ORGANIC FARMING RESEARCH FOUNDATION

Project report submitted to the Organic Farming Research Foundation:

Project Title:

Integrating conservation of generalist predators and specialist parasitoids in Pacific Northwest organic vegetables

FINAL PROJECT REPORT

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Project period: 2003 - 2004

Report submitted: March 2005

SUMMARY

Although organic farms are characterized by an abundant fauna of beneficial insects, insect pest problems abound. One factor limiting natural pest control on organic farms may be the low diversity and abundance of particular kinds of natural enemies. Similarly, natural enemy populations may not be sufficiently large during key parts of the season, to mitigate damage from certain pests. One tactic to increase the efficacy of natural enemies is to provide resources such as over-wintering habitat and nectar plants within the field. These types of habitat modifications are thought to build predator and parasitoid populations adjacent to the crop, thus improving pest control. We evaluated two commonly advocated natural enemy conservation tactics: beetle banks and alyssum plantings.

Over the course of two growing seasons we found higher ground and rove beetle densities in fields with than without beetle banks. However, predation of sentinel fly eggs was not affected by the density of predator beetles. We conducted two field experiments, to examine two factors that could limit fly egg consumption by predator beetles. We found that high densities of the ground beetle *Pterostichus melanarius* could limit egg predation, because *P. melanarius* is a predator of the smaller beetles that are the most effective egg predators. We also found that aphids could distract small beetles from feeding on fly eggs. Alyssum plantings were evaluated in small plot experiments. We found that the parasitism of cabbage aphids on broccoli and cabbage was not improved with increased proximity to alyssum strips.

The results of our study demonstrate several limitations of conservation biological control that growers need to be aware of before investing in natural enemy 'friendly' habitat. We showed that not all of the natural enemies conserved by a conservation tactic are beneficial for biological control, in particular large predators that primarily feed upon other predators. Also, we demonstrated that it is important to measure whether any success in natural enemy conservation actually results in improved pest control in adjacent agricultural fields.

INTRODUCTION

Natural enemies are an integral part of organic production. Organic agricultural practices generally result in a more hospitable environment for beneficial organisms than do conventional practices (Letourneau and Goldstein 2001). Despite the generally higher density of natural enemies in organic fields, pest problems continue to plague organic growers. Pests are especially problematic for growers of vegetable polycultures, because many crops are continually planted in the same field, although in different locations. Rotation of crops among beds may not reduce pest levels since many pests can disperse easily. Cultural practices such as timing of plantings to avoid peaks in pest populations may not be practical for many growers because of the need to provide product to customers at specific times. Thus, our challenge is to increase the effectiveness of biological control within complex mixed-vegetable polycultures.

Natural enemy effectiveness may in part be limited by the size (density) of enemy populations and by the variety (species richness) of beneficial species (Altieri and Whitcomb 1979, Altieri and Letourneau 1982). A number of agricultural practices have been shown to be detrimental to natural enemies by directly killing individuals, for example tillage (Symondson et al. 1996, Kromp 1999, Landis et al. 2000). Additionally, resources such as food and shelter that enemies need for survival may be limited on farms, because of practices such as weed control (Kromp 1999). The lack of these additional resources would limit the variety of species able to persist in an agricultural field. One approach to addressing the problem of limited biocontrol in organic production is conservation biological control. The objective of conservation biological control is to manipulate habitat in order to enhance the populations of important natural enemies (Barbosa 1998).

Under conservation biological control a varied assemblage of natural enemies can be established in fields. Some natural enemies will be specialized on specific pests. For example, the cabbage aphid (*Brevicoryne brassicae*) is attacked by a specialist parasitoid wasp (*Diaretiella rapae*). Other natural enemies are more generalized in their feeding, with broad diets that include many species and stages of pests. For example, ground beetles, rove beetles and spiders have been shown to be predators of root maggot (*Delia* spp.) eggs, carrot rust fly (*Psilae rosae*) eggs, aphids, and slugs (Ramert 1996, Symondson et al. 2002, Snyder and Ives 2001, 2003). Separate conservation strategies for specialist parasitoid wasps and generalist predators have been developed in numerous studies. Our objective was to evaluate conservation tactics for generalist ground-dwelling predators and specialist parasitoid wasps, respectively. We examined two conservation strategies, beetle banks for predators and alyssum plantings for parasitoids, for their ability to bolster natural enemy populations and reduce pest densities on organic vegetable farms in the Pacific Northwest.

We focused our study on the biocontrol of cole crop pests, because cole crops are an important component of mixed-vegetable organic farms, providing growers with season-long income. Also, conventional cole crop seed production is important in northwestern Washington. The region accounts for 20 to 100% of the US supply for the various types of cole crop seed (Brussels sprouts, cabbage, Chinese cabbage, cauliflower, collards, kale, rutabaga, etc.) (du Toit and Derie 2003). Many seed growers in the region are interested in the development of organic seed production to diversify their agricultural markets. By developing effective strategies for conservation biocontrol of cole crop pests within organic polycultures, we hoped to lay some important foundations for the development of organic cole crop seed production in this region.

OVERALL OBJECTIVES AND PROJECT MODIFICATIONS

As outlined in our initial proposal our project objectives were as follows:

1) Evaluate in-field refuges for predator conservation and the control of root maggots (*Delia* spp.) and aphids.
2) Evaluate efficacy of floral plantings for conservation of root maggot and aphid parasitoids.
3) Transmit our findings to growers.

Modifications to the originally proposed work plan were as follows:

Objective 1. – Through some preliminary experiments we became interested in the relationship between aphid and fly egg predation by generalist predators. So our first objective changed slightly to examine the impact of aphids on root maggot control by generalist predators. We also examined the impact of the predation of some predators by others, on root maggot biocontrol. We did not, as originally proposed, examine habitat use by predator beetles because we were unable to develop a marking system that we felt could be reliably read over the course of the growing season.

Objective 2. – The focus of this objective was redirected solely onto aphid parasitoids; due to time constraints we were not able to gather data on root maggot parasitoids.

IN-FIELD REFUGES ("BEETLE BANKS")

Background and Rationale

Habitats consisting of perennial grasses, forming thick tussocks or sod-layers, have been shown to support higher densities of beetles and spiders than are found in other habitats (Dennis and Fry 1992, Hassall et al. 1992, Thomas et al. 1992a,b, Denys and Tscharntke 2002). Grassy habitats provide stable microclimates for beetles and spiders, which is important for the predators' ability to over-winter (Desender 1982). Such habitats can be located along the field margin or within the field. A limitation of predator refuges along field margins appears to be the limited dispersal capabilities of the natural enemies themselves. Thomas et al. (2001) showed that some ground beetle species stayed locally in small patches within an agricultural field throughout the summer, while other species clustered around the field margin, and a few species had a broader dispersal range covering a larger area of the field. In our previous studies of natural enemy density and activity along grassy field margins, we have found that, at times, in-field activity of natural enemies was higher 20m into fields from grassy, than from bare ground, margins. These results suggest that increasing the density of predators within the field may require habitat manipulations closer to the crop.

In order to increase the within-field diversity and density of predators, Thomas et al. (1991, 1992a,b) developed in-field refugia for predators ("beetle banks") by planting different species of perennial grasses (*Dactylis glomerata, Lolium perenne, Agrostis stolonifera* and *Holcus lanatus*) along strips of raised earth in the middle of cereal fields. These researchers found that densities of predatory beetles and spiders were significantly higher in the refuges than in non-

refuge portions of the field, in the first and second winters after the beetle banks were planted. However, very few of the previous beetle bank studies have adequately assessed the impact of conserved predators on pest control (Kleijn and Sutherland 2003). For example, Thomas et al. (1991) observed declining predation of sentinel *Drosophila* pupae as distance from a refuge increased, suggesting that carabid species enhanced by the refuge would have an impact only on directly-adjacent pest populations. But Thomas et al.'s study did not include a control, to compare in-field predation of *Drosophila* pupae in fields without in-field refuge habitat. So it is unclear whether there truly was an overall improvement in biocontrol with addition of beetle banks (Landis et al. 2000). Similarly, Collins et al. (2002) reported reduction in aphid densities on winter wheat adjacent to beetle banks, but again this study was not replicated (several fields with beetle banks) and did not include a control (fields without beetle banks). Replicated studies of beetle banks and comparison with control fields are therefore critical for rigorous evaluation of this conservation tactic.

In greenhouse trials, egg predation by ground and rove beetles has been estimated to contribute to 17 to 30% mortality of the egg stage of root maggots (Kromp 1999). In field cage experiments conducted in 2002, we found that significantly more fly eggs were eaten in treatments that included ground and rove beetles than in treatments that had reduced beetle populations (Prasad and Snyder 2004). But ground and rove beetles are also generalist predators and so can also eat other types of prey, which may reduce the number of fly eggs eaten in the field. For example, Humphreys and Mowat (1993) found that fewer fly eggs were eaten by ground beetles in plots with high densities of Collembola. Of the 12 most commonly occurring species of ground-dwelling beetles on farms in the Pacific Northwest, five were found to readily eat *Delia* spp. eggs in Petri dish arenas (Prasad and Snyder 2004). These five included the ground beetles *Bembidion lampros*, *Bembidion tetracolum*, *Bradycellus congener*, and *Amara littoralis*, as well as the rove beetle *Aleochara bilineata* (Prasad and Snyder 2004). All of these beetles are < 1cm in length and are vulnerable to predation by the larger (>1.5 cm in length) ground beetle *Pterostichus melanarius* (Prasad and Snyder, 2004). *Pterostichus melanarius* rarely eats small prey such as fly eggs, but does eat larger herbivores such as caterpillars, slugs and smaller ground and rove beetles. Thus, in terms of fly biological control, *P. melanarius* may be a predator of the smaller more effective egg predators, rather than a predator of pest fly eggs. In our study we compared the beetle fauna and predation of sentinel eggs, on farms with and without beetle banks. We also examined the impact of alternative prey and predation among predators on fly biocontrol.

Methods

Beetle bank establishment

Beetle banks were established on each of three organic mixed-vegetable farms, located in Ladner, British Columbia; Mt. Vernon, Washington; and Carnation, Washington. A fourth beetle bank was established in a radish field, managed conventionally for weeds and nutrients but without insecticide input, at the Washington State University research farm in Mt. Vernon, WA. Beetle banks were planted between April and June 2002, by broadcasting orchard grass (*Dactylis glomerata* L.) seed in strips 1.5 m wide and from 30 to 60 m long. We also located control fields, lacking beetle banks, so that we could compare beetle activity-density in the presence versus absence of an in-field refuge. In 2003, we compared the beetle fauna on the three organic beetle bank farms with three control fields that were also managed organically. These three control

fields consisted of one mixed vegetable field, in Mt. Vernon, WA, and two broccoli monocultures, in Ladner, BC. In 2004, the beetle bank on one of the organic farms was tilled under, therefore we included the field at the university research farm as one of our beetle bank fields that year. The control fields, in 2004, consisted of two organic mixed vegetable fields, in Mt. Vernon, WA and Ladner, BC. The third control field was a cauliflower monoculture, also in Mt. Vernon, under integrated insect management and conventional weed and nutrient management. Thus in both years we attempted to control for the variation in field management by ensuring that an equal number of beetle bank and control fields were managed in a similar manner.

Beetle bank survey (Winter)

To assess the role of beetle banks as a winter habitat for beetles, we conducted a soil survey in January 2003. Soil samples were taken from three locations: within the beetle bank, from a haphazardly selected area adjacent to the beetle bank, and from a haphazardly selected area within control fields without beetle banks. We had four replicates of each type of location. At each location in each field three soil samples, consisting of a 9 cm diameter and 20 cm deep soil core, were taken. Soil samples were sorted by hand and the number of arthropods observed over the course of 30 minutes of hand sifting was recorded. Mean number of beneficial beetles per location/field was analyzed using one-way ANOVA.

Beetle survey (Growing Season)

Beetle activity was assessed using pitfall traps consisting of a 12-cm long piece of PVC pipe, buried 12-cm deep into the ground and housing a 10-cm high X 7.5 cm diameter plastic cup. Fifty ml of a soap and water solution were placed in the cup to trap arthropods. To exclude rainfall and plant debris a Styrofoam bowl was placed over the pitfall trap, supported with metal wires 15 cm above the trap opening. For both years, we sampled for ground-active beetles three times: between May 20 - 25, August 8 - 12, and September 25 - 29. For each sampling session a new pitfall trap hole was dug, and all traps were removed after three days. In fields containing beetle banks, traps were placed within 5 m of banks (and no less than 20 m from field margins), and in control fields traps were placed 20 m from margins. Trap contents were drained of soap and water and stored in ethanol until they were sorted and identified to species or morphospecies.

Predation of sentinel eggs

To determine the biocontrol efficacy of conserved beetles, we measured predation of sentinel Diptera eggs during the 2004 field season. Previous results indicated no preference among the commonly occurring carabid and staphylinid species for eggs of either *Musca domestica* (house fly) or the economically important *D. radicum* (Prasad and Snyder 2004). Thus we used the easily-propogated *M. domestica* as a surrogate for the various pest Diptera [*M. domestica* colony maintenance is described in Prasad & Snyder (2004)]. To facilitate handling, a group of five eggs (< 24 h old) were placed on 2-cm^2 pieces of peat cut from transplant pots (Plantation Products, Inc., Norton MA). Each piece of peat with eggs (an "egg card") was placed at the base of a plant and then covered with a 0.5-cm layer of soil (Finch & Elliot 1994). We used a total of five egg cards (25 eggs in each field), spaced 1 m apart along a 5-m transect that ran parallel to either the

beetle bank or, in control fields, the nearest field margin. Placement of egg cards relative to the beetle bank and/or field margin was similar to pitfall trap location (see above), however the sentinel egg and pitfall trap transects were approximately 2 m apart. Egg cards were placed in fields during the pitfall trap surveys, that is in May, August and September. For each sampling session eggs were placed in fields during the late afternoon and were collected 24 h later, when the pitfall traps were also collected.

For our on-farm comparison of beetle densities between fields with versus without beetle banks, beetle activity-densities were analyzed using repeated measures MANOVA. To homogenize variances, data were square root transformed prior to analysis. The relationship between small beetle and *P. melanarius* activity-densities, and the proportion of sentinel eggs eaten, for each sampling date, was examined using multiple regression.
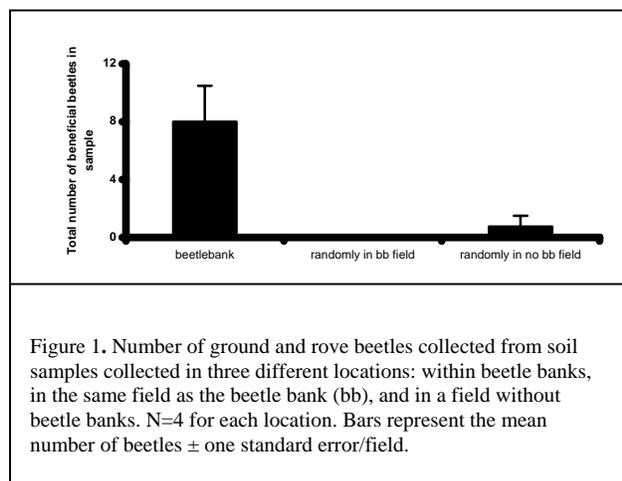
Field experiments

Based on the results of the on-farm observations we were interested in two types of interactions that may have limited egg predation by beetles in the field. First we examined the impact of *P. melanarius*, the large predator that we suspected was eating smaller predators. Second, we manipulated densities of aphids to see if they acted as an alternate prey in this system, disrupting fly egg predation by small beetles. The basic protocol for both experiments was the same. Experimental units were 2 X 2 X 2 m cage consisting of a PVC pipe frame and covered on all sides, but the bottom, with a fine mesh screen. Cages were set up in a 1.5-acre radish field at the university research farm. Each experiment consisted of four experimental manipulations, conducted inside a cage and also an Open (un-caged) control treatment (Table 1). For each experiment we assessed the impact of the different natural enemy treatments by measuring the predation on 20 sentinel *M. domestica* eggs. Each treatment was replicated five times.

Table 1. Summary of field cage experiments, and treatments, to examine the impact of intraguild predation and aphid alternative prey on fly biocontrol by generalist beetle predators.

Experiment	Experimental Treatments
Experiment 1 (Small Beetles + *P. melanarius*)	-uncaged & no manipulation open plot (Open) -no beetles added to cage (Removal) -28 small beetles with no *P.melanarius* (0X) -28 small beetles with 7 *P. melanarius*/cage (1X) -28 small beetles with 28 *P. melanarius*/cage (4X)
Experiment 2 (Aphid Manipulation)	-uncaged & no manipulation open plot (Open) -Removal treatment (beetles taken out) (Removal) -28 small beetles with no aphids (No) -28 small beetles with 30 aphids (Low) -28 small beetles with 300 aphids (High)

Results

Predator densities in beetle banks (in winter)

Figure 1. Number of ground and rove beetles collected from soil samples collected in three different locations: within beetle banks, in the same field as the beetle bank (bb), and in a field without beetle banks. N=4 for each location. Bars represent the mean number of beetles ± one standard error/field.

Significantly more predator beetles were recovered in soil samples from the beetle bank, than in areas adjacent to the beetle bank in the same field, or within fields without banks (Fig. 1; $P = 0.008$).

Figure 2. Beetle activity – density in fields with and without beetle banks, in 2003 and 2004.

Predator response to beetle banks (in the growing season)
As expected, total beetle activity-density was significantly higher in fields with beetle banks than without in both 2003 (Fig. 2A; *Treatment $P = 0.03$; Time $P = 0.16$; Treatment X Time $P = 0.17$*) and in 2004 (Fig. 2B; *Treatment $P = 0.097$ one-tailed; Time $P = 0.12$; Treatment X Time $P = 0.33$*). The most abundant species or morphospecies of small beetles captured over the course of both years from both types of fields were *B. tetracolum* (13.6 % of total catch), *B. lampros* (17.0 %), *B. congener* (12.0 %), *Amara* spp. (7.6 %) and an Aleocharine morphospecies (23.0%). Although relatively low in abundance compared to the total catch (5.9 %), *Aleochara* spp and *P. politus* were the other abundant staphylinids.
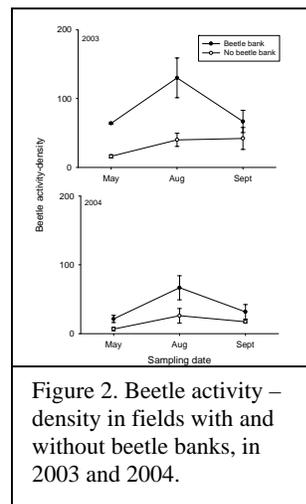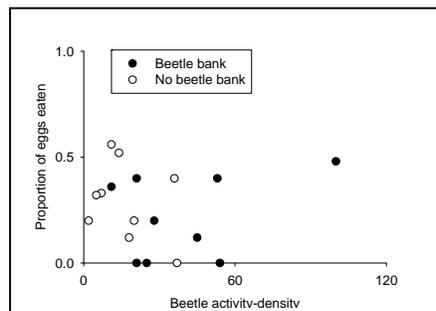
Predation of sentinel eggs

Figure 3. Predation of sentinel *Musca domestica* eggs in fields with and without beetle banks during 2004. Each point represents proportion of eggs eaten out of 25 and total beetle activity-density during the same sampling period.

There was no relationship between beetle activity-density and predation of sentinel eggs (Fig. 3). In May 2004, predation of sentinel eggs in the field was not correlated with either small beetle activity-densities (correlation coefficient = -0.03, $P = 0.77$) or *P. melanarius* activity-densities (correlation coefficient = -0.10, $P = 0.24$). Similar results were also observed in August (small beetles correlation coefficient = -0.01, P = 0.26; *P. melanarius* (correlation coefficient = -0.01, $P = 0.13$) and in September (small beetle correlation coefficient = -0.04, $P = 0.08$; *P. melanarius* correlation coefficient = 0.001, $P = 0.80$).

Impact of large predators and aphids on egg predation

The frequency of egg predation was significantly lower in the highest (4X) *P. melanarius* density treatment than in the 0X or 1X treatments (Fig. 4A; *Treatment: $P = 0.01$*; *Time: $P = 0.41$*; *Treatment X Time: $P = 0.58$*). Egg predation declined with increasing aphid density (Fig. 4B; *Treatment: $P = 0.02$*; *Time: $P < 0.01$*; *Treatment X Time: $P = 0.44$*). The significant aphid effect was driven by reduced egg consumption in High compared to No ($P = 0.02$ for High vs. No, Tukey-Kramer post-hoc comparison); egg consumption in Low was similar to both High and No ($P > 0.05$ for all other post-hoc comparisons).
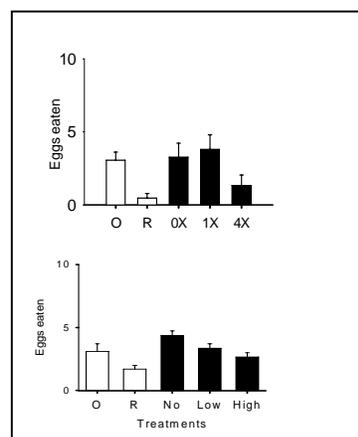

Figure 4. Results of intraguild predation (A) and alternate prey (B) experiments. Egg predation was measured every 48-h for 8 days. Data represents mean egg predation over course of experiments.

FLORAL PLANTINGS

Background and Rationale

It has long been known that parasitoids require more than just hosts for successful reproduction (Wolcott 1942). These requirements include favorable microhabitats, alternative hosts, protection from natural enemies, and food (Barbosa and Benrey 1998). The connection between food availability for adult wasps and successful parasitoid reproduction is probably the best understood. Numerous studies have demonstrated that pollen, floral and extrafloral nectar, and aphid honeydew can increase the longevity and fecundity of female parasitoids (e.g. Baggen and Gurr 1998; Hagley and Barber 1992; Idris and Grafius 1995; Stapel et al. 1997; Takasu and Lewis 1993). Parasitoid survivorship, immigration, and retention may also be increased by the presence of these foods (Altieri and Whitcomb 1979; Altieri and Letourneau 1982; Stapel et al. 1997; Wäckers 1994). In the field, the availability of parasitoid food plants has been shown to translate into higher parasitization rates (Grossman and Quarles 1993; Leius 1967; Stapel et al. 1997), and field parasitization rates are positively correlated with the success of biological

control programs (Hawkins et al. 1993). Thus, the conservation of parasitoids by providing food plants holds great promise for the improvement of biological control.

Sweet alyssum, *Lobularia maritime*, has been shown to be effective for parasitoid conservation. The flowers are highly attractive to parasitoids because they contain shallow nectaries and the plant blooms most of the year. Sweet alyssum has been shown to increase parasitization of the cabbage aphid in broccoli (Luna et al. 1998) and the green pea aphid, *Myzus persicae*, in lettuce fields (Grossman and Quarles 1993). The objective of this part of the study was to evaluate sweet alyssum for natural enemy conservation and aphid control.

Methods

We planted 4 blocks of broccoli and cabbage. Each block was 50 meters long and 2 meters wide and included 4 rows of plants. In the middle of each block we planted a 2 X 2 meter area with alyssum. Four plants at each of 5 distances from the alyssum (0-5, 5-10, 10-15, 15-20, and 20+ meters) were visually searched and the number of aphids, aphid mummies, adult parasitoids, and all other natural enemies was recorded. We did this in both directions from the alyssum, for a total of 10 samples per block. Visual surveys were conducted on 6 dates (July 1, 11, 19, 25; Aug 1, 8). A random number table was used to select the plants that were visually inspected at each distance, so the same plants were not sampled at each sample date.
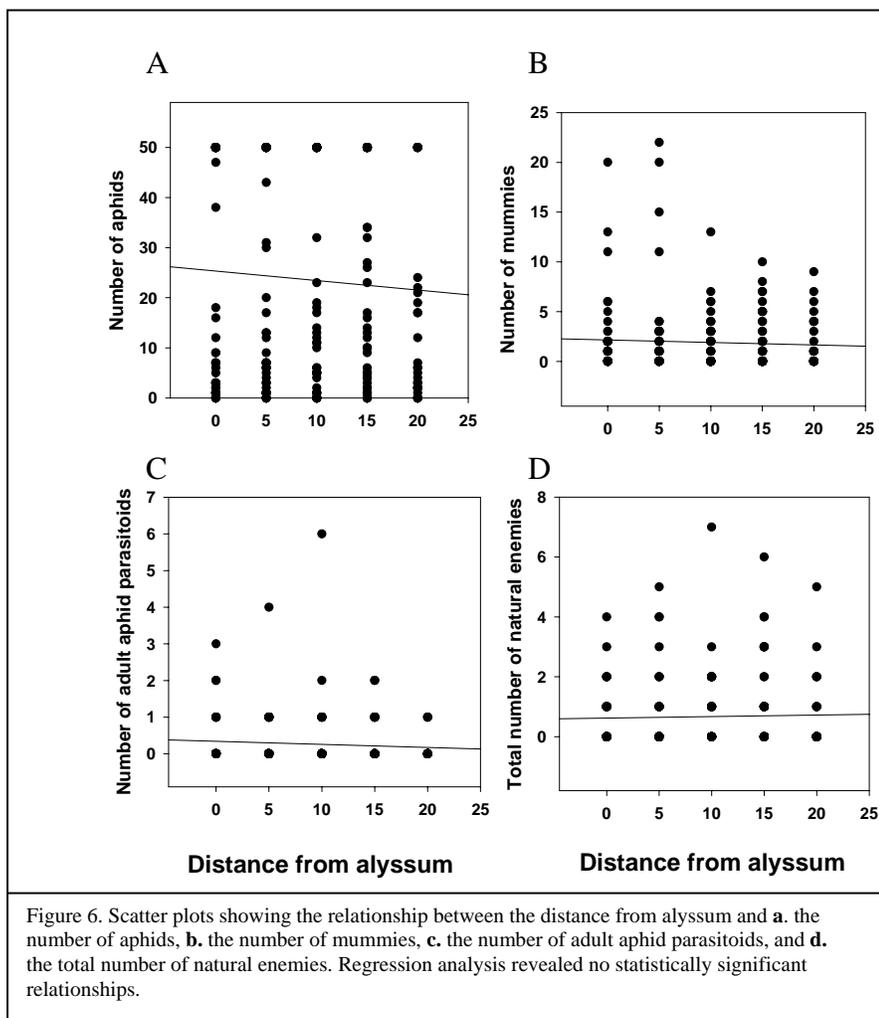
To examine the relationship between distance from alyssum refuges and aphid and natural enemy populations, we used regression analysis. There was no statistically significant relationship between the distance from alyssum and the number of aphids for any of the 6 sample dates. All 6 sample dates were combined (that is, all data points were treated as if they were independent) for the regression analysis shown in Table 2, and
we tested for a relationship between the distance from alyssum and the number of un-hatched mummies, adult parasitoids, and the total number of natural enemies. Note that because aphid density did not vary with distance from alyssum, any significant relationship would not be caused by natural enemies responding to variation in aphid density. It is reasonable to expect that these observations truly are independent of each other because the time between each sample date was long enough that it would be extremely unlikely that the same individuals would be counted more than once.

Results

There was no significant relationship between the distance from alyssum and the number of aphids (Fig. 6A; $P = 0.38$), mummies (Fig. 6B; $P = 0.45$), adult parasitoids (Fig. 6C; $P = 0.20$), or the total number of natural enemies (Fig. 6D; $P = 0.66$) (see also Table 2).

Table 2. Results from regression analysis for effect of proximity to alyssum strips on aphids, aphid mummies, adult parasitoids and total natural enemy densities on broccoli and cabbage plants.

Response variable	beta	t	P-value
Aphids	-0.18923	-0.88	0.38
Mummies	-0.02502	-0.75	0.45
Adult parasitoids	-0.00841	-1.28	0.20
Total natural enemies	0.005093	0.45	0.66

Figure 6. Scatter plots showing the relationship between the distance from alyssum and **a.** the number of aphids, **b.** the number of mummies, **c.** the number of adult aphid parasitoids, and **d.** the total number of natural enemies. Regression analysis revealed no statistically significant relationships.

DISCUSSION

The objective of any natural enemy conservation tactic is not only to improve densities of predators and parasitoids in fields, but also to reduce pest populations. Unfortunately, few studies of habitat enhancement for conservation biological control have examined the impact of the manipulation on pest densities (Kromp 1999, Kliejn and Sutherland 2003). For the last two years we have conducted detailed studies of the efficacy of two conservation tactics, beetle banks and floral plantings. For each type of tactic we examined whether target natural enemy populations increased in fields including, or closest to, the conservation tactic. We then examined if densities of two target pests, flies and aphids, declined as a consequence of the habitat manipulation. In both sets of studies we also observed several unexpected outcomes that will likely impact the efficacy of these tactics in the field. Each of these aspects, natural enemy enhancement, pest suppression, and unexpected impacts, will be discussed for the two tactics separately. This will be followed by general recommendations regarding conservation biological control on mixed-vegetable organic farms and for future research.

Beetle banks - Our results indicated that the predator beetle fauna on organic vegetable farms in the Pacific Northwest was enhanced with the addition of beetle banks to the interior of fields. Beetle densities were higher in beetle banks during the winter, indicating that these habitats provided beetles with shelter. Similar results have been observed in a number of other studies (e.g., Thomas et al. 1992a). During the field season we also observed higher beetle densities in fields with beetle banks than without. This finding was consistent over both years of our study. However, the differences between beetle bank and no beetle bank fields was less dramatic in 2004. In part this reflects the difference in the use of two organic monoculture fields in 2003 as controls and two organic polyculture fields in 2004 for the same purpose. Many small farms have high field margin to field ratios, thus these fields have built-in beetle banks. However, we emphasize that previous studies have established that carabid and staphylinid beetles have specific habitat requirements during the winter (Thomas et al. 1991, 1992b, Collins et al. 2002), and thus beetle banks and/or field margins should be managed to provide the tussocky grass habitat favored by these predators. The impact of providing this specific habitat for ground and rove beetle can be seen during the spring of both years, when in-field densities of small beetles were 2- to 4-times higher in organic fields with than without beetle banks (Fig. 1A and B).

Although we found higher predator densities in fields with beetle banks, there was no pattern in sentinel egg predation that indicated a relationship between beetle densities and pest suppression. These results contradict the findings of a previous study, in which aphid densities on winter wheat were observed to be lower adjacent to a beetle bank (Collins et al. 2002). However, in their study, Collins et al. (2002) only found improved biological control in one of the three measurements of aphid density. So, from both our study and that of Collins et al. (2002), the relationship between natural enemy conservation and biological control of target pests remains ambiguous. The lack of a clear relationship between predator density and herbivore suppression can in part be attributed to the omnivorous nature of carabids and staphylinids. Our field cage experiments demonstrated two ways that omnivory could account for the limited predation of fly eggs by conserved beetles: predation of small beetles by the larger ground beetle *Pteroschicus melanarius*, and predation of aphid alternative prey in preference to our target fly eggs.

From previous studies with our guild of beetles, we know that predation among predators is a possible interaction when *P. melanarius* and small beetles are present together (Prasad & Snyder 2004). Our field data also showed dramatically higher densities of *P. melanarius*, the species that eats other predators, in fields with beetle banks by the end of both growing seasons (Fig. 1C and D). In our first cage experiment we mimicked the ratios of small beetles to *P. melanarius* observed in our beetle bank fields, 1:0, 4:1, and 1:1. We observed a decline in egg predation in treatments with the highest *P. melanarius* density. Similarly, in our second cage experiment we mimicked three different aphid densities observed in the field, none, low and outbreak. In this experiment we added the same number of small beetles to all three types of cages. We found a gradual decline in fly egg predation with increasing aphid density. Other studies have shown that Collembola can also distract ground and rove beetles from feeding on fly eggs (Humphreys & Mowat1993). Thus in this one system we have shown that two forms of omnivory, predation among predators and predation of alternative prey, can limit conservation biological control of the target fly pest.

Floral plantings – We were interested in the role of sweet alyssum as a tactic for conserving parasitoid wasps because previous results had shown this species to be highly effective (Luna et al. 1998). However, in our first summer we observed little evidence that alyssum would improve pest control. We found no evidence that parasitoid or predator densities increased in sweet alyssum plots (Fig. 6C-D), and no evidence that parasitism of aphids on *Brassica* plants increased with the addition of sweet alyssum (Fig. 6B), or that percentage parasitism increased (Fig. 6A). Finally, and most problematic, we found dramatically higher crucifer flea beetle densities in sweet alyssum (unpublished data). One of our cooperating growers also reported increased flea beetle densities adjacent to alyssum plantings.

Recommendations – The results of this study suggest that there are several negative factors that growers need to weigh before implementing conservation biocontrol tactics on their farms. First, when the targets of conservation biological control are generalist predators, it is important to consider the response of any large, particularly aggressive predator(s) to the conservation tactics. We observed dramatically higher densities of the large beetle *Pterostichus melanarius* in fields with beetle banks by the end of each growing season. High *P. melanarius* densities were associated with reduced egg predation by smaller beetles. Some conservation tactics may be especially favorable to large predators that feed heavily on other predators. For example, *P. melanarius* has been shown to respond especially well to a variety of natural enemy conservation techniques, including application of straw or manure to the soil (Symondson *et al*. 1996; Raworth *et al*. 2004) and reduced insecticide input (Shah *et al*. 2003). If other top predators respond to conservation tactics as enthusiastically as does *P. melanarius*, then improved pest control as a result of higher densities of generalists cannot be assumed. Second, conservation biological control tactics can also increase densities of alternative prey, which may further distract predators from feeding on target pests.

The findings of our research contradict much of the popular wisdom regarding the role of habitat manipulations in conserving natural enemies and subsequent impacts on pests. In neither system was there strong evidence for an improvement in biological control with the provision of natural enemy 'friendly' habitat. One reason for the discrepancy between our findings and those of some other studies in the beetle bank literature, is that we included control fields (or plots), and that our treatments were replicated. We recommend that similar studies examining the

impact of conservation practices on pest suppression include replication, on either multiple plots or farms, and that proper control treatments be included in all experiments. Despite the limitations we discovered from our studies, we recommend that future beetle bank studies focus more on larger herbivores, such as slugs and caterpillars, which are the favored prey of *P. melanarius*.

PROJECT IMPACTS

Our research program is focused on both the applied and basic aspects of conservation biological control. The data resulting from the OFRF and WSCPR grants have been shared with both growers and other researchers in a variety of formats. In addition, we have also included a list of manuscripts that resulted from, directly or indirectly, research funded by the OFRF.

Grower Outreach and Information Dissemination:

Presentations at Grower Meetings:

Snyder, W.E. and Prasad, R.P. 2005. Ecological challenges of conservation biological control. Talk presented at Western Washington Horticultural Association Meeting. January 11, Sea-Tac, WA.

Prasad, R.P. and Snyder, W.E. 2005. The challenges of successful conservation biocontrol in vegetable fields. Talk presented at Western Washington Horticultural Association Meeting. January 11, Sea-Tac, WA.

Snyder, W.E. 2004. Strategies to conserve beneficial insects and spiders. Talk presented during the *Making the Bugs Work For You Symposium* at Washington Tilth Annual Meeting. November 12, Portland OR

Prasad, R.P. 2004. Identification and biology of common vegetable pests and natural enemies. Coquitlam Organic Growers Association Meeting. May 31, Coquitlam BC.

Prasad, R.P. and Snyder, W.E. 2003. Natural enemies of root maggots (*Delia* spp.). Talk presented at Pacific Northwest Vegetable Association Annual Meeting. November 19, Pasco WA.

Prasad, R.P. 2003. Research up-date and informal presentation at annual Puget Sound Seed Growers' Executive Meeting and tour of research plots as part of Vegetable Seed Growers' Field Day. July 29, Mt. Vernon WA.

Prasad, R.P. 2003. Insect pests of (cole crop) seed: Identification and Control. Talk presented to Puget Sound Seed Growers' Association Meeting. February 27, Mt. Vernon WA.

Informal Extension Presentations:

Bug-scaping Faire, Oregon State University, Corvallis OR. An informal presentation in which growers learn about various farmscaping strategies in a market or "faire" format. February 2004 and December 2004.

Farm Walks for Growers, Washington State University. A series of farm walks conducted over the course of the summer, in which growers and WSU extension agents and researchers discussed problems associated with organic production on small farms. We presented

information on natural enemy conservation and root maggots. July 12 (Full-Circle Farm), July 14 (Mother Flight Farm) and August 10 (Dona Flora Farm).

On-line Resources: http://personal.palouse.net/gchang/SpudPreds.html
The above web-site is currently in construction. When complete we plan on introducing the site to growers at field days and also with an article in the Washignton Tilth Producers quarterly newsletter.

Scientific Outreach

Presentations at Scientific Meetings

Snyder, W.E. and Straub, C.S. 2005. Biodiversity and aphid biological control. Entomological Society of America – Pacific Branch Meeting Asilomar, CA.

Prasad, R.P. and Snyder, W.E. 2005. Indirect effects in a multiple predator – prey food web. Entomological Society of America – Pacific Branch Meeting Asilomar, CA.

Prasad, R.P. and Snyder W.E. 2004. Effect of alternative prey and intraguild predators on biocontrol. Entomological Society of America. Salt Lake City, UT.

Prasad, R.P. and Snyder, W.E. 2004. Factors limiting conservation biocontrol by carabids and staphylinids. Ecological Society of America, Portland OR.

Prasad, R.P. 2004. Both intra-guild predation and alternative prey limit conservation biological control. Entomological Society of America - Pacific Branch Meeting, Bozeman MT.

Prasad, R.P. and Snyder, W.E. 2003. Natural enemy diversity and biological control of dipteran pests. Entomological Society of America, Cincinnati OH.

Publications (including manuscripts in review and in preparation):

Prasad, R.P. and Snyder, W.E. 2004. Predator interference limits fly egg biological control by a guild of ground-active beetles. *Biological Control*. 31:428-437.

Prasad, R.P. and Snyder, W.E. *In review*. Trait-mediated indirect effects in multiple predator-prey webs: the role of predator behaviour. Submitted to *Ecology Letters*

Prasad, R.P. and Snyder, W.E. *In review*. Omnivory complicates conservation biological control targeting generalist predators. Submitted to *Journal of Applied Ecology*

Related publications & manuscripts
Snyder, W.E., Chang, G.C. and Prasad, R.P. *In press*. Biodiversity and successful conservation biological control: is there a relationship? In Barbosa, P. and Castellanos, I. (editors), *Ecology of Predator-Prey Interactions.* Oxford University Press, London.

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Organic vegetable production plays an important role in improving farmers' income and peoples' quality of life. The ban of synthetic pesticides and fertilisers in organic farming represents a... Yang N, Zang L, Wang S et al (2014) Biological pest management by predators and parasitoids in the greenhouse vegetables in China. Biol Control 68:92–102. https://doi.org/10.1016/j.biocontrol.2013.06.012 CrossRefGoogle Scholar. Zhang F, Li S, Xiao D et al (2015) Progress in pest management by natural enemies in greenhouse vegetables in China. Integrating conservation of generalist predators and specialist parasitoids in Pacific Northwest org William E. Snyder. Read more. 1. A host specialist parasitoid is thought to have greater efficiency in locating hosts or greater ability to overcome host defence than a generalist species. This leads to the prediction that a specialist should locate and parasitise more hosts than a generalist in a given arena. The work reported here tested these predictions by comparing the host-searching behaviour of Diadegma semiclausum (a [Show full abstract] specialist) and Cotesia plutellae (an oligophagous species), two parasitoids of larval Plutella xylostella. View full-text. Article. Host-parasitoid models in temporally and spatially varying environment. 2001. Generalist predators disrupt biological control by a specialist parasitoid. Ecology 82:705–716. Available online at: https://doi.org/10.1890/0012-9658(2001)082[0705:GPDBCB]2.0.CO;2 (verified 6 Apr 2020). Snyder, W. E., and A. R. Ives. 2003. Interactions between specialist and generalist natural enemies: parasitoids, predators, and pea aphid biocontrol. Ecology 84:91–107. This is an eOrganic article and was reviewed for compliance with National Organic Program regulations by members of the eOrganic community. Always check with your organic certification agency before adopting new practices or using new materials. For more information, refer to eOrganic's articles on organic certification. Generalist predators and parasitoids are considered to be important regulators of aphids. The former not only feed on these pests, but might also consume parasitoids at all stages of development. This direct or coincidental interference affects the natural control of aphids, the scale of which is largely unknown, and it has rarely been examined under natural conditions. Here, molecular diagnostics were used to track trophic interactions in an aphid-parasitoid-generalist predator community during the build-up of a cereal aphid population. We found that generalist predators, principally carabid and staphylinid beetles as well as linyphiid spiders, had strong trophic links to both parasitoids and aphids. Particularly, the abundance of parasitoids and species richness of both parasitoids and predators increased with the structural connectivity of rice bunds, which have proven to be an important element in other studies as well (11), but which can hardly be captured with coarser-resolution land-use maps. (1996) Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. Ecology 77:1975–1988. OpenUrl CrossRef.