The Influence of Vegetative Diversity on the Natural Control of *Lygus hesperus* by *Geocoris spp.* in Organic Strawberry Farms

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ABSTRACT

Diversified agricultural systems have shown promising benefits for increasing biodiversity and ecosystem services. Integrating knowledge about the effects of landscape and local vegetation on pest suppression can improve potentially costly and toxic pest management in agroecosystems. The western tarnished plant bug, Lygus hesperus, (Hemiptera: Miridae), is currently heavily studied in efforts to minimize the extensive damage it causes to strawberry fruit systems. This study will present the relationships between landscape and local vegetative diversity and L. hesperus pest suppression in organic strawberry farms in Central Coast California. Fifteen organic strawberry systems were evaluated. In the first sample round I compared monoculture strawberry farms in an agriculturally intensive landscape and polyculture strawberry farms surrounded by bountiful natural habitat. For the second sample round I included monoculture farms surrounded by bountiful natural habitat and polyculture farms in an agriculturally intensive landscape were compared to explore L. hesperus pest pressure and damage to strawberries. The abundance of a L. hesperus natural enemy, Geocoris spp. (big-eyed bug), were compared to abundance of L. hesperus and fruit damage in all four farm site types to examine the interaction between vegetative diversity and natural pest control. My results show that crop diversity is more important than landscape diversity for determining L. hesperus and Geocoris spp. abundance in organic strawberry farms. Furthermore, landscape complexity and crop diversity did not directly influence fruit damage. It can be concluded that vegetative diversity may indirectly affect fruit damage by influencing pest abundance, which is directly associated with fruit damage.

KEY WORDS

Landscape ecology, crop diversity, agroecosystems, Lygus hesperus, edge effects

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INTRODUCTION

To maintain demand with the growing interest in organic fruits and vegetables, organic farmers have expanded their production to a larger-scale and still face pest problems. Organic farms on a large-scale of production are heavily influenced by chemical usage practices for pest management compared to small-scale organic farms. Organic strawberry growers can face many challenges in controlling insect pests, since organic chemical measures of control are expensive and have low efficacy (Rhainds et al. 2002; Swezey et al. 2007). An alternative and ecologically sensitive method of insect pest control regularly used in organic production is commonly known as Integrated Pest Management (IPM). Integrated Pest Management is an approach that emphasizes maintenance of natural ecosystem processes in agricultural systems (Cumming and Spiesman 2006). Integrated Pest Management methods have been previously incorporated in strawberry production areas to control pests such as the western tarnished plant bug (*Lygus hesperus*). Despite the many successes in pest regulation with the use of IPM, incorporating landscape ecology into IPM would improve agroecosystem management by facilitating ecosystem services such as natural pest control with insect predators (Cumming and Spiesman 2006).

Understanding the relationships between landscape scale vegetative diversity and insect populations can help to build a framework for the design and management of agroecosystems, particularly for successful pest suppression by natural enemies. The existence of diverse vegetative habitats at the landscape scale has been associated with the enhanced presence of predators to agricultural pests (Bianchi et al. 2006; O'Rourke et al. 2011). Diversity in landscape structures influences ecosystem services provided by insects, by supporting generalist predator populations such as *Harmonia axyridis*, to suppress the soybean pest, *Aphis glycines* (Gardiner et al. 2009). Alternative vegetation in agricultural landscapes provides alternative hosts resources that benefit natural enemies as well as become a source for predators to export natural control services into adjacent cropping systems (Tscharntke et al. 2005b; Rand et al. 2012). Insect pest 'spill over' effects from surrounding pest infested cultivated land are known to occur on adjacent farms (Gosme et al. 2012). Although landscape diversity in agricultural systems have shown to provide ecosystem services such as pest control, the benefits have yet to be studied in an organic strawberry system (Gardiner et al. 2009; O'Rourke et al. 2011).

The western tarnished plant bug, Lygus hesperus (Hemiptera: Miridae), is a common pest that causes great economic loss for numerous crops including strawberries. Lygus hesperus is a concern in large production areas such as Santa Cruz, Watsonville, and Salinas growing regions of the California Central Coastline (Swezey et al. 2007). Although strawberries are not native hosts for L. hesperus, the colonization of this crop by L. hesperus on the California Central Coast is a result of the absence of other host plants in the area during dry periods (Udayagiri and Welter 2000). A study showed in simplified landscapes the crop is the only food source available for herbivores, this attracts specialized pests and consequently causes large pest populations and yield loss (Poveda et al. 2012). Local (on-farm) vegetative diversity is most significant in highly simplified landscapes, since simple landscapes are known to have low ecosystem services compared to diversified landscapes (Tscharntke et al. 2005a). Crop diversity has also shown to suppress the incidence of insect pests by enhancing natural enemies when compared to farms with a single crop species (Letourneau et al. 2011; Kremen and Miles 2012). Hypotheses to explain potential mechanisms of reduced pest incidences in diversified farms are the "Enemy Hypothesis" and the "Resource Concentration Hypothesis". The "Enemy Hypothesis" explains that lower herbivores found in farms with crop diversity are due to a greater attractiveness to natural enemies because of resources and habitats that are available than in monocultures (Pimentel 1961; Root 1973). The "Resource Concentration Hypothesis", alternatively known as the "Disruptive Crop Hypothesis", explains that the probability of herbivores finding their host plant is higher in monocultures than in mixtures of several species in which the specialist herbivore is less likely to find its host plant due to the presence of mixed phytochemical cues (Tahvanainen and Root 1972; Root 1973; Vandermeer 1989). The effects of crop diversity in organic strawberry farms have yet to be investigated.

Oviposition by *L. hesperus* adults and feeding by adult and nymph generations are both known to deform young strawberry fruits (Udayagiri and Welter 2000, Swezey et al. 2007). Chemical insecticides are the most effective method at controlling *L. hesperus* in conventional strawberry production, however, Pickett et al. (1994) found *L. hesperus* damage to strawberries was reduced by 43-74% with the use of tractor-mounted vacuum devices compared to untreated controls. This suggests that a non-chemical method for controlling pests can be largely effective. Other studies have also found promising results in non-chemical *L. hesperus* pest control using IPM practices with specialist parasitoid wasps, alfalfa hedgerows, and bug vacs. Taking

advantage of high abundance of predators diversified farms offer may provide natural control of *L. hesperus* by insect predators and reduce the need for chemical and mechanical inputs.

Integrated Pest Management research has greatly prevented fruit damage in strawberry production in the California Central Coast, but additional research to understand the role of generalist predators such as *Geocoris spp*. can also be beneficial to IPM. The big-eyed bug, *Geocoris spp*. (Heteroptera: Geocoridae) such as *Geocoris pallens* and *Geocoris punctipes* are generalist predators of *L. hesperus* in strawberries (Robert Bugg, pers. comm., consulting biologist). Predation by *Geocoris spp*. is known to be most effective at suppressing *L. hesperus* nymphs compared to *L. hesperus* adults in cotton crops (Zink and Rosenheim 2008). Nevertheless, it is not clear how generalist predator *Geocoris spp*. respond to different landscape and local (on-farm) spatial scales in organic strawberry systems for the control of *Lygus hesperus*.

The goal of this study is to determine whether there is a relationship between landscape and local scale vegetative diversity and the natural control of the strawberry pest L. hesperus by the generalist predator *Geocoris spp.* in organic strawberry farms. More specifically, I ask whether increasing vegetative diversity on the farm by growing multiple types of crops can provide an effective IPM strategy to substitute chemical pest control of L. hesperus. To tease out the effects of landscape and local scale diversity on natural control in strawberries I asked two main questions: (i). How do landscape complexity and crop diversity affect Lygus hesperus and Geocoris spp. abundances in strawberry crops? (ii). How does landscape and crop diversity reduce Lygus hesperus damage? I hypothesize (i). sites with greater vegetative diversity will support higher average natural enemies (Geocoris spp.) abundance because of increased resources provided by natural habitat and diversity of crop plant hosts. In the most vegetative diverse sites, I expect to find the lower abundances of the strawberry pest L. hesperus associated with higher abundances of their natural enemies, Geocoris spp. (ii). There will be less strawberry damage in the most vegetative diverse sites. If vegetative diverse sites can mediate more natural control of L. hesperus then this should result in less pest presence and less fruit damage. If my hypotheses are correct, farmers may benefit from the natural control services insect predators offer and reduce chemical input costs to control this strawberry pest.

METHODS

Experimental sites

I conducted two sample rounds, the first sample round was during the second week of July 2012 as one of the seasonal population incidences of *Lygus hesperus* in the California Central Coast occurs in July (Swezey et al. 2007). The second sample round was conducted in the second week of August 2012 due to logistical time constraints instead of attempting to align with the seasonal population incidence. Though it was understood that *L. hesperus* should still be detected at this time. I sampled 15 California Certified Organic Farming (CCOF) strawberry farm sites in Santa Cruz and Watsonville California. Using only organic farms as opposed to a mix of organic and conventional reduces chemical input variation. Organic farming does still use chemical inputs, however, those used by organic growers will likely be similar across organic farms. In addition, I required both monoculture and polyculture farm sites to be under organic practice. Polyculture farms tend to be organically managed, thus to remain consistent and control for variation, I sampled organic monoculture farms. I defined monoculture farms as having one crop type (strawberry) in greater than five acres and polyculture farms as having more than five crop types in less than five acres (non-strawberry crops varied per site).

In the first sample round, to see if I could detect any effects of vegetative diversity on predator and pest abundances, I compared the most extremely contrasted sites with regards to vegetative diversity. To be more specific, I compared the least diverse sites, three monoculture farms in a 'simple' intensive agricultural landscape setting (MS sites), to the most diverse sites, four polyculture farms in a 'complex' non-crop vegetative landscape setting (PC sites). Landscape was classified as 'simple' if the farms are located in agriculturally intensive areas with 0-10% surrounding natural habitat. Landscape was classified as 'complex' if the farms are surrounded by more than 30% natural habitat (Kremen et al. 2004; Tscharntke et al. 2005a). Landscape diversity was characterized by digitizing 2 km buffers around field sites using aerial photos in ArcGIS 10.0 (ArcGIS® software by Esri). To tease out effects of landscape versus local crop diversity on natural pest control, I included two more site types in the second sample round. Four monoculture farms in a 'complex' non-crop vegetative landscape setting (MC sites) and three polyculture farms in a 'simple' intensive agricultural landscape setting (PS sites) were

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included in the second sample round (Fig. 1). In addition, another PC site was included in the second sample round resulting with a total of five PC sites. I used the same varieties of strawberries across as many sites as possible; varieties include two University of California (UC) varieties and one proprietary variety.

I expected pest abundances to be higher in edge versus field because studies have shown that 'spill over' from neighboring conventional fields act as sources for pest migration (Gosme et al. 2012). Non-crop vegetation from the complex landscape can serve as an alternate habitat for natural enemies, thus I also expected higher abundances of natural predators on the edge versus field. To test for these spill over effects I conducted my sampling along two 80 meter transects to compare the field and edge in each farm. I initiated one transect on the first bed of strawberries, parallel to the longest non-strawberry crop edge (0m) and the second 15–20m into the field from the edge. In the first sample round I conducted 40 samples per farm site and 30 samples per farm site in the second sample round. Results from my first sample round indicated strong statistical effects. Given the power of the first results and logistical constraints of doubling the number of sites to sample, I decided to lower the sampling effort in the second sample round. Each sample was composed of three healthy strawberry plants. Overall, for the first sample round I evaluated 120 plants for insect sampling (40 samples) and 40 plants for fruit damage at each site. In the second sample round I evaluated 90 plants (30 samples) for insect sampling and 30 plants for fruit damage.



Figure 1. Graphical depiction of the four farm site types. Top left: monoculture/simple (MS); top right: polyculture/complex (PC); bottom left: polyculture/simple (PS); bottom right: monoculture/complex (MC). Different symbols inside the boxes represent different crops surrounding strawberries in polyculture sites. The shapes outside the boxes on the right represent natural habitat.

Insect Sampling

I counted *Lygus hesperus* nymphs and *Geocoris* spp. using a plant beating method with a hand-held beating tray as described in Zalom et al. (1993). *Geocoris spp.* are only known to predate on *L. hesperus* nymphs and the flying mobility of *L. hesperus* adults would be challenging to count, thus I only used *L. hesperus* nymph data to evaluate mean *L. hesperus* abundance. The hand-held beating tray is made up of muslin cloth stretched over a 12-inch diameter embroidery hoop. I systematically sampled strawberry plants by beating the upper portion of a strawberry plant 4–6 times to dislodge any *L. hesperus* and *Geocoris* spp. from the plants, catching them on the beating tray. I identified *L. hesperus* and *Geocoris* spp. to genus level in the field immediately after beating and recorded their abundances after each beating. For the purpose of this project identification to species level was not necessary.

Fruit Damage

After three plants within each sample were beaten, I randomly selected one of the three plants to evaluate *L. hesperus* fruit damage. I had selection criteria where if the plant selected did not have fruits or was diseased, then I would chose a different plant from the three. I recorded the number of damaged and undamaged strawberries on each chosen sample plant. As described by University of California IPM management guidelines, strawberry fruits that had straw-colored seeds and had indentations that were not due to a lack of pollination were indicators of *L. hesperus* damage (Fig. 2).



Figure 2. Examples of strawberry damage due to pest and pollination. Top: malformed strawberry with fertilized straw-colored seeds due to *Lygus hesperus* damage (A and B). Bottom: malformed strawberry with unfertilized and underdeveloped ovules due to lack of pollination (C and D).

Statistical Analyses

Lygus hesperus and Geocoris spp. abundance

Means and standard errors of *L. hesperus* nymph and *Geocoris* spp. abundances were generated using a statistical software, R (Version 2.15.1 http://cran.r-project.org). Linear mixed-effects models by the Laplace approximation as a multivariable analysis were used to explore the

relationships between landscape and crop diversity (Package lme4 version 0.9999999-0). A Poisson distribution was used in my evaluations since Geocoris spp. and L. hesperus nymph counts did not meet assumptions of normal (Gaussian) distribution. The response variable was either L. hesperus or Geocoris abundance and I considered the fixed effects of crop type (polyculture, monoculture), landscape context (complex, simple), field position (edge, field), and sample round (round 1, round 2). I considered the interaction between crop type and landscape context on L. hesperus and Geocoris spp. abundances because as predators and prey, the abundance of one should affect the abundance of the other. I also expected that different landscape and crop type context should affect the location of L. hesperus and Geocoris spp in the field, therefore, I tested for an interaction between crop type and field position as well as an interaction between landscape context and field position. Since the sites appeared to differ within each site type, I expected variation between sites and within site types and I accounted for this variation in my analysis by using site as a random variable in all three models. All possible interactions were considered in each model and any non-significant interactions were eliminated from the models after an ANOVA analysis that tested the significant difference between each model. When the analysis showed significant differences between the field positions and sample round I included them as a variable in the model. If field position or sample round did not show significant differences, then the data were pooled for the site type.

Strawberry damage

I computed proportions of *L. hesperus* damaged berries to undamaged berries by dividing the number of damaged fruits by total fruits per plant. Fruit damage was evaluated using a generalized linear mixed model almost identical to the insect abundance models except I used a Binomial distribution because with proportional data the response variable is the number of successes versus failures. I used the same explanatory variables as the insect abundance models. Since the analysis did not show field position to be significantly different I pooled the data for each site type and found the mean and standard error of fruit damage. I included *L.* hesperus and *Geocoris spp.* in the model since I expected *Geocoris spp.* to influence the presence of *L. hesperus* hence regulate fruit damage.

RESULTS

Lygus hesperus abundance

Both landscape context and crop diversity influenced pest abundance. *Lygus hesperus* pest abundance was significantly higher in simple landscape sites (Fig. 3; MS and PS; p<0.05) suggesting that farms surrounded by natural habitat had less pest pressure; (MS= 0.66 ± 0.07 ; PS= 0.31 ± 0.08 ; PC= 0.04 ± 0.01 ; MC= 0.56 ± 0.11 ; Fig. 3). *Lygus hesperus* abundance was also higher in monoculture sites than polyculture sites despite the landscape context (Fig. 3; MS and MC; p<0.001) suggesting that crop diversity may also play a role in reducing pest pressure. When considering the interaction between *L. hesperus* and landscape complexity within the polyculture crop sites, *L. hesperus* abundance was higher in the simple landscape compared to the complex landscape setting (p<0.05). Thereby suggesting polyculture farms surrounded by natural habitat have less pests. As expected, location within the field also had an effect on pest abundance, where abundance was higher in the 'field' position, compared to the 'edge' position for all sites (p<0.001). When considering the interaction between interaction between landscape diversity and field position, *L. hesperus* abundance was lower in the 'field' position in simple landscape sites (MS and PS) (p<0.001) suggesting that natural habitat surrounding conventional farms may be contributing to 'spill over' pest effects.



Fig. 3. Means of *L. hesperus* nymph abundance with their standard errors for each site type. Monoculture/complex (MC), polyculture/complex (PC), monoculture/simple (MS), and polyculture/simple (PS) sites. There were significantly more *L. hesperus* in simple landscape site types (p < 0.05) and significantly less in polyculture site types (p < 0.001).

Geocoris spp. Abundance

Crop diversity influenced predator abundance while landscape diversity did not. *Geocoris spp.* adult abundance was overall significantly greater in polyculture crop (PS and PC) sites despite landscape complexity suggesting crop diversity is important for increasing predator abundance (MC= 0.07 ± 0.02 ; PC= 0.52 ± 0.05 ; MS= 0.23 ± 0.04 ; PS= 0.08 ± 0.03 ; p<0.01; Fig. 4). Landscape diversity did not have an effect on *Geocoris spp.* abundance suggesting landscape diversity does not play a role in *Geocoris spp.* abundance (p> 0.10). *Geocoris spp.* abundance showed to be significantly lower in sample round one compared to sample round two (p< 0.01), this suggests we missed their population peak during the second sample round since it was later in the strawberry growing season.



Fig. 4. Means of *Geocoris spp.* adult abundance with their standard errors for each site type. Monoculture/complex (MC), polyculture/complex (PC), monoculture/simple (MS), and polyculture/simple (PS) sites. There were significantly more *Geocoris spp.* abundance in polyculture crop sites (p<0.01).

Fruit Damage

There was a significant interaction between damaged fruit and *L. hesperus* abundance. Fruit damage increased with increased pest abundance (MC= 0.08 ± 0.01 ; PC= 0.04 ± 0.005 ; MS= 0.12 ± 0.01 ; PS= 0.07 ± 0.01 ; p<0.001; Fig. 5), while neither landscape (p> 0.10) nor crop diversity (p> 0.10) influenced fruit damage. This suggests fruit damage is directly related to pest abundance and indirectly related to landscape and crop diversity. When considering the interaction between crop diversity and *L. hesperus* abundance, fruit damage was lower in polyculture sites with lowest *L. hesperus* abundance (p< 0.01).



Fig. 5. Mean proportion of damaged fruit with their standard errors for each site type. Monoculture/complex (MC), polyculture/complex (PC), monoculture/simple (MS), and polyculture/simple (PS) sites. Fruit damage significantly increased with increased *L. hesperus* abundance (p<0.001).

DISCUSSION

My results show that crop diversity may provide the same benefits as landscape complexity in determining pest and predator abundance in organic strawberry farms. Both landscape complexity and crop diversity reduce *Lygus hesperus* abundance and indirectly reduce pest damage to strawberries (Fig. 3). These results were what I expected based on the known importance of vegetative diversity for suppressing pests (Bianchi et al. 2006; Letourneau et al. 2011). Letourneau et al. (2011) shows on farm vegetative diversity suppresses herbivores, enhances predators, and reduces crop damage. Bianchi et al. (2006) found that the existence of diverse natural habitat surrounding agricultural crops enhance the presence of natural predators to agricultural pests by conserving biodiversity. O'Rourke et al. (2011) similarly found corn rootworm pest densities reduced in diverse landscapes since natural enemies rely on alternative habitats for diverse food sources and habitats.

I provide evidence that crop diversity can facilitate natural control of *L. hesperus* with the generalist predator *Geocoris spp.* in organic strawberry farms. Crop diversity in polyculture farms has been associated with enhancing natural enemies and to reduce herbivore densities

(Altieri and Nicholls 2004). Monoculture farms do not provide the resources for natural enemies to provide natural control services (Rusch et al. 2010). Similarly, my results indicate there were fewer *L. hesperus* (p<0.001; Fig. 3) and more *Geocoris spp.* (p<0.01; Fig. 4) in the diversified polyculture sites compared to the monoculture sites, indicating that strawberry farms with no crop diversity have higher risks of pest incidence. I hypothesized sites with crop diversity would provide the habitat to support more *Geocoris spp.* in turn, provide more *L. hesperus* suppression. Crop diversity in this agroecosystem may facilitate greater natural control of *L. hesperus* as suggested by the "Enemy Hypothesis" because of the attractiveness of on farm vegetative diversity to predators offered in polycultures compared to monocultures (Pimentel 1961; Root 1973). It is possible that lower *L. hesperus* abundance was found in the polyculture sites as explained in the "Resource Concentration Hypothesis", alternatively known as the "Disruptive Crop Hypothesis", because mixed chemical cues provided by crop diversity may have prevented *L. hesperus* from finding and utilizing strawberries (Tahvanainen and Root 1972; Root 1973; Vandermeer 1989).

If simple agroecosystems cannot provide the appropriate resources for natural enemy abundance, crop damage can be drastically higher in these systems. Poveda et al. (2012) found the decline in landscape diversity can increase pest abundance and result in a negative effect on crop production and high crop diversity can be resilient to pest outbreaks, thus potentially have an indirect effect on crop yield. Similarly to Poveda et al. (2012), I found strawberry fruit damage is indirectly associated with landscape and crop diversity since L. hesperus abundance had a direct significant interaction with crop and landscape diversity. I hypothesized if diversified sites could mediate more natural control of L. hesperus nymphs, then this should result in lower proportions of L. hesperus damaged berries. Although my statistical analysis did not show direct significance with fruit damage and diverse vegetation, there is a pattern of lower fruit damage found in polyculture sites compared to monoculture sites within each landscape context (MC= 0.08 ± 0.01 ; PC= 0.04 ± 0.005 ; MS= 0.12 ± 0.01 ; PS= 0.07 ± 0.01 ; Fig. 5). Overall natural control did not show to be efficient enough to control fruit damage in monoculture sites. Since Geocoris spp. are known to control the nymphal stages of L. hesperus (Bugg et al, in review), this early stage predation is significant to control strawberry fruit damage before it can reach economic damage thresholds. My study suggests diversified crop vegetation promotes

natural predator presence, which can be essential to prevent economic damage thresholds from being exceeded in organic strawberry agroecosystems.

A meta-analysis of farming systems on pests and natural enemies showed that small fields with increased crop diversity combined with the absence of chemical herbicides may serve to increase habitat diversity and reduce pest populations through natural enemy abundance (Garratt et al. 2011). Despite all strawberry farms being managed organically, the monoculture farms were on a larger scale of production compared to the polyculture farms. Most of the monoculture growers used bug vacuum machines and organic pesticides for L. hesperus control, indicating L. hesperus abundances are already in high outbreak incidences. Geocoris spp. can suppress arthropod pests and are most effective at controlling when pest densities are relatively low (Bugg et al., in review). Thus, pest suppression by Geocoris spp. may not be as efficient in monoculture sites where L. hesperus nymph abundances are high, in contrast to polyculture sites. Another study reported the abundance of aphid pests were even higher in sprayed fields compared to non-sprayed fields (Krauss et al. 2011). Despite the additional use of tractormounted vacuum devices and organic pesticides for L. hesperus control, I still found significantly higher mean abundances of L. hesperus nymphs in monoculture sites. This provides evidence that the smaller scale and most diversified organic farms such as the polyculture farms in this study receive natural control of pests as an ecosystem service compared to large-scale organic strawberry monocultures.

Composition and structure of the surrounding landscape does affect biodiversity by providing different habitats that offer a variety of niches for a variety of species to inhabit (Rosenzweig 1995; Weibull et al. 2003). I hypothesized a higher abundance and presence along the field edge of *Geocoris spp*. in complex landscape sites compared to simple landscape sites because I expected vegetative diversity at the landscape level to provide sources of natural enemies and alternative habitats. However, my results did not indicate a significant relationship with *Geocoris spp*. and landscape diversity (p> 0.10; Fig. 4) nor did they indicate a significant difference between *Geocoris spp*. abundances at the edges and in the center position of the field, suggesting *Geocoris spp*. was more evenly dispersed across the sites than I had expected. My study did not show an enhanced natural predator abundance in the diverse landscape sites, instead an enhanced presence in the diversified crop sites indicating that *Geocoris spp*. density may be linked most to on-farm diversity in organic strawberry farms. Natural enemies are also

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known to interact their time in alternative habitats in diverse landscapes, resulting in higher distribution throughout a whole farm (Östram et al. 2001). This is complicated though by the interaction of landscape complexity and crop diversity. Rand et al. (2006) shows generalist predators seek refuge in adjacent natural or semi-natural habitats to survive disturbances in crops. Most of the monoculture growers used alternative methods of control for *L. hesperus* such as bug vacuum machines that disturb and remove all the insects on the strawberry plants. It is possible that these disturbances from bug vacuuming encourages *Geocoris spp.* to relocate to other potential habitats or are completely removed. Perhaps these predators were present in the landscape vegetation instead of the crop vegetation. Potentially explaining why I may not have detected *Geocoris spp.* to be associated with landscape diversity since I only sampled vegetation on the farm and not the landscape vegetation, thereby missing *Geocoris* distribution patterns. To address this I suggest sampling the landscape vegetation to clarify the relationship between the predator and landscape vegetation.

I hypothesized a reduced abundance of the strawberry pest L. hesperus in sites with complex landscapes compared to simple landscapes because I expected a higher predator presence, thus natural control in complex sites. My results did show a lower abundance of L. hesperus in sites with complex landscapes (p<0.05, Fig. 3), suggesting pest abundance is directly influenced by landscape diversity. Within the polyculture sites L. hesperus abundance was significantly greater in simple landscapes compared to complex landscapes (p<0.001) further showing that high vegetative diversity in landscapes is associated with low pest pressure. I only accounted for one natural enemy of L. hesperus in my study. Although I did not find a significant interaction between *Geocoris spp.* with landscape diversity, there are other predators that could be controlling L. hesperus in these sites and potentially contributing to lower pest abundances in the complex landscape sites. Overall pest abundance was significantly greater in the center field position versus the edge (p<0.001). However, the interaction between field position and field type was significant and indicated that within the simple landscape, there were more pests at the field edges than the center. This makes sense if pests are 'spilling over' from neighboring conventional farms without the presence of natural habitat buffers between them (Gosme et al. 2012). My results suggest there may be migration of L. hesperus between neighboring farms in simple landscapes but additional sampling of L. hesperus in neighboring fields is needed to confirm these "spill over" effects.

Limitations

I found significant results with two sampling rounds, to improve this study sampling the vegetation in the landscape setting throughout the strawberry season could clarify predator and landscape interactions. *Geocoris spp.* abundance resulted to be significantly varied between sample round one and two. Two sample rounds may not be enough to truly understand these insect population dynamics, thus continuous sampling for *L. hesperus*, *Geocoris spp.*, and fruit damage throughout the California Central Coast strawberry season would allow better understanding of *Geocoris spp.* populations over time.

Conclusions

Managing insect pests in organic strawberry farms is challenging since there are few efficient organic pesticides on the market and they are an additional expense to growers. Initially I thought it was important for farms to be surrounded by natural habitat vegetation to provide sources for natural enemies, but my results suggest controlling the diversity on farms can be just as important. Here, I provide evidence that farms with vegetative diversity facilitates natural control of *L. hesperus*. Based on these findings I suggest planting multiple crop species in farms can be effective to enhance IPM. This approach of diversifying crop species on farms is important for growers who do not have their farms surrounded by natural habitat. It is understandable that management of multiple crops faces many logistical and economic challenges and constraints but by diversifying farms growers can benefit from natural predator interactions and reduce their expenses for chemical inputs and costs to fuel their tractor mounted vacuum devices. With increasing literature providing evidence of ecosystem services diversified farms offer, a transition in farming structure from specialized, large-scale production to diversified farming can be encouraged in policy formation to promote diversified farming programs.

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APPENDIX I: R Script for data analysis

To read file into R:

- >lygus<-read.csv("~/Desktop/CleanData_201333.csv", header=T,sep=",")
- > View(lygus)
- > attach(lygus)
- > se<-function(x) sqrt(var(na.omit(x))/length(na.omit(x)))</pre>
- > names(lygus)
- > levels(lygus\$field_.pos)
- > levels(lygus\$farm_type)
- > levels(lygus\$site)
- > unique(lygus\$sample_round)

This is for all Lygus data:

- > farm_type_mn_L<-tapply(lygus\$lygus_nymphs,lygus\$farm_type, length)</pre>
- > farm_type_mn_L
- > farm_type_mn_L<-tapply(lygus\$lygus_nymphs,lygus\$farm_type, mean)</pre>
- > farm_type_mn_L
- > farm_type_se_L<-tapply(lygus\$lygus_nymphs,lygus\$farm_type, se)</pre>
- > farm_type_se_L

This is for all Geocoris data:

- > farm_type_mn_G<-tapply(lygus\$geocoris,lygus\$farm_type, mean)</pre>
- > farm_type_mn_G
- > farm_type_se_G<-tapply(lygus\$geocoris,lygus\$farm_type, se)</pre>
- > farm_type_se_G

To separate farm type into 2 groups (1) represents landscape (2) represents crop diversity:

- > status <- rep("land", nrow(lygus))</pre>
- > status[lygus\$farm_type=="PC"] <- "C"</pre>
- > status[lygus\$farm_type=="MC"] <- "C"</pre>
- > status[lygus\$farm_type=="PS"] <- "S"</pre>
- > status[lygus\$farm_type=="MS"] <- "S"</pre>
- > lygus\$land<-as.factor(status)
- > unique(lygus\$land)
- > status <- rep("crop", nrow(lygus))</pre>
- > status[lygus\$farm_type=="PC"] <- "P"</pre>
- > status[lygus\$farm_type=="MC"] <- "M"</pre>
- > status[lygus\$farm_type=="PS"] <- "P"</pre>
- > status[lygus\$farm_type=="MS"] <- "M"</pre>
- > lygus\$crop<-as.factor(status)
- >unique(lygus\$crop)
- > cropC <- subset (lygus, farm_type== "PC" | farm_type== "MC", select = date:crop)</pre>

Chosen Lygus model:

> mod1_lnymphs <- lmer (lygus_nymphs~land*crop + land*field_.pos +land*geocoris + crop

```
*field_.pos + crop*geocoris+(1|site), data=lygus, family=poisson)
> mod1_lnymphs
```

Chosen Geocoris model:

```
> mod5_geocoris <- lmer (geocoris~land*crop + land*field_.pos + crop *field_.pos +
crop*sample_round + (1|site), data=lygus, family=poisson)
> mod5_geocoris
```

This is for all fruit damage data:

> aa<- aggregate(list(prop_dam=lygus\$prop_dam), by = list(farm_type=lygus\$farm_type), FUN
= "mean")</pre>

>aa

```
> bb<- aggregate(list(prop_dam=lygus$prop_dam), by = list(farm_type=lygus$farm_type), FUN
= "se")</pre>
```

> bb

```
> cc<- aggregate(list(prop_dam=lygus$prop_dam), by = list(field_.pos=lygus$field_.pos,
site_type=lygus$farm_type), FUN = "mean")
> cc
```

Binomial fruit damage model:

```
> binom <- cbind(lygus$undamaged, lygus$damaged) #successes, failures
```

```
> mod1_undam <- lmer (binom~ land*crop+ land*lygus_nymphs +crop*lygus_nymphs+
land*geocoris +crop*geocoris+ lygus_nymphs*field_.pos +land*field_.pos+ crop*field_.pos
```

```
+(1|site), data=lygus, family=binomial)
```

```
> summary(mod1_undam)
```