BioControl (2005) 50: 205–222

Ground predator abundance affects prey removal in highbush blueberry (*Vaccinium corymbosum*) fields and can be altered by aisle ground covers

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Received 26 January 2004; accepted in revised form 14 June 2004

Abstract. Habitat management to conserve natural enemies has increased biological control of insect pests in various cropping systems [Annu. Rev. Entomol. 45: 175–201, 2000]. We wanted to determine if insect predation in highbush blueberry, *Vaccinium corymbosum* L. (Ericales: Ericaceae), is influenced by manipulation of edaphic arthropod community and whether management of ground cover in aisles between blueberry rows enhances this community. The first question was studied in blueberry plots bounded by trenches permitting selective movement into plots (ingress) or out of plots (egress), as well as unbounded control plots. We observed a significant effect of boundary type on the arthropod communities' relative abundance as measured with pitfall traps, with relative abundance highest in ingress plots, intermediate in control plots and lowest in egress plots. Effects of ground arthropod abundance on predation rates were assessed with onion fly, *Delia antiqua* (Meigen) (Diptera: Anthomyiidae), pupae as sentinel prey. Pupa recovery was greatest in egress boundary plots, intermediate in control plots and lowest in ingress boundary plots. Regression analyses indicate pupal recovery rate decreased as a function of carabid abundance as well as the abundance of non-insect ground predators. To determine if ground cover management influenced natural enemy abundance, aisles were clean cultivated or planted with three ground covers (clover, ryegrass, or buckwheat). Increasing ground cover had a significant effect on the relative abundance of *Harpalus pensylvanicus* De Geer (Coleoptera: Carabidae). In addition to conserving natural enemies for control of blueberry insect pests, we discuss additional benefits of ground covers that may increase their utility for blueberry production.

Key words: biological control, Carabidae, conservation, cover crop, Opiliones

Introduction

Highbush blueberries, *Vaccinium corymbosum* L. (Ericales: Ericaceae) are grown in more than 30 states on over 16,400 hectares in the United States

(Anon, 2004), with the greatest proportion of this production (41% in 2002 based on area harvested) in Michigan. Blueberries are harvested for sale as fresh and processed fruit, and for both markets there are stringent quality standards that include zero tolerance for contamination of fruit by larvae of blueberry maggot, *Rhagoletis mendax* Curran (Diptera: Tephritidae), and adult Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae). To meet these standards, broad-spectrum insecticides are applied to over 90% of highbush blueberry production east of the Rockies where these pests are found, with greatest use during the pre-harvest period (late July to early August) when pest are most active (Pritts and Hancock, 1992). Alternative approaches to pest management are needed to help reduce the need for insecticide applications. Enhancement of natural enemies by habitat management is one strategy that may be added to existing IPM programs to increase biologically based methods of pest management.

Conservation of natural enemy abundance through habitat management has reduced pest pressure within certain agroecosystems (Landis et al., 2000). Ground beetles are generalist arthropod predators that are natural enemies of several insect pests (Sunderland, 2002). Brust et al. (1985, 1986) showed that application of broad-spectrum insecticides to cornfields reduced densities of carabids and other predators. Epstein et al. (2000) observed higher populations of carabids, centipedes, staphylinids, and spiders in apple orchards where pheromones replaced a management program using broad-spectrum insecticides. In addition to the removal of chemical inputs that suppress natural enemies, altering tillage practices (Brust et al., 1985, 1986; Fan et al., 1993; Cárcamo, 1995), and adding cover crops (Lys and Nentwig, 1992; Lys, 1994) or refuge habitats (Lee and Landis, 2002) have been shown to increase carabid abundance.

Selective manipulation of natural enemy populations has been attempted in different crop systems to determine if an existing natural enemy community has the potential to affect pest populations (Chambers et al., 1983; Helenius, 1990; Holland and Thomas, 1997; Holland, 1998). In general, these studies have attempted to artificially increase or decrease natural enemy abundance while measuring its effect on prey removal or pest abundance. A recent example by Menalled et al. (1999) was conducted in corn plots surrounded by different boundaries that selectively affected dispersal of edaphic arthropods. These boundaries decreased the relative abundance of carabids when compared to the non-boundary situation. Boundaries designed to augment carabid populations had a higher relative abundance than the natural population, although the difference was not statistically significant. Within these bounded cornfields, carabid abundance was positively correlated with predation, as measured by the removal of sentinel prey.

We had two goals for this study; to determine (1) if predation in a blueberry field is affected by manipulation of the edaphic arthropod community and (2) if this community, particularly ground beetles, are affected by ground cover in the aisles between blueberry rows. To accomplish our first goal, we attempted to artificially manipulate ground arthropod population densities in a blueberry field using the boundary designed by Menalled et al. (1999) and measure prey removal within these plots. For our second goal, we compared the relative abundance of arthropods under blueberry bushes bordered with varying ground cover. These ground covers were selected from a larger study investigating the role of ground cover and clean cultivation on local *P. japonica* populations. Clean cultivation of aisles within blueberry fields can reduce local *P. japonica* populations (Isaacs et al., in press), but there are horticultural considerations preventing widespread adoption of cultivation. The low soil pH (4.5–6) required for production of blueberry (Pritts and Hancock, 1992) is a limitation to the selection of potential ground covers, so acid-tolerant ground covers were established to determine their potential for reducing the suitability of blueberry fields for *P. japonica*.

Materials and methods

Ground arthropod community manipulation

This research was conducted during the 2003 growing season at the Michigan State University Trevor Nichols Research Complex, Fennville, Michigan. Two ranges of highbush blueberry bushes within an unmanaged blueberry field of approximately 0.4 ha were chosen for the study. To control for possible carabid density differences within these two ranges, four blocks were established, resulting in a completely randomized block design. Each block contained five rows of blueberry bushes with individual rows containing 11 bushes. Three of the five rows within each block were randomly assigned a different boundary type. The three boundary types assigned within each block were ingress boundaries, egress boundaries, and an unbound control (Figure 1A). The ingress boundaries were designed to increase the ground arthropod community composition by allowing movement into the plot but not out of the plot. These boundaries consisted of 22.9 cm deep trenches, 15.9 m long and 3.2 m wide, surrounding a row of 12 blueberry bushes. The inside wall of the trench was sloped while the outside wall was vertical with a 25.4 cm space between the walls. The vertical wall was covered with a plastic sheet to inhibit the arthropods from climbing out. During field observations performed by Menalled et al. (1999) it was noted that arthropods were unable to climb such a plastic covered vertical wall. The egress boundaries were designed to decrease the ground arthropod community composition by allowing movement out of the plot but not into the plot. Dimensions of the egress boundary were the same as

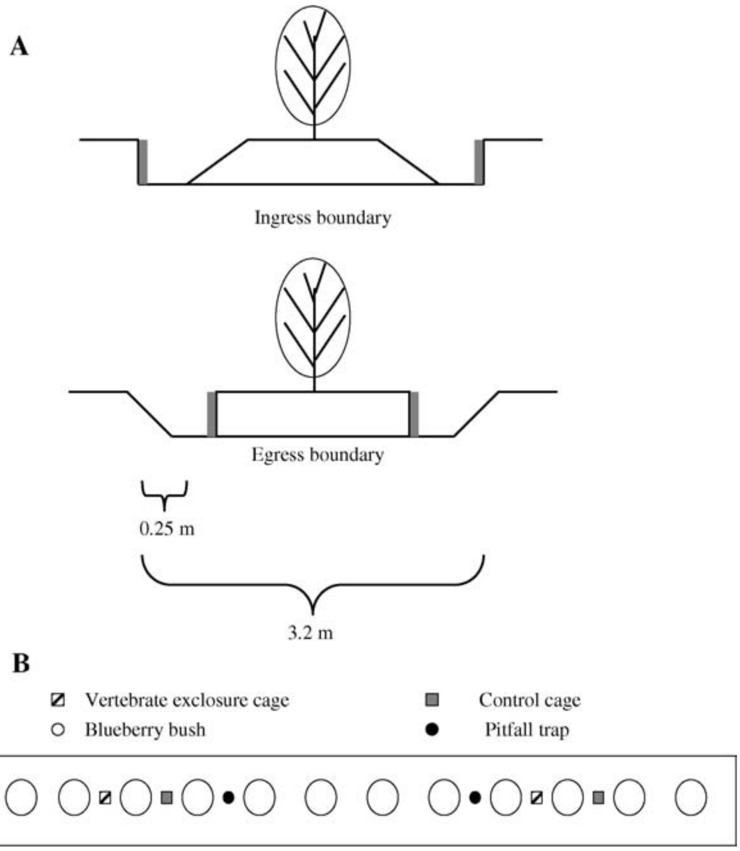

Figure 1. Cross-sections of the ingress and egress boundaries (A) with the plastic barrier represented by dark gray bars, and (B) location of pitfall traps and prey removal cages for a generalized row of blueberry bushes.

the ingress boundary, however, the inside wall of the egress boundary was vertical and covered with a plastic sheet while the outside wall was sloped. All boundaries were completed on 23 May 2003.

The unbounded rows served as a control to assess the naturally occurring ground arthropod community. To ensure that weed growth within the trenches did not aid in ground arthropod movement into or out of the plots, glyphosate herbicide (Roundup, Monsanto, St. Louis, MO) was applied within the trenches on 25 July. Weeds growing within the trenches were removed by hand thereafter. Insecticides were not used in any of the plots.

Pitfall traps were used to assess ground arthropod community relative abundance within each treatment. Two pitfall traps were placed within each treatment, approximately 5 m apart (Figure 1B). Pitfall traps were comprised of an inner and an outer plastic cup, each 11.8 cm in diameter and 14.6 cm deep.

Holes were punched in the bottom of the outer cup to allow water drainage. A rain guard measuring 18.7 cm by 15.2 cm that was supported by four 8.9 cm long nails covered each trap. The pitfall traps were monitored for five consecutive days beginning 17 June, 21 July and 18 August 2003. All collected arthropods were identified, recorded, and returned to their respective plots.

Field predation study

We assessed the effect of ground arthropod abundance on prey removal within each treated row. These assessments were performed beginning on 9 June prior to the June pitfall trapping study and on 28 July and 25 August 2003 following each respective pitfall trapping study. The June assessment was performed before pitfall trapping to ensure that the carabid population was large enough to measure significant differences in prey removal before summer aestivation.

Two different types of prey removal cages were used. Vertebrate exclosure cages prevented vertebrates from removing pupae while allowing invertebrates to remove pupae. Control cages prevented both vertebrates and invertebrates from removing pupae and were used to determine unknown losses of pupae due to handling (Menalled et al., 1999). Vertebrate exclosure cages were constructed using wire mesh of 34.3 cm by 34.3 cm by 6.4 cm (length × width × height). Control cages were constructed using vertebrate exclosure cages with the addition of a fine wire mesh lining the inside of the cage to prevent invertebrates from removing prey. A plastic roof covered both types of cages to shield pupae from rain. Two pairs of vertebrate and invertebrate exclosure (control) cages were placed under blueberry bushes within each treated row (Figure 1B). The distance between a vertebrate and control cage was 1.1 m and the distance between the two pairs of cages within a treatment was 6.9 m.

In each cage, twenty freeze-killed pupae of onion fly, *Delia antiqua* (Meigen) (Diptera: Anthomyiidae), were used as prey and placed in the field for 3 days. Menallad et al. (1999) have demonstrated that carabids feed on both frozen and live pupae at similar rates in laboratory studies. Pupae were placed on 14.6 cm by 11.4 cm Scotch-Brite pads (3M, St. Paul, MN) within each cage to reduce loss of pupae and to aid in recovery. After the 3 days, the pupae were collected and the number recovered was recorded. A pupa was considered recovered only if it was fully intact. Those pupae remaining on the pad with evidence of predator damage such as bite marks were not recorded as recovered.

Effect of ground covers on carabid beetles

This research was conducted in a planting of highbush blueberry, *V. corymbosum*, var. Bluecrop and Jersey also at the Trevor Nichols Research Complex. The blueberry plants were 4 years old, on a 3.65 m × 1.2 m planting spacing, with 12 bushes in each row over an area of 0.41 ha. The area between the bush rows was cultivated in the spring of 2003 and then planted with seeds to create plots with either perennial ryegrass (*Lolium perenne* L.), alsike clover (*Trifolium hybridum* L.), buckwheat (*Fagopyrum esculentum* Moench), or unplanted. The latter treatment was kept bare by application of glyphosate. Treatments were arranged within the planting in a randomized complete block design, with four replicates.

In each plot, 2 pitfall traps were placed under two blueberry bushes within a row in four replicates of each ground cover treatment. Each row was bordered on either side by the same ground cover treatment. Traps were emptied every 24 h for 3 consecutive days on 12–15 August, 15–18 September, and 20–23 October. Collected beetles were counted and identified to species.

Statistical analysis

To determine the effects of boundary type on ground beetle abundance, a split-plot analysis of variance (ANOVA) was used with time (June, July, August) as the split factor. A split–split plot ANOVA was used to determine the effect of boundary type (control, ingress, egress) on the proportion of pupae removed per treatment, with time and boundary type as the first and second split factors, respectively. The number of ground beetles collected in each treatment was square root transformed and the proportion of pupae removed was arcsin transformed to meet the assumptions of ANOVA (Sokal and Rohlf, 1995). Statistical analyses were performed with SAS (PROC MIXED, SAS Institute, 2000). A series of least-square means tests on simple effects were calculated on sliced data after main treatment and first order interactions were detected.

Linear regression was used to determine the relationship between the number of invertebrates collected in pitfall traps and subsequent pupae removed. Pitfall trap captures and pupae removed were combined from each month. The proportion of ground arthropods collected in each treatment was used to account for the significant effect time had on pitfall trap captures of Carabidae (see Results below), as well as other ground arthropods captured (Araneae, Opiliones and Chilopoda). Separate regressions were conducted to determine the relationship between carabids and combination of other ground arthropods (Araneae, Opiliones and Chilopoda) to prey removed.

To determine the effects of ground cover on carabid beetle abundance a split-plot analysis of variance (ANOVA) was used with time (August, September, October) as the split factor. The effect of ground cover was determined on the total number of carabid beetles found in pitfall traps, as well as on *Harpalus pensylvanicus*, and all other carabids excluding *H. pensylvanicus*. Also, the effect of ground cover on carabid larvae was analyzed with ANOVA during the October sampling period. All statistical analyses were performed with SAS (PROC GLM, SAS Institute, 2000), and when a significant effect of ground cover occurred, mean comparisons (LSD, treatment means significantly different when $p < 0.05$) were conducted.

Results

Ground arthropod community manipulation

In total, 173 individuals from seven different groups of ground-dwelling arthropods were collected across the three barrier treatments. The number of ground arthropods collected was greatest in the ingress boundary plots, intermediate in the control plots, and lowest in the egress boundary plots (Table 1). Carabid response to the boundaries mirrored that of the arthropod community. However, carabids were not always the most abundant arthropod collected. In June, Araneae were the most abundant arthropod collected, and in July Opiliones were the most abundant. Interestingly, the relative abundance of Staphylinidae larvae in June and Cydnidae in August were greater in the egress than either the ingress or control plots (Table 1).

Carabid species richness and total abundance were both greatest in the ingress boundary plots, intermediate in the control plots, and lowest in the egress boundary plots (Table 2). In total, 40 carabid beetles representing eight

Table 1. Abundance of ground arthropods[a] in plots with an ingress boundary, no boundary (control), or an egress boundary during June, July, and August 2003

June		July		August	
Total[b] (ingress, control, egress)		Total[b] (ingress, control, egress)		Total[b] (ingress, control, egress)	
Araneae	28 (11, 10, 7)	Opiliones	29 (26, 2, 1)	Carabidae	11 (9, 2, 0)
Carabidae	24 (14, 8, 2)	Carabidae	5 (4, 1, 0)	Opiliones	9 (8, 1, 0)
Diplopoda	18 (9, 2, 7)	Chilopoda	3 (2, 1, 0)	Cydnidae	3 (0, 1, 2)
Chilopoda	9 (7, 1, 1)	Araneae	2 (1, 1, 0)	Chilopoda	3 (2, 1, 0)
Opiliones	9 (1, 6, 2)	Cydnidae	1 (0, 1, 0)	Araneae	3 (2, 1, 0)
Staphylindae[c]	9 (0, 1, 8)	Diplopoda	1 (0, 0, 1)		
Cydnidae	6 (1, 3, 2)				
Combined total	103 (43, 31, 29)	Combined total	41 (33, 6, 2)	Combined total	29 (21, 6, 2)

[a] Arachnida identified to order, Insecta identified to family, with Carabidae further identified to genus (Table 2).
[b] Arthropods collected after five consecutive days of pit fall trapping below two blueberry bushes within a plot.
[c] Staphylindae were collected as larvae.

Table 2. Abundance of carabid species in ingress boundary, control, and egress boundary plots during 5-day sampling periods in June, July, and August 2003

Species	Seasonal total	Total by treatment		
		Ingress	Control	Egress
Anisodactylus nigerrimus (Dej.)	16	10	5	1
Pterostichus melanarius (Ill)	6	5	1	0
Poecilus lucublandus (Say)	5	2	3	0
Amara impuncticollis (Say)	4	3	0	1
Pterostichus commutabilis (Motsch)	3	3	0	0
Anisodactylus sanctaecrusis (F.)	2	2	0	0
Amara cupreolata Putz.	2	2	0	0
Unidentified	2	0	2	0
Total	40	27	11	2

different species were collected in the plots, with seven species collected in the ingress boundary plots, four in the control plots, and two in the egress boundary plots.

The abundance of carabid beetles in pitfall traps was not significantly different among blocks ($F = 1.21$, df = 3, 6; $p = 0.38$). However, both a significant treatment effect ($F = 8.48$, df = 2, 18; $p < 0.01$) as well as a significant difference over time ($F = 6.87$, df = 2, 6; $p = 0.03$) were observed, with fewer carabids found in July than in June or August (Figure 2). A time by boundary interaction was not observed ($F = 0.75$, df = 4, 18; $p = 0.57$). In June, sig-

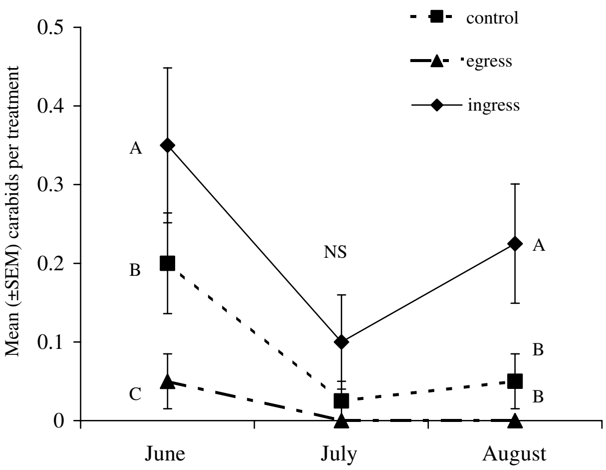

Figure 2. Mean beetles collected per boundary treatment. Within each month, letters denote significant differences at the $p \leq 5\%$ level.

nificantly more carabids were captured in the ingress boundary plots than the egress boundary plots or the control plots (Figure 2) and fewer beetles were captured in egress boundary plots than the control plots. In July, the pattern of carabid abundance was similar to that observed in June, but there were no significant differences among the treatments. In August the trend in carabid abundance continued, with significantly more carabids found in the ingress boundary treatments than either the egress or control plots.

Field predation study

Recovery of pupae in the field predation study was not affected by block ($F = 0.49$, df = 3, 6; $p = 0.70$) or time ($F = 0.67$, df = 2, 6; $p = 0.55$). A significant effect of boundary type ($F = 6.96$, df = 2, 18; $p < 0.01$) and cage type ($F = 39.24$, df = 1, 27; $p < 0.0001$) were observed. For the combination of the three treatments and dates, more pupae were recovered from control cages (17.5 ± 0.4; mean pupae per cage ± SEM) than vertebrate exclosure cages (10.5 ± 0.8, mean pupae per cage ± SEM). There was not a significant affect of boundary type on the amount of prey recovered from the control cages (analysis not shown). We did observe a significant boundary type by cage type interaction ($F = 5.96$, df = 2, 27; $p < 0.01$), although the time by boundary type interaction ($F = 1.41$, df = 4, 18; $p = 0.27$), time by cage type interaction ($F = 0.67$, df = 2, 27; $p = 0.52$) and time by boundary type by cage type interaction ($F = 0.26$, df = 4, 27; $p = 0.90$) were not significant.

Although not always statistically significant, the mean number of pupae recovered from the vertebrate exclosure cages was greatest in the egress boundary plots, intermediate in the control plots, and lowest in the ingress boundary plots (Figure 3). Throughout the 3-month study, fewer pupae were recovered from the ingress boundary plots than any other treatment. In August, the number of pupae recovered in the vertebrate exclosure cages was significantly less in the ingress boundary plots than the egress boundary plots (Figure 3). Regression analyses (Figure 4) suggest mean number of pupae recovered decreased with an increase in number of carabids ($F = 5.40$, df = 1, 7; $p = 0.05$), or an increase in the sum of Araneae, Opiliones and Chilopoda ($F = 5.76$, df = 1, 7; $p = 0.05$).

Effect of ground covers on carabid beetles

During the 3-month sampling period, we collected a total of 453 carabids comprised of 18 species (Table 3), with greatest capture and species richness of carabids in August. During each sampling period, *H. pensylvanicus* was the

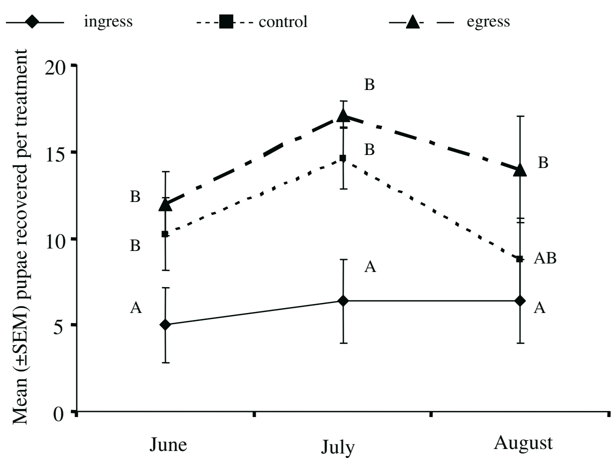

Figure 3. Mean onion fly pupae recovered in vertebrate exclosure cages. Within each month, letters denote significant differences at the $p \leq 5\%$ level.

most common species collected, representing 67% of the total species collected overall.

We observed an effect of ground cover on the relative abundance of all carabids in general and *H. pensylvanicus* specifically (Table 4). When *H. pensylvanicus* was subtracted from the carabids collected, ground cover was not observed to affect the relative abundance of the remaining species (Table 4). Specifically, ground cover did not affect the relative abundance of *Chalenius tricolor* Dejean (Coleoptera: Carabidae) and *Cratacanthus dubius* Beauvois (Coleoptera: Carabidae) the second and third most frequently collected species (analysis not shown). For all carabids and *H. pensylvanicus* specifically, the lowest relative abundance was in pitfall traps under blueberry bushes surrounded by bareground (Figure 5A), with the highest level of relative abundance observed in bushes surrounded by clover and ryegrass. For *H. pensylvanicus* specifically, we observed a time by ground cover interaction. This interaction can be observed in the varying effect of buckwheat on *H. pensylvanicus* relative abundance in August to September (Figure 5B).

We also collected carabid larvae in pitfall traps. Two larvae were collected in ryegrass in September and 18 were collected in October. During October, ground cover had a significant effect on the relative abundance of carabid larvae ($F = 7.42$, df $= 3,35$; $p < 0.01$), with four fold more larvae collected in clover (mean larvae $\pm$ SEM, 1.17 ± 0.2) than in any of the other treatments (0.08 ± 0.05, 0 ± 0, 0.25 ± 0.1 for bareground, buckwheat and ryegrass respectively).

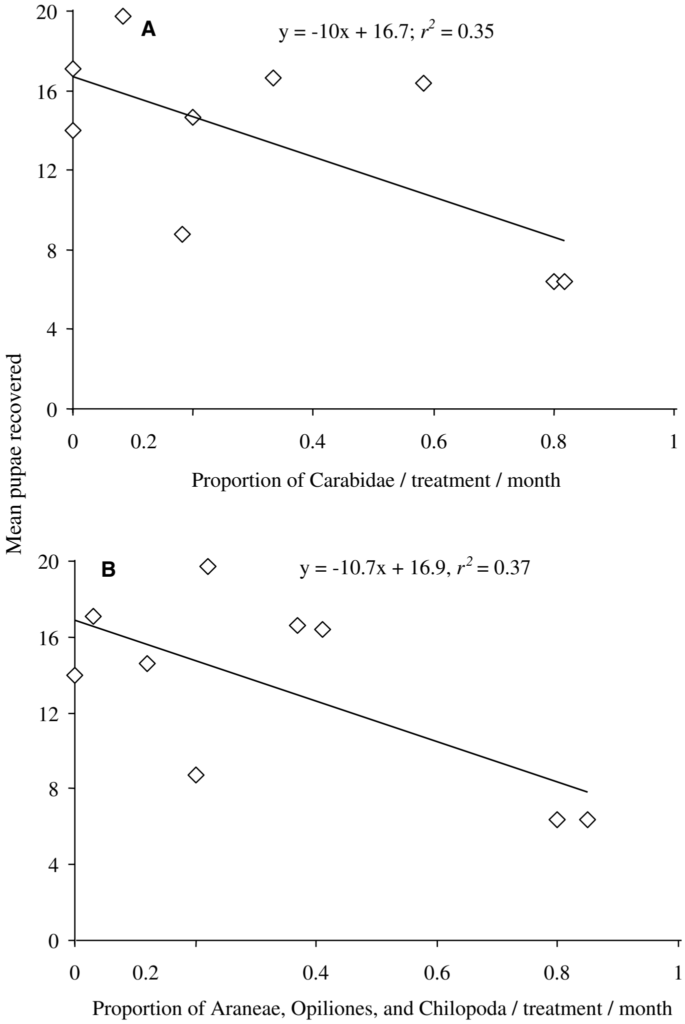

Figure 4. Relationship between mean number of onion fly pupae recovered during the three field trials to the (A) proportion of total Carabidae per treatment per month, and to the (B) proportion of total Araneae, Opiliones and Chilopoda per treatment per month.

Discussion

Our study demonstrates that manipulation of epigeal predators has a direct effect on prey removal in blueberry fields and that selected ground covers can manipulate carabid beetles, a significant member of this predatory community. Directional trenches successfully manipulated the community of ground arthropods around an unmanaged stand of blueberry bushes (Table 1), with

Table 3. Species collected in the ground cover experiment during August, September, and October 2003

August		September		October	
Species	Total	Species	Total	Species	Percentage
Harpalus pensylvanicus (DeG.)	181	*H. pensylvanicus* (DeG.)	93	*H. pensylvanicus* (DeG.)	8
Chlaenius tricolor Dej.	61	*C. tricolor* Dej.	10	*H. herbivagus* Say	5
Cratacanthus dubius (Beauv.)	32	*H. indianus* Csiki	7	*P. permundus* (Say)	2
Amara cupreolata Putz.	9	*D. obtusa* (LeC.)	1	*S. quadricipes* Chaudoir	1
H. indianus Csiki	5	*H. affinis* (Schr.)	1	*C. tricolor* Dej.	1
H. affinis (Schr.)	5	*P. longicornis* (Say)	1	Unidentified	2
Agonum octopunctatum (Say)	2	Unidentified	9		
Agonum cupripenne (F.)	2				
Stenolophus lineola (F.)	2				
Diplocheila obtusa (LeC.)	2				
Colliuris pensylvanica (L.)	1				
H. puncticeps (Steph.)	1				
Anisodactylus rusticus (Say)	1				
Unidentified	8				

Table 4. ANOVA examining the effect of ground cover on adult carabid relative abundance under blueberry bushes

Source	Carabids			*H. pensylvanicus*		All other carabids[b]	
	df[a]	*F*	*p*	*F*	*p*	*F*	*p*
Block	3	0.57	0.67	1.59	0.019	0.01	0.96
Time	2	63.85	0.0001	51.64	0.0001	34.65	0.0001
Time * block	4	2.42	0.05	3.74	0.007	0.30	0.88
Cover	3	6.19	0.0006	9.75	0.0001	0.57	0.64
Time * cover	6	1.44	0.20	2.30	0.04	0.47	0.83

[a] Error df = 125.
[b] Total carabid abundance minus *H. pensylvanicus*.

more arthropods in the ingress and fewer in the egress bounded plots compared to the control plots. Although these treatments were not always significantly different from each other, the ranking (ingress > control > egress) was maintained throughout the study.

In an earlier study, Menalled et al. (1999) used the same boundary design to manipulate arthropod abundance in cornfields. More carabids were collected than any other arthropod, whereas in our blueberry study, non-carabid arthropods were dominant. The importance of predators other than carabid beetles within our study site should not be overlooked, since these may be effective biocontrol agents. Of the seven arthropod groups detected in pitfall traps (Table 1), five of these groups (Carabidae, Opiliones, Araneae, Chilopoda and Staphylinidae) are predators, while some species of Diplopoda are also predatory, although most are scavengers. Interestingly, we found the greatest number of cydnid adults and staphylinid larvae in the control and egress boundary plots (Table 1). Cydnidae feed on the roots of plants and are not considered predacious (Borror et al., 1992). It is possible that both of these insects served as prey for predators in the ingress boundary plots, resulting in the differences recorded among boundary types in cydnid and staphylinid larvae abundance.

Like Menalled et al. (1999), we observed greater prey removal in the ingress bounded plots than either the control or egress bounded plots (Figure 3). Unlike this earlier study, there was no significant difference in the amount of prey removed from the control and egress bounded plots, and the relationship between treatments was consistent across time (ingress > control > egress). Even in August when we collected one cydnid in the egress plots we observed a significant amount of predation as determined by comparing pupal recovery in the control versus the vertebrate exclosure cages. Despite this apparent lack of predators toward the end of the season, there were significant amounts of prey removed (Figure 3). The blueberry under-story was often densely covered with

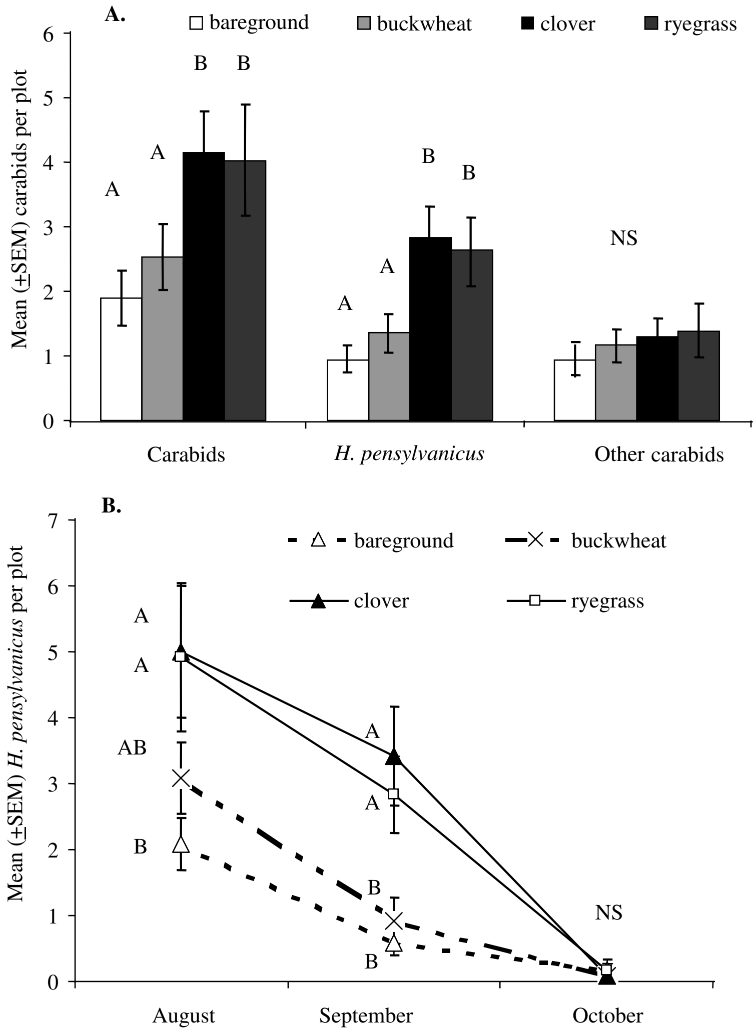

Figure 5. Relative abundance of carabids under blueberry bushes in response to different ground covers planted within the aisles (A) for the months of August, September, and October 2003 combined. Columns labeled with the same letter were not significantly different (LSD, $p = 0.05$). The first set of four columns represents all carabids collected, the second set is only *H. pensylvanicus*, and the final set is all other carabids minus *H. pensylvanicus*. For *H. pensylvanicus* (B), the temporal pattern of relative abundance is reported for each month separately. Within each month, letters denote significant differences at the $P \leq 5\%$ level.

weeds. Dense vegetation can reduce arthropod movement and may have contributed to our underestimation of the predatory community by pitfall trapping.

Our regression analyses (Figure 4) suggest that non-carabid predators may play as important a role in prey removal as carabids. The amount of variation in prey removal explained by the proportion of carabids (Figure 4A) was similar to that explained by the proportion of Araneae, Opiliones and Chilopoda combined (Figure 4B). Previous studies have emphasized the important role of non-carabid predators in agroecostystems (Brust et al., 1986; Cárcamo and Spence, 1994; Holland and Thomas, 1997). In cornfields, Brust et al. (1986) found a correlation between the abundance of Lycosidae, Staphylinidae, Chilopoda and Phalangidae with predation rates. In that study, Phalangidae were occasionally the predominant predator especially in early June. Cárcamo and Spence (1994) found no correlation between carabid activity and prey removal in four different crops, suggesting that other arthropod predators were responsible. Although the abundance of non-carabid predators was not recorded, Cárcamo and Spence (1994) observed predation by Opiliones. These experiments support the conclusion that non-carabid predators may also be contributing to prey removal in blueberry fields.

In comparison to our boundary experiment (Table 2), we collected more species of carabids but fewer arthropods in the ground cover experiment (Table 3). Differences in successional stage may account for these dramatic differences. The boundary experiment site has not been commercially managed for over 5 years, while the ground cover study site was planted in 1999. The carabid community in the ground cover study more closely resembles that of commercial blueberry fields in southwestern Michigan (M.E. O'Neal, unpublished data).

At the ground cover study site, *Harpalus pensylvanicus* was the dominant species across the 3-month sampling period (Table 4) and had the greatest response to ground cover (Figure 5A), with increased relative abundance in blueberry rows surrounded by ryegrass and clover. *H. pensylvanicus* has been reported as a predator of insects (Sunderland, 2002), specifically those within an orchard setting (Riddick and Mills, 1994), and weed seeds (White, 1999), and is active as an adult from June to October (Kirk, 1973). The second most common ground beetle in our ground cover study, *C. tricolor*, is also predaceous (Sunderland, 2002), and has been shown to feed on *P. japonica* eggs and larvae (Terry et al., 1993). The augmentation of these species using ground covers may in turn reduce levels of blueberry pests that overwinter on the soil surface beneath blueberry bushes, such as blueberry maggot (*R. mendax*), cranberry fruitworm (*Acrobasis vaccinii* Riley, Lepidoptera: Pyralidae), and perhaps weed seeds, although further studies are needed to demonstrate this impact on pest abundance. Carabid larvae may also be a source of predation. During the August and September sampling, we collected only two carabid larvae, both in ryegrass. There was a sharp increase in carabid larvae relative abundance in October, when significantly more were collected in clover than any of the ground cover treatments. This may have significance for biological control of key blueberry insect pests, as *H. pensylvanicus* larvae are predaceous. In laboratory assays, they feed on Japanese beetle (*P. japonica*) grubs at a rate of one every 2 days (Hallock, 1929).

Although we were able to augment the number of beneficial insects under blueberry bushes with the use of a boundary trench, production practices limit their use as a pest management tool. By providing ground cover, we successfully increased the abundance of ground beetles under blueberry bushes in relatively small field plots. The potential for ground cover management to conserve beneficial insects has yet to be fully explored for blueberry production. Flowering ground covers may enhance populations of beneficial insects, providing nectar and pollen resources for natural enemies such as syrphids, coccinellids and parasitoid wasps (Landis et al., 2000), as well as native blueberry pollinators. Ground covers that bloom after blueberry may enhance populations of native Hymenoptera, increasing the potential for a diverse suite of species to provide pollination services. There is evidence from lowbush blueberry, *Vaccinium angustifolium* Aiton (Ericales: Ericaceae) that native wild bees are more efficient pollinator than *Apis mellifera* (Hymenoptera: Apidae) (Stubbs and Drummond, 2001; Javorek et al., 2002). By changing the type of ground cover planted in blueberry fields, growers may be able to achieve multiple functions that will help achieve pest management goals. Depending on the ground cover used, these functions may be suppressive to pests and beneficial for natural enemies and pollinators.

Acknowledgements

Our thanks to John C. Wise, Aaron Kosinsky, Keith S. Mason, and Jason Koopman for technical assistance with this research. Thanks also to Foster Purrington for identification of the ground beetles and James R. Miller for providing the onion fly pupae. We thank the Michigan Blueberry Growers Association, USDA Crops at Risk program (grant 2001-51100-11514), and the Michigan Agricultural Experiment Station for funding this research.

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