, *Pterostichus melanarius* (Illiger), and *Scaphinotus marginatus* Fischer (Coleoptera: Carabidae). Individual carabids were starved with water for 24 h and given either 50 *O. sulcatus* eggs on wet filter paper in a 14 cm diameter Petri dish, or ten *O. sulcatus* 5th instar larvae or five pupae placed on top of 4 mm of moistened sieved loam in a 0.59 l plastic container. All carabid species were tested for consumption of *O. sulcatus* larvae, but only some species for consumption of eggs and pupae depending on availability. The number of prey consumed was checked after 24 h. In a second study, predation of *O. sulcatus* larvae by adult carabids of the same five species was monitored in infested potted strawberry plants. A strawberry plant in a 3.8 l pot was inoculated with ten *O. sulcatus* fourth-instar larvae one week prior to experimentation. This allowed pest larvae to burrow, feed, and establish before introduction of carabids. One adult carabid or none (control) was placed per strawberry plant and prevented from escape by enclosing the upper part of the pot in a 30 × 30 × 30 cm Bug Dorm (BioQuip, Rancho Dominguez, California, USA). After one week of exposure, the soil from the strawberry plants was removed to count the number of surviving *O. sulcatus* larvae. A t-test with the control determined whether each carabid species significantly reduced the proportion of *O. sulcatus* larvae recovered from the pot (arcsine-transformed). In a third study, only *P. melanarius* were used due to availability. Starved adults were placed separately into 2.4 l containers with 7.6 cm of

loam, and five *O. sulcatus* 4–5th instar larvae that were: (1) placed on the surface, (2) buried 1.3 cm below, or (3) 5 cm below. Larvae were counted after 24 h. A Pearson's  $\chi^2$  analysis tested for the effect of depth on the presence or absence of predation, and an ANOVA tested the effect of depth on the proportion of larvae consumed (arcsine-transformed).

### Field experiments

A 0.134 and 0.036 ha field of 'Hood' strawberries were planted on 12–13 May 2008. No insecticides were used in the fields, but manual weeding and herbicide applications of Poast (sethoxydim), Roundup (glyphosate), Stinger (clopyralid), Spartan 4F (sulfentrazone), and Aim (carfentrazone) were done in 2008–2009. To determine the role of carabids in weevil control, carbid densities were manipulated in small enclosed 'augmented' and 'exclusion' plots, and unenclosed control plots. Barriers used to manipulate predator densities provide an effective test of whether carabids can have an impact on pest levels (Menalled et al. 1999; Sunderland 2002). Plots were 2 × 2 m in size containing two rows with ~14 plants, plants in and outside the control plots overlapped at the border. Plots were arranged in four blocks, and set at least 8.3 m apart from each other. Plots were enclosed with 1.5 mm thick plastic HDPE black bamboo barrier (Bamboo Garden, North Plains, Oregon, USA) set 10 cm below- and 28 cm above-ground. Exclusion plots had beetles continuously removed via pitfall trapping. About 400 *P. melanarius* were added to each augmented plot between 14 July and 22 September in 2008, and 243 *P. melanarius* and 40 *N. brevicollis* were added to augmented plots between 20 May and 21 September in 2009. These species were used because they were caught in substantial numbers: *P. melanarius* comprised 96.8% and 79.2% of total captures in 2008 and 2009, respectively, and *N. brevicollis* comprised 14% of total captures in 2009. To monitor naturally-occurring activity within the same fields, control plots were of the same dimensions without enclosures. To monitor carbid activity density in plots, one live pitfall trap consisting of a 946 ml dry plastic cup was placed in the center of each plot. Pitfall traps were opened on Monday and closed Thursday morning, and checked daily for three consecutive days each week. Each morning carabids were identified to species and re-released into the

same augmented and control plots, and removed from exclusion plots. Trapping occurred from 14 July to 30 October in 2008, and from 7 May to 1 October in 2009, and then every other week 12–29 October in 2009.

After manipulating carbid densities, predation was monitored with sentinel *O. sulcatus* larvae and pupae, and red clover seeds, *T. pratense*. For larval predation, two strawberry plants were randomly selected per plot for infestation. Ten lab-reared 5th instar *O. sulcatus* were inoculated per plant. After 20–28 days, inoculated plants were dug up and carefully screened for surviving larvae. Surviving larvae were expected to remain in the larval stage because the 5th instar develops for 119–115 days, and the 6th instar develops for 130–211 days before pupating (La Lone and Clarke 1981). New replacement strawberry plants were immediately transplanted into plots. Larval predation tests were conducted when larger *O. sulcatus* larvae would be expected in the field: 18 July–15 August, 21 August–17 September, 1–23 October in 2008, 28 July–17 August, 19 August–8 September, and 17 September–7 October in 2009. For pupal predation, seven lab-reared *O. sulcatus* pupae were buried 2 cm belowground near strawberry plants in both rows. After two–three days, burial sites were dug up. Pupal predation tests were conducted on 20–22 May, 27–29 May and 3–5 June in 2009. For weed seed predation, two seed feeding stations were set up per plot. At each station, 50 *T. pratense* seeds were placed on a 11 × 14 cm scouring pad level with the soil surface. Placement of seeds on the scouring pad prevented seed loss during handling and minor disturbances, seed loss was less than 1% using scouring pads in total exclusion cages in Menalled et al. (1999). A 25 × 16 × 5 cm plastic container with large vents on the side was set over each station, with binder clips raising it 2 cm above-ground. The cover allowed carabids access to the station, but protected it from birds, rodents and rain. After three–seven days, seeds from feeding stations were counted. Weed seed predation tests were conducted on 26–29 August, 5–8 September, 8–12 September, 15–22 September in 2008 and 21–23 July, 17–20 August, 31 August–4 September, 17–21 September in 2009.

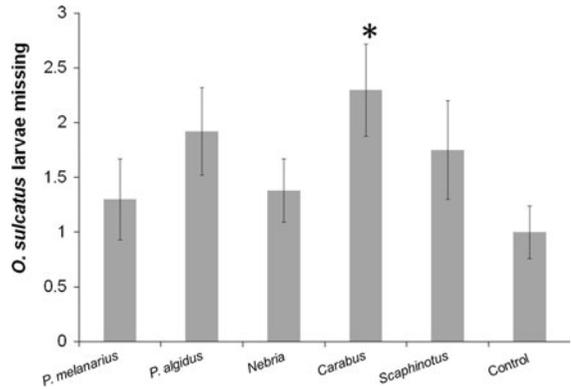
Lastly, the impact of carabids on yield was monitored by collecting strawberries during harvest 8–14 July 2008, and 29 May–16 June 2009. Undamaged strawberries considered marketable were counted and weighed.

Carabid pitfall captures, *O. sulcatus* larval removal, *O. sulcatus* pupal removal, weed seed removal, and strawberry yield were compared between treatments. A repeated measures ANOVA included the effect of treatment, block (random effect), week or month, year (if applicable), and interaction terms, each plot was the subject where samples were repeatedly taken. Week was a continuous variable in the model because sampling sometimes occurred on different weeks of the year. The capture of all carabid species was analyzed together rather than separately by species because one or two species comprised 96.8% and 93.2% of total captures in 2008 and 2009, respectively. Prior to analyses, the proportion of *O. sulcatus* larvae and weed seeds removed were also standardized on a per day basis. Also, carabid pitfall counts were log-transformed, and proportional data on prey removal were arcsine-transformed to homogenize the variances. A Tukey HSD was used to compare means if treatment effects were significant. All analyses were conducted in JMP®7 (SAS 2007).

**Results**

Laboratory studies

In the first laboratory study, adult carabids consumed *O. sulcatus* at the egg, larval and pupal stages (not all stages were tested with each species). *Carabus nemoralis* ate  $1.6 \pm 0.4$  (mean  $\pm$  SE) larvae and  $4.0 \pm 1.0$  pupae, *N. brevicollis* ate  $27.7 \pm 4.6$  eggs,  $2.1 \pm 0.4$  larvae and  $2.1 \pm 0.5$  pupae, *P. algidus* ate  $37.8 \pm 3.6$  eggs,  $3.2 \pm 0.6$  larvae and  $2.8 \pm 0.9$  pupae, *P. melanarius* ate  $33.5 \pm 15.5$  eggs and  $1.9 \pm 0.3$  larvae, and *S. marginatus* ate  $0.7 \pm 0.2$  larvae ( $n = 12, 2, 3, 12, 9, 17, 11, 2, 18,$  and  $9$ , respectively). In the second study when adult carabids were tested in potted strawberry plant arenas, *C. nemoralis* appeared to remove *O. sulcatus* larvae when compared to the control treatment with the removal of 1.3 *O. sulcatus* larvae in one week (Fig. 1). Adults of *P. melanarius*, *N. brevicollis*, and *S. marginatus* showed no significant difference, and *P. algidus* showed a marginal difference from the control ( $P = 0.087$ ) (Fig. 1). In the third study, when prey was placed at different soil depths, 85% of *P. melanarius* tested had consumed *O. sulcatus* larvae at the soil surface which was more frequent than the 43% that consumed larvae



**Fig. 1** Mean number ( $\pm$ SE) of *O. sulcatus* larvae missing from the potted strawberry plant after exposure to one adult carabid for one week or no carabid (control),  $n = 10, 12, 14, 10, 8,$  and  $16$ , respectively. Asterisk denotes significant difference from the control using a *t*-test

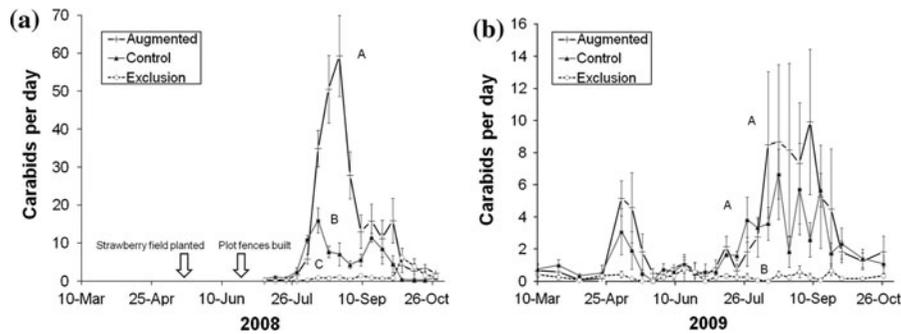
buried 1.3 cm, and 18% that consumed larvae buried 5 cm below (Table 1). Also in the third study, *P. melanarius* consumed a greater number of *O. sulcatus* larvae at the surface than 1.3 and 5 cm below (Table 1).

Field studies—predation and strawberry yield

Pitfall trapping confirmed that different activity-densities were created in the treatment plots. In 2008, significantly more adult carabids were captured in augmented plots compared to control plots, and in control plots compared to exclusion plots (Fig. 2a). In 2009, significantly more carabids were captured in augmented and control plots compared to exclusion plots (Fig. 2b). Also, there was a significant year effect, carabid captures declined in 2009. Maximal captures were 59 per day in augmented plots and 16 in

**Table 1** Number of *P. melanarius* tested, percent of *P. melanarius* that fed, and mean number  $\pm$  SE of *O. sulcatus* larvae eaten when placed at different soil depths in 24 h laboratory trials

Depth	<i>n</i>	Percent of <i>P. melanarius</i> that fed (%)	No. of <i>O. sulcatus</i> larvae eaten
On the soil surface	27	85	$2.6 \pm 0.31$
1.3 cm below	21	43	$0.48 \pm 0.13$
5 cm below	22	18	$0.23 \pm 0.11$
			df = 2, $\chi^2 = 22.7,$ $F_{2,67} = 30.4,$ $P < 0.001$ <span style="float: right;"><math>P &lt; 0.001</math></span>



**Fig. 2** Mean number ( $\pm$ SE) of adult carabids trapped per day in carbid density-manipulation plots in **a** 2008 and **b** 2009. Letters denote significant differences within a year by Tukey HSD. Repeated measures: treatment  $F_{2,8} = 24.0$ ,  $P < 0.001$ , week

$F_{1,519} = 13.3$ ,  $P < 0.001$ , year  $F_{1,519} = 24.6$ ,  $P < 0.001$ , treat.  $\times$  week  $F_{2,519} = 4.5$ ,  $P = 0.012$ , treat.  $\times$  year  $F_{2,519} = 4.8$ ,  $P = 0.009$ , week  $\times$  year  $F_{1,519} = 0.018$ ,  $P = 0.89$ , treat.  $\times$  week  $\times$  year  $F_{2,519} = 9.3$ ,  $P < 0.001$

control plots in 2008 compared to ten in augmented plots and 6.6 in control plots in 2009. There was a significant week effect (Fig. 2) because activity of adults is seasonal and expected to change during the spring, summer and fall.

Manipulation of carabids did not significantly impact predation belowground on *O. sulcatus* larvae or pupae: there was no effect of treatment nor interactions with treatment but there was an effect of month on prey removal (Table 2). A linear regression indicated no relationship between the number of carabids captured with the percent of *O. sulcatus* larvae removed within the same plot during each trial ( $F_{1,70} = 0.49$ ,  $P = 0.49$ ), nor with the percent of *O. sulcatus* pupae removed ( $F_{1,34} = 1.6$ ,  $P = 0.21$ ). However, carbid presence did significantly impact above-ground removal of *T. pratense* seeds in 2008: there was a significant overall treatment effect as well as treatment interaction effects (Fig. 3). A linear regression indicated that weed seed removal significantly varied with carbid captures, particularly in 2008 (2008–2009:  $F_{1,94} = 8.1$ ,  $P = 0.005$ ,  $r^2 = 0.05$ , %seeds removed per day =  $0.039 + 0.00037 \times$  carabids; 2008 only:  $F_{1,46} = 37.0$ ,  $P < 0.001$ ,  $r^2 = 0.43$ , %seeds removed per day =  $0.015 + 0.0005 \times$  carabids).

Manipulation of carbid numbers led to significant differences in the number of marketable fruits, but not yield in terms of weight (Table 2). More marketable fruits were harvested from control than exclusion plots, indicating that the exclusion of carabids reduced the quality of strawberry fruit. There was a significant year effect on yield and number of fruits because first year strawberry plants were establishing, and the

second year plants produced a large quantity of fruit for harvest.

## Discussion

Laboratory tests indicate that the common carbid species consumed egg, larval and pupal stages of *O. sulcatus* presented on the soil surface or filter paper, confirming laboratory and greenhouse observations made by Evenhuis (1983), and Garth and Shanks (1978). However, carabids in our laboratory study appeared less likely to consume prey in more complex arenas: when prey larvae were buried 1.3 or 5 cm in the soil, or when prey larvae burrowed into the soil of a potted strawberry plant. Although potted strawberry trials with *C. nemoralis* were different from the control, a low predation rate of 1.3 *O. sulcatus* larvae was observed in one week. Thus, studies where carabids are given exposed prey should be cautiously interpreted especially when the prey occurs belowground. Another laboratory study found a similar impact. *Pterostichus melanarius* reduced damage to oilseed rape caused by *Deroceras reticulatum* Müller, a surface dwelling slug, but it did not reduce damage caused by *D. laeve* Müller, a root feeding slug (Oberholzer et al. 2003).

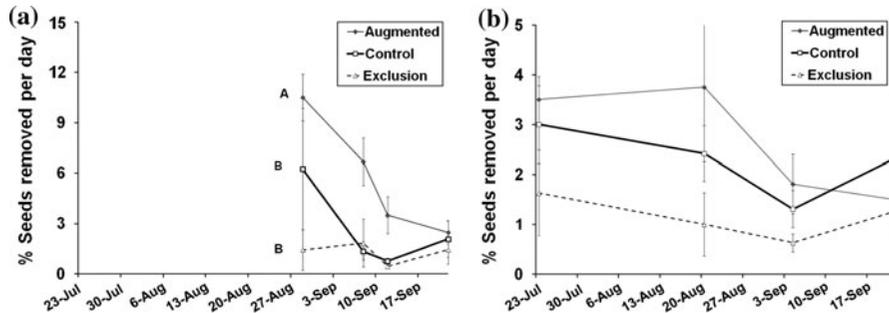
In our field experiments with carbid density manipulation, the barriers successfully excluded carabids both years, and successfully augmented carabids the first year but not the second year. The barrier may not have been as effective augmenting carabids during the second year because of wear and tunnels having been made by emigrating beetles. In any case, when

**Table 2** Mean percent  $\pm$  SE of *O. sulcatus* larvae and pupae removed, and mean yield among carabid density-manipulation plots

					Statistics	
% Removal of <i>O. sulcatus</i> larvae		2008 Aug	Sep	Oct		
	Augmented	66.7 $\pm$ 6.2	75.8 $\pm$ 9.4	48.3 $\pm$ 2.2	trt $F_{2,6} = 1.85, P = 0.23$	
	Control	77.4 $\pm$ 3.7	71.0 $\pm$ 9.3	51.7 $\pm$ 4.4	mo $F_{2,45} = 13.4, P < 0.001$	
	Exclusion	70.8 $\pm$ 5.2	63.3 $\pm$ 5.5	35.9 $\pm$ 4.2	trt $\times$ mo $F_{4,45} = 0.84, P = 0.50$	
		2009 Aug	Sep	Oct	yr $F_{1,45} = 10.2, P = 0.0025$	
	Augmented	80.0 $\pm$ 0.7	50.0 $\pm$ 16.7	75.8 $\pm$ 8.3	trt $\times$ yr $F_{2,45} = 0.50, P = 0.61$	
	Control	81.7 $\pm$ 5.5	40.0 $\pm$ 11.6	65.0 $\pm$ 6.7	mo $\times$ yr $F_{2,45} = 13.0, P < 0.001$	
	Exclusion	79.2 $\pm$ 3.7	35.0 $\pm$ 14.0	57.5 $\pm$ 7.3	trt $\times$ mo $\times$ yr $F_{4,45} = 0.086, P = 0.97$	
	% Removal of <i>O. sulcatus</i> pupae		2009 May 22	May 25	June 5	
Augmented		35.7 $\pm$ 12.4	32.1 $\pm$ 18.8	14.3 $\pm$ 12.4	trt $F_{2,6} = 0.40, P = 0.684$	
Control		50.0 $\pm$ 18.0	42.9 $\pm$ 19.3	10.7 $\pm$ 6.8	mo $F_{2,18} = 6.0, P = 0.01$	
Exclusion		33.3 $\pm$ 8.9	60.7 $\pm$ 18.8	21.4 $\pm$ 5.8	trt $\times$ mo $F_{4,18} = 0.75, P = 0.568$	
# Fruits			2008	2009		
		Augmented	22.7 $\pm$ 1.9 ab <sup>a</sup>	425 $\pm$ 104 ab		trt $F_{2,6} = 6.0, P = 0.037$
	Control	31.0 $\pm$ 2.3 a	547 $\pm$ 67 a		yr $F_{1,9} = 82.7, P < 0.001$	
	Exclusion	19.3 $\pm$ 3.8 b	359 $\pm$ 61 b		trt $\times$ yr $F_{2,9} = 1.26, P = 0.33$	
Yield (kg)		2008	2009			
	Augmented	0.14 $\pm$ 0.016	3.8 $\pm$ 1.1		trt $F_{2,6} = 3.1, P = 0.119$	
	Control	0.12 $\pm$ 0.007	4.8 $\pm$ 0.8		yr $F_{1,9} = 132, P < 0.001$	
	Exclusion	0.11 $\pm$ 0.17	3.1 $\pm$ 0.06		trt $\times$ yr $F_{2,9} = 1.37, P = 0.302$	

trt treatment, mo month, yr year

<sup>a</sup> Letters denote significant differences among treatments by Tukey HSD in 2008 and 2009, in other comparisons no significant differences were observed



**Fig. 3** Mean percent ( $\pm$ SE) of *T. pratense* seeds removed from carabid density-manipulation plots in **a** 2008 and **b** 2009. Letters denote significant differences within a year by Tukey HSD. Repeated measures: treatment  $F_{2,7} = 7.6, P = 0.018$ , week

$F_{1,75} = 12.3, P < 0.001$ , year  $F_{1,75} = 9.3, P = 0.003$ , treat.  $\times$  week  $F_{2,75} = 4.4, P = 0.016$ , treat.  $\times$  year  $F_{2,75} = 6.9, P = 0.002$ , week  $\times$  year  $F_{1,75} = 3.9, P = 0.053$ , treat.  $\times$  week  $\times$  year  $F_{2,75} = 2.7, P = 0.076$

densities of mainly *P. melanarius* were augmented/reduced in 2008 and reduced in 2009, no clear trend was observed with the removal of sentinel *O. sulcatus* larvae and pupae, nor was there a correlation between carabid pitfall captures and prey removal. Both laboratory and field studies with prey presented within

the soil suggest that adult *P. melanarius* may exert limited pest control belowground on *O. sulcatus*.

Carabid larvae are primarily subterranean and potentially important predators belowground. However, the habits of carabid larvae are elusive with most examples from laboratory or semi-field studies

(Thomas et al. 2009; Frank et al. 2010). In our study, few carabid larvae were collected from soil samples or in pitfall traps to study their potential impact. Although not examined in our field study, carabid adults could potentially affect *O. sulcatus* populations by preying on eggs laid near the soil surface or at the base of plants. However, this may have been unlikely for our field study given that *P. melanarius* was the dominant species. Few of the small *Bembidion* spp. carabids that typically prey on eggs were captured in our fields, and the presence of large carabids like *P. melanarius* has led to intraguild predation of smaller carabids and reduced predation on egg pests (Prasad and Snyder 2004; Vankosky et al. 2011).

Our study confirms other studies on the importance of carabids for weed seed removal (Tooley and Brust 2002). In our field trials as carabid density increased, removal of *T. pratense* seeds on the surface also increased in the first year of the study. This suggests that carabids, primarily *P. melanarius*, were either consuming or caching the seeds in the field. In other laboratory trials, *P. melanarius* fed on grass seed even when insect prey were present (Johnson and Cameron 1969), and seeds comprised of 31% of *P. melanarius*' diet when given a choice of aphids, mealworms, wheat seedlings and seeds of *Poa trivialis* L., *Viola arvensis* Murray, and *Alopecurus myosuroides* Huds. (Tooley and Brust 2002). It is also possible that the sentinel weed seeds in our field trials during August and September may have reduced predation in our other trials with belowground *O. sulcatus* larvae. Other carabid species have been shown to feed less on insect prey when grass seeds are present (Frank et al. 2010, 2011).

In our study, the number of marketable strawberries was lower in exclusion than in control plots. Unmarketable fruit appeared damaged by birds or slugs. Although not examined, the barriers visibly limited plant growth and may have provided a protected habitat for slugs. These factors combined with the near absence of *P. melanarius* in exclusion plots may have led to greater damage by slugs and thereby fewer marketable strawberries in the exclusion plots than the control plots. In other studies, *P. melanarius* have reduced the number of epigeic-feeding *D. reticulatum* slugs, and enhanced the survival of oilseed rape seedlings in laboratory arenas (Oberholzer et al. 2003). *Pterostichus melanarius* have had a significant effect on slug population growth in a five-year field study (Symondson et al. 2002). Another large carabid,

*Harpalus pennsylvanicus* (DeGeer), was found to consume *D. reticulatum* based on molecular analysis of 165 adults collected from strawberry fields (Eskelson et al. 2011). In the same study, no carabids fed on *D. laeve* slugs even though this species was more abundant than *D. reticulatum*. While the feeding habits of *D. laeve* in strawberries was not described, the belowground feeding habits of *D. laeve* in oilseed rape (Frank 1998) have been cited as a reason why *P. melanarius* did not provide biological control (Oberholzer et al. 2003). In summary, our laboratory and field studies suggest that carabids, primarily *P. melanarius* adults, may have limited impacts on a belowground pest such as *O. sulcatus*, but may have beneficial impacts above-ground with weed seed removal and strawberry yield.

**Acknowledgments** We thank Randy Cram, Nikko Fujita, Danielle Lightle, Joe Snead, and Thomas Whitney with field maintenance and assistance; Jim LaBonte for carabid identification; and Laurel Moulton for comments on the manuscript. Funding was provided by the Oregon Strawberry Commission, Agricultural Research Foundation and USDA CRIS# 5358-22000-032-00D.

## References

- Bomford MK, Vernon RS (2005) Root weevil (Coleoptera: Curculionidae) and ground beetle (Coleoptera: Carabidae) immigration into strawberry plots protected by fence or portable trench barriers. *Environ Entomol* 34:844–849
- Cross JV, Easterbrook MA, Crook AM, Crook D, Fitz Gerald JD, Innocenzi PJ, Jay CN, Solomon MG (2001) Review: natural enemies and biocontrol of pests of strawberry in northern and central Europe. *Biocon Sci Tech* 11:165–216
- DeFrancesco J, Gill J, Kaufman D, Gütt P (2002) Crop profile for strawberries in Oregon. National Informational System for Regional IPM Centers, <http://www.ipmcenters.org/cropprofiles/docs/orstrawberries.html>
- Eskelson MJ, Chapman EG, Archbold DD, Obyrcki JJ, Harwood JD (2011) Molecular identification of predation by carabid beetles on exotic and native slugs in a strawberry agroecosystem. *Biol Control* 56:245–253
- Evenhuis HH (1982) Control of the black vine weevil, *Oti-orhynchus sulcatus* (Coleoptera: Curculionidae). *Meded Fac Landbouww Rijksuniv Gent* 47: 675–678
- Evenhuis HH (1983) Role of carabids in the natural control of the black vine weevil, *Oti-orhynchus sulcatus*. *Mitt Deutschland Ges angew Entomol* 4:83–85
- Floate KD, Doane JF, Gillott C (1990) Carabid predators of the wheat midge (Diptera, Cecidomyiidae) in Saskatchewan. *Environ Entomol* 19:1503–1511
- Frank T (1998) The role of different slug species in damage to oilseed rape bordering on sown wildflower strips. *Ann Appl Biol* 133:483–493

- Frank SD, Shrewsbury PM, Denno RF (2010) Effects of alternative food on cannibalism and herbivore suppression by carabid larvae. *Ecol Entomol* 35:61–68
- Frank SD, Shrewsbury PM, Denno RF (2011) Plant versus prey resources: influence on omnivore behavior and herbivore suppression. *Biol Control* 57:229–235
- Garth GS, Shanks CH (1978) Some factors affecting infestation of strawberry fields by black vine weevil (Coleoptera-Curculionidae) in Western Washington. *J Econ Entomol* 71:443–448
- Johnson NE, Cameron RS (1969) Phytophagous ground beetles. *Ann Entomol Soc Am* 62:909–914
- La Lone RS, Clarke RG (1981) Larval development of *Otiorhynchus sulcatus* (Coleoptera: Curculionidae) and effects of larval density on larval mortality and injury to rhododendron. *Environ Entomol* 10:190–191
- Menalled FD, Lee JC, Landis DA (1999) Manipulating carabid beetle abundance alters prey removal rates in corn fields. *BioControl* 43:441–456
- Monzó C, Sabayer-Munoz B, Urbaneja A, Castanera P (2011) The ground beetle *Pseudophonus rufipes* as predator of *Ceratitidis capitata* in citrus orchards. *Biol Control* 2011:17–21
- Oberholzer F, Escher N, Frank T (2003) The potential of carabid beetles (Coleoptera) to reduce slug damage to oilseed rape in the laboratory. *Eur J Entomol* 100:81–85
- Prasad RP, Snyder WE (2004) Predator interference limits fly egg biological control by a guild of ground-active beetles. *Biol Control* 31:428–437
- SAS (2007) JMP<sup>®</sup> statistics and graphics guide, Version 7.0.1. SAS Institute, Cary
- Sunderland KD (2002) Invertebrate pest control by carabids. In: Holland J (ed) *The agroecology of carabid beetles*. Intercept, Andover, pp 165–214
- Symondson WOC, Glen DM, Ives AR, Langdon CJ, Wiltshire CW (2002) Dynamics of the relationship between a generalist predator and slugs over five years. *Ecology* 83:137–147
- Thomas RS, Harwood JD, Glen DM, Symondson WOC (2009) Tracking predator density dependence and subterranean predation by carabid larvae on slugs using monoclonal antibodies. *Ecol Entomol* 34:569–579
- Tooley JA, Brust GE (2002) Weed seed predation by carabid beetles. In: Holland J (ed) *The agroecology of carabid beetles*. Intercept, Andover, pp 215–229
- Vankosky MA, Carcamo HA, Dossdall LM (2011) Identification of potential natural enemies of the pea leaf weevil, *Sitona lineatus* L. in western Canada. *J Appl Entomol* 135:293–301
- 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
- Zaller J, Moser D, Drapela T, Frank T (2009) Ground-dwelling predators can affect within-field pest insect emergence in winter oilseed rape fields. *BioControl* 54:247–253

### Author Biographies

**Jana C. Lee** is a research entomologist working in small fruits and ornamental crops using biological control and semiochemicals with a current focus on spotted wing *Drosophila*, raspberry aphid, and brown marmorated stink bug.

**David L. Edwards** is a research technician working on arthropod pest management, with a focus on fungus gnats, black vine weevils and spotted wing *Drosophila*.