THE EFFECTS OF LOCAL AND LANDSCAPE CONTEXT ON LEAFHOPPER (HEMIPTERA: CICADELLINAE) COMMUNITIES IN COFFEE AGROFORESTRY SYSTEMS OF COSTA RICA

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AUTHORIZATION TO SUBMIT DISSERTATION

This dissertation of Mariangie Ramos submitted for the degree of Doctor of Philosophy with a major in Entomology and titled "The effects of local and landscape context on leafhopper (Hemiptera: Cicadellinae) communities in coffee agroforestry systems of Costa Rica", has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies at the University of Idaho (UI), and to the Postgraduate School at Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) for approval.

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ABSTRACT

Sharpshooters (Hemiptera: Cicadellidae: Cicadellinae) are potential vectors of *Xylella fastidiosa*, the bacterial causal agent of coffee “crespera” disease. This study examined the effects of local (shade composition, organic or conventional management, and weed management) and landscape (surrounding land uses) context on sharpshooter communities in coffee agroforestry systems (CAFS) within the Volcánica Central-Talamanca Biological Corridor (VCTBC), in Costa Rica. On a broader perspective, this study also sought to evaluate how the ecosystem service of natural pest control overlaps with other ecosystem services provided by CAFS and how decision makers view these services.

The abundance and species richness of sharpshooters were evaluated in four CAFS types present in the VCTBC, using yellow sticky traps and Malaise migration traps in 2005 and 2006. Approximately 73 species of sharpshooters were found in CAFS within the VCTBC. Sharpshooters were more abundant from June to September and declined afterwards. Sharpshooter communities were distinct in each agroforestry system, and coffee sharpshooter communities were more similar to pasture than to forest sharpshooter communities. Shade was a key local variable, negatively affecting sharpshooter abundance. Weed management did not affect sharpshooter communities. Sharpshooters were more abundant at edges of coffee farms, and appeared to move from forests to coffee farms. Surrounding area in forest was positively correlated to sharpshooter abundance. Surrounding area in fallow was positively correlated to species richness.

Overlapping of GIS layers of ecosystem services provided by CAFS revealed that there is more land of the VCTBC where natural pest control overlaps with watershed services than with biodiversity services. Interview data showed that natural pest control was more important for decision makers than all other services, except connectivity. Decision makers value ecosystem services in the planning of corridor activities, in addition to location and organization level of corridor areas.

Although research is needed on the epidemiology of *X. fastidiosa*, we found that species that have tested positive for the presence of the bacteria are negatively affected by shade. Increasing shade could be a strategy for management of these species in coffee agroforestry systems. This practice also increases the level of other ecosystem services provided by coffee agroforestry systems.

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DEDICATION

To the beautiful people of Costa Rica, for their love of peace and agriculture.

To the fiery people of Puerto Rico, for their love of justice and movement.

To my mom, dad, sisters and grandparents, for raising me, loving me and inspiring me every day.

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CHAPTER 1

Introductory Chapter

Traditionally, there has been an apparent dichotomy between agricultural production and environmental quality. This is mainly based on the fact that land use and cover change to agriculture causes biophysical changes to the environment, which may result in habitat loss and fragmentation, soil degradation, species introductions, and changes in vegetation (Grau *et al.* 2003). However, all agricultural systems are not equal and these effects may vary depending on the type of agricultural system in use. Agricultural areas can provide important ecosystem services to society (e.g. watershed services, biodiversity conservation, carbon sequestration, scenic beauty, etc.), if they are managed adequately. For example, in Costa Rica, the national environmental services payments program includes agricultural areas with agroforestry practices as areas that provide these services (Wünscher *et al.* 2008).

The discipline of Agroecology was developed to study and design more sustainable agricultural production systems or agroecosystems that will provide food while maintaining the natural resource base (Gliessman 2002). Agroecology recognizes that practices that lead to sustainability vary from place to place and are dependent on cultural, social and economic processes happening in the area, in addition to purely biophysical ones. However, a generally accepted beneficial practice for agroecological insect management is to have agroecosystems with higher plant diversity than monocultures. This view comes mainly from the observation of successional communities (Nicholls and Altieri 2004), traditional (local or indigenous) agroecosystems (Altieri 2004) and natural vegetation areas (Gliessman 2002), where insect herbivore outbreaks are less observed than in monocultures. Increased plant diversity is hypothesized to contribute to insect herbivore regulation by: 1) providing resources for natural enemies (Root 1973), 2) making it harder for herbivores to find crop plants (Root 1973), or 3) providing an associational resistance (Tahvanainen and Root 1972).

Strategies to increase plant diversity in agroecosystems in space or time include intercropping, alley cropping, live fences, natural or planted hedges, cover crops, rotations and fallows (Gliessman 2002). Many of these strategies are considered agroforestry practices. Agroforestry systems are more diversified forms of agricultural production commonly found in the tropics (Nair 1993). Agroforestry systems are formed by at least one woody perennial that interacts biologically with another plant species, and at least one of them is managed for production (Somarriba 1992). Thus, agroforestry systems can range in diversity from complex “jungle rubber” (Gouyon *et al.* 1993) and home gardens to shaded monocultures, like *Erythrina*-shaded coffee. In the Volcánica Central-Talamanca Biological Corridor (VCTBC) of Costa Rica, coffee agroforestry systems are the prevalent agroforestry systems, ocuppaying aproximately 14% of its area (Murieta 2005).

Coffee species evolved on the forest understory of current Ethiopia, and have been traditionally planted under the shade of trees for centuries. Today, levels of shade tree canopy diversity can vary greatly. The most commonly used classification of coffee agroforestry systems is that of Moguel and Toledo 1999 (Figure 1.1). In their classification, coffee agroforestry systems can range from rustic systems were coffee is planted in the forest understory to shaded monocultures, were only one shade species is used. Weeds provide additional plant diversity in coffee agroforestry systems. The ground plant cover of coffee plantations in the neotropics can range from 20-90 species (Somarriba *et al.* 2004). For example, De Melo *et al.* (2002) found 45 species of weeds in experimental coffee plots of Costa Rica. The species richness of weeds in coffee systems apparently increases with a decrease in shade (Goldman and Kigel 1986, cited in Somarriba *et al.* 2004).

More than 850 species of insects are known to feed on coffee worldwide, of which about 200 are Neotropical (Le Pelley 1973). However, in the Americas, coffee has few insect pests. The main ones in the Americas are the coffee berry borer (*Hypothenemus hampei*), the coffee leaf miner, *Perileucoptera coffeella*, several coccids and pseudococcids (*Planococcus citri*, *Pseudococcus longispinus*), shoot borers (*Plagiohammus maculosos*, *P. mexicanus, P. spinipennis*), and the red mite (*Oligonychus coffeae*; Perfecto and Ambrecht 2003). *Perileucoptera coffeella*, *Pl. mexicanus* and *Pl. spinipennis* are native to the Americas. Recently, greater attention has been paid to sharpshooters

(Hemiptera: Cicadellidae: Cicadellinae) feeding on coffee. Sharpshooters are the potential vectors of *Xylella* fastidiosa, a generalist, xylem-limited bacterium that causes diseases in coffee in Brazil (atrofia das ramas do cafeiro) and Costa Rica (crespera) (Redak *et al.* 2004).

Xylella fastidiosa is a generalist bacterium that causes diseases in many plants of economic importance including grape, almond, alfalfa, peach, citrus, numerous ornamental and tree species, but that is also present in natural vegetation (Hopkins and Purcell 2002). Its sharpshooter vectors are also generalists that feed on xylem fluids. These generalist strategies in the pathogen and the vector, combined with the high diversity of Cicadellinae in the Neotropics may suggest that many sharpshooter species can be vectors of *X. fastidiosa*. Most sharpshooters tested for *X. fastidiosa* exhibit positive results (Almeida *et al.* 2005). However, sharpshooter vector ecology is the key for the spread of *X. fastidiosa*. Studies in other crops have revealed that the natural spread of diseases caused by *X. fastidiosa* depends on sharpshooter: 1) habitat and host selection, 2) vector density and mobility, and 3) spatial and temporal distribution (Purcell 1985).

Due to the recent discovery of *X. fastidiosa* as the bacterial agent of crespera disease in Costa Rica (Rodríguez *et al*. 2001), little is known about its sharpshooter vectors, their ecology or how management practices may affect them. A previous study in the region, revealed that leafhoppers were the most abundant Auchenorrhyncha family in coffee agroforestry systems of the region, and that the presence of shade trees affected their abundance (Rojas *et al.* 2001). Additionally, Auchenorrhycha community similarity was due more to proximity of plots than to shade trees (Rojas 1999), suggesting landscape effects on community composition. The objective of this study was to determine the role of local (management and shade tree composition) and landscape (adjacent land uses) factors in the structure of sharpshooter communities. The specific objectives were to:

1. Determine the effect of farm vegetational and structural diversity, management practices and landscape factors on sharpshooter communities in coffee agroforestry systems.
2. Determine the effect of near land uses (forests and pastures) on coffee sharpshooter communities, and relate to patterns of *X. fastidiosa* presence in coffee agroforestry systems.
3. Determine the effect of weed management practices on sharpshooter communities in coffee plantations.
4. Understand how decision makers involved in the implementation of a biological corridor perceive ecosystem services provided by coffee agroforestry systems and determine if they consider ecosystem services for the prioritization of areas within the corridor for resource allocation.

Objectives were met by carrying several studies in coffee agroforestry systems within the VCTBC, Costa Rica. The next chapter of this dissertation focuses on both local and landscape variables affecting sharpshooter communities. The third chapter examines sharpshooter community structure in forest, pasture and coffee land uses, the movement of sharpshooters between these land uses and how that relates to the presence of *X. fastidiosa* in coffee plants. The fourth chapter looks at a specific local variable, weed management, and how it affects sharpshooter communities. The fifth chapter applies dissertation results to develop GIS layers that were used by decision makers involved in the implementation of conservation efforts within the VCTBC. This latter chapter was done in collaboration with other students and researchers as part of an interdisciplinary effort. The final chapter summarizes the main findings of the dissertation and discusses possible implications.

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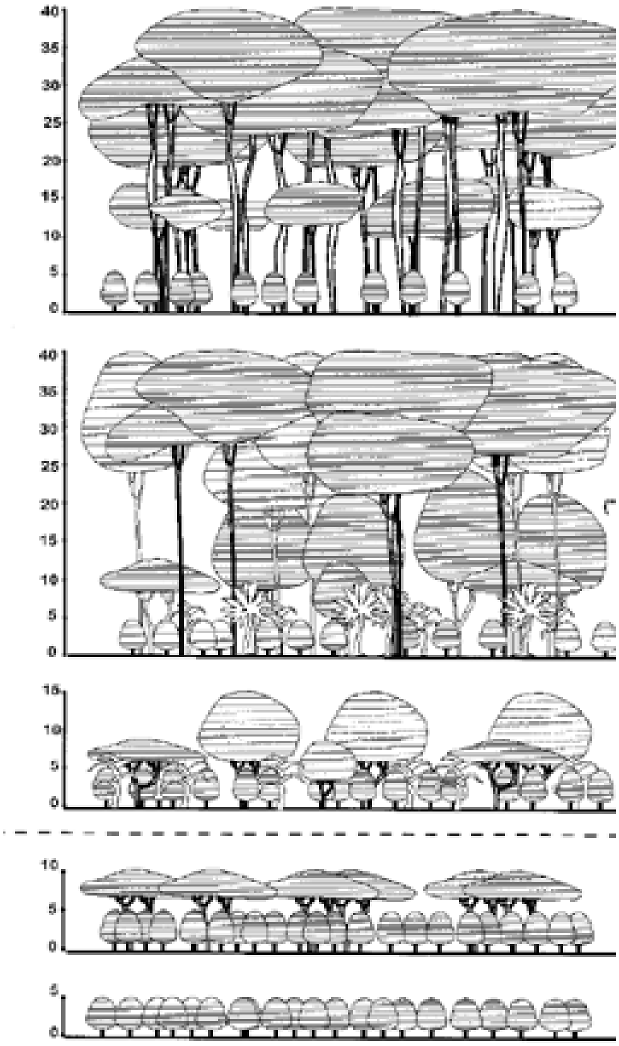

Figure 1.1. Various types of coffee agroforestry systems, showing vegetational complexity and height of canopy (from Moguel and Toledo 1999).

CHAPTER 2

The effect of local and landscape context on leafhopper (Hemiptera: Cicadellinae) communities in coffee agroforestry systems

Abstract

Sharpshooters are potential vectors of *Xylella fastidiosa*, the bacterial causal agent of coffee “crespera” disease. Little is known about *X. fastidiosa* vector ecology in Costa Rica. We examined effects of local (shade, management, weed cover) and landscape (surrounding area in coffee, forest, pastures, and fallows) factors on sharpshooter species abundance and richness in coffee agroforestry systems. We monitored sharpshooters seven times from 2005 to 2006 using yellow sticky traps in four farm treatments: a) organic two-strata systems with *Erythrina poeppigiana* shade trees, b) organic three-strata with *Cordia alliodora-Musa-E. poeppigiana* shade species, c) conventional two-strata with *E. poeppigiana* shade trees, and d) conventional three-strata with *C. alliodora-Musa-E. poeppigiana* shade species. Shade percentage and weed cover data were collected during each sampling. Landscape context was characterized by determining land use (coffee, pasture, forest, and fallow) percentage within two different radii (100 and 500 m) around each farm. There were no significant differences in overall sharpshooter abundance or species richness among treatments. Some sharpshooter species were significantly more abundant in conventional two-strata systems than in other systems examined and discriminant analysis demonstrated different sharpshooter species assemblages for each farm treatment. Shade was a key local variable, negatively affecting sharpshooter abundance. Proportion of land in fallow was positively correlated with sharpshooter species richness at 100 and 500 m radii, but other land cover types had no effect. Sharpshooter assemblages and some individual species differed among coffee shade systems, but landscape variables had a weak effect on overall sharpshooter abundance.

Keywords. *Coffea arabica*, sharpshooters, tropical agroecosystems, insect biodiversity, organic agriculture

Resumen

Los cicadelinos son los vectores potenciales de *Xylella fastidiosa*, la bacteria que causa la crespera del café Actualmente se conoce poco de la ecología de los vectores de *X. fastidiosa* en Costa Rica. Este estudio examinó los efectos de variables locales (sombra, manejo y cobertura de malezas) y del paisaje (área circundante con café, bosque, pastizales y barbechos) en la abundancia y riqueza de cicadelinos en sistemas agroforestales de café. Se realizaron siete muestreos de cicadelinos durante los años 2005 y 2006, utilizando trampas adhesivas amarillas. Los muestreos se realizaron en cuatro sistemas agroforestales: a) sistemas orgánicos con sombra de *Erythrina poeppigiana*, b) sistemas orgánicos con sombra de *Cordia alliodora-Musa-E. poeppigiana*, c) sistemas convencionales con sombra de *E. poeppigiana*, y d) sistemas convencionales con sombra de *C. alliodora-Musa-E. poeppigiana*. En cada muestreo, también se tomaron datos sobre la cobertura de malezas y el porcentaje de sombra. El contexto paisajístico de cada finca se evaluó calculando el área circundante (en radios de 100 y 500 m) de cada tipo de uso de la tierra (café, pastizales, bosque y barbechos). Según el análisis discriminante, cada sistema agroforestal tuvo comunidades distintas de cicadelinos, pero no hubo diferencias significativas en la abundancia o riqueza de cicadelinos entre los tratamientos. Algunas especies fueron significativamente más abundantes en los sistemas convencionales con sombra de *E. poeppigiana* que en los otros. El porcentaje de sombra fue una variable local importante, afectando negativamente la abundancia de cicadelinos. La riqueza de especies estuvo positivamente correlacionada con el área en barbechos en ambas escalas estudiadas (100 y 500 m). Las comunidades de cicadelinos y algunas especies fueron afectadas por el sistema agroforestal, pero las variables del paisaje tuvieron un efecto leve sobre la abundancia de especies.

Palabras clave. *Coffea arabica*, chicharritas, saltahojas, agroecosistemas tropicales, biodiversidad de insectos, agricultura orgánica.

Introduction

Agroforestry can provide important ecological services, such as biodiversity conservation, watershed services and carbon sequestration (Perfecto *et al.* 1996; Pérez-Nieto *et al*. 2005; Dossa *et al.* 2008), including a reduction in insect pest damage to crops (Schroth *et al*. 2000). Agroforestry systems are formed by at least one woody perennial that interacts biologically with another plant species, and at least one of them is managed for production (Somarriba 1992). Thus, agroforestry systems can range in diversity from complex "jungle rubber" (Gouyon *et al.* 1993) and home gardens to shaded monocultures, like *Erythrina*-shaded coffee. Increased plant diversity is hypothesized to reduce herbivore populations in crops due to an increase in natural enemies or reduction in the concentration of the crop species, making it more difficult for herbivores to find the crop species (Root 1973).

For agroforestry systems, it has been hypothesized that shade tree species can provide "associational resistance" to crops, expressed as changes in the environment (e.g. microclimate) of the agroforestry system that make the crop species less susceptible to pests (Rao *et al.* 2000). However, a review on pests and diseases in agroforestry systems advises that attention should be given to specific biotic (species-species interactions) and abiotic (microclimatic) variables, and not to rely solely on increased plant diversity as a potential control means (Schroth *et al*. 2000).

Coffee (*Coffea arabica*) is an example of a crop that can be grown in agroforestry systems with different levels of intended plant diversity. In the Neotropics, the main sources of plant diversity in coffee agroforestry systems are the shade canopy and the ground cover, since the crop itself has little genetic diversity (Somarriba *et al.* 2004). The diversity of shade tree species per farm can range from one species in shaded monocultures to 54 species in traditional coffee systems of Southern Mexico (Moguel and Toledo 1999), and ground cover plant species richness can range from bare ground to 20-90 species (Somarriba *et al.* 2004). Most studies examining the effect of shade tree diversity on arthropods, have focused on the effects of such tree diversity on insect diversity. More complex coffee agroforestry systems have higher levels of insect diversity, but the response of coffee insect pests is variable (Staver *et al.* 2001; Teodoro *et al.* 2008).

The first objective of this study was to determine the effect of local coffee farm practices (shade structure and organic/conventional management) on xylem-feeding leafhopper (Hemiptera: Cicadellinae; sharpshooters) communities in coffee agroforestry sytems of Costa Rica. Sharpshooters are mainly Neotropical (90% of species) and most species within this subfamily can be vectors of *Xylella fastidiosa* (Redak *et al*. 2004), the bacterium that causes crespera disease in coffee, a rather recently detected disease in Costa Rica (Rodríguez *et al.* 2001). Increased habitat diversity, as that observed in multi-species agroforestry systems, has been shown to negatively affect the abundance of leafhoppers due to increased rate of parasitism (Murphy *et al.* 1998).

The second objective of this study was to determine the effect of landscape context on sharpshooter communities. Some coffee agroforestry systems in Mesoamerica are embedded in complex landscapes that have remnants of natural forest. Forests may be sources of leafhoppers (Irwin *et al*. 2000). Many other coffee insect herbivores and their natural enemies respond to the presence of forest in these landscapes. For example, natural enemies like ants (Perfecto and Vandermeer 2003) and parasitoids (Klein *et al.* 2006), exhibit a decline in species richness with increasing distance from forest. Additionally, a decrease in parasitism has been observed with increasing distance from forest (Klein *et al.* 2006). The leaf-cutting ant *Atta cephalotes*,, an important coffee pest, also have a positive response to proximity to forest, having higher nest densities near edges with forest fragments (Varón 2006). Insectivorous birds, which are known to reduce coffee insect herbivore populations (Borkhataria *et al.* 2006, Perfecto *et al.* 2004), are influenced by the amount of forest cover surrounding coffee farms in 1km radii (Florian 2005).

To address our objectives, we conducted field surveys to assess the abundance and richness of sharpshooter species in coffee farms under organic or conventional management and varying in vegetational and structural complexity. We also obtained data on landscape variables and examined relationships between these variables and sharpshooter communities.

Materials and Methods

1. Site description

The study was conducted in coffee farms within Cordillera Volcánica Central-Talamanca Biological Corridor (VCTBC), on the Caribbean watershed of Costa Rica. The VCTBC (Figure 2.1) is part of the Mesoamerican Biological Corridor Project, which attempts to connect protected areas through management of the agricultural matrix, restoration and reforestation (Miller *et al.* 2001). The VCTBC has an extension of approximately 72,000 ha, and is dominated by agricultural land uses (28% pasture, 14% coffee, 6% sugarcane and 3% other crops), with only 40% of its area under forest cover (Murieta 2005). Coffee is the main agricultural crop in the area, and coffee production systems in the corridor range from conventional farms without shade trees to organic farms with multiple shade tree species.

Small farms (less than 5 ha) were selected randomly from two GIS databases run by either the Costa Rican Coffee Institute (ICAFE) or the Association of Organic Producers of Turrialba (APOT), which include information about management and vegetational structure. Therefore, based on the abundance of different agroforestry systems in the VCTBC, four agroforestry treatments were selected for this study: a) organic two-strata systems with *Erythrina poeppigiana* shade trees (OE), b) organic three-strata with *Cordia alliodora*-*Musa* spp.-*E. poeppigiana* shade trees (OD), c) conventional two-strata with *E. poeppigiana* shade trees (CE), and d) conventional three-strata with *C. alliodora-Musa* spp.-*E. poeppigiana* shade trees (CD). Organic farms with only *E. poeppigiana* as shade species were the less diverse (based on the number of species of trees) organic farms present in the area. The most diverse organic farms had up to 11 species of trees, but the *C. alliodora-Musa* spp.-*E. poeppigiana* combination was the most diverse typology with sufficient replicates, thus it was selected for our surveys. Five farms per type were selected, except for the OD typology, for which only four farms were available (for a total of 19 farms). During the study, two farms changed their management; one of them was substituted by another farm with the same management, also selected randomly from the databases.

2. Sharpshooter sampling

Sharpshooters were sampled in the selected farms three times in 2005 and four times in 2006. In each farm, four plots of 25 x 10 m were randomly established. In each plot, two yellow sticky traps (21.5 x 27.9 cm) were placed in the North-South cardinal direction at a height of 1.2 m, for a total of eight traps per farm per sampling time. Traps were collected after one week in the field. All samples were taken to the Entomology Laboratory at CATIE, where sharpshooters were identified using a reference collection and counted. Aid with species identification was provided by Carolina Godoy at Instituto Nacional de Biodiversidad (INBio), in Costa Rica. Species richness was determined by counting the number of species per trap side, and abundance by counting the total number of sharpshooter individuals per trap side.

3. Additional local context variables

During each sharpshooter sampling, local variables were measured at each trap location. Percentage of shade was evaluated using a densitometer (Bellow and Nair 2003). All species (species richness) and number of individuals of weeds present in a 1 m^2 frame placed on the ground were recorded. Weed height and percentage of weed cover were also evaluated within the 1 m^2 frame. Temperature, relative humidity and wind speed were recorded using a Kestrel 3500 Pocket Weather Meter (Nielsen-Kellerman Company, Boothwyn, PA).

In addition, a farm characterization was performed for each farm in 2006. In each 25 x 10 m plot described above, all crop and shade tree species and individuals were recorded. Diameter at breast height (DBH) and height were measured for each individual shade tree. Available coffee leaf resources per plot were estimated by: a) selecting four coffee plants, b) calculating their branch with leaves volume per plant (BLVP), and c) multiplying the mean BLVP by the total number of coffee plants in the plot. The BLVP was estimated using the following equation:

$$\mathrm{BLVP} = \pi(d/2)^2 h$$

where *"h"* is the height of the section of the coffee plant that has branches with leaves and *"d"* is the diameter of the section of the plant that has branches with leaves (modified from Favarin *et al.* 2002). Information on farm size, area in coffee, farm history, fertilizer use, pesticide use, weed control regime and pruning of *E. poeppigiana* were collected by a structured interview with the farm owner/manager.

Precipitation information was obtained by using the WorldClim database (available online at: http://www.worldclim.org/) and the CATIE Meterological Station rain database (available online at: www.catie.ac.cr). Using ArcGIS 9.1 and the WorldClim database, the average rain relationship for CATIE and each farm was calculated for each farm for each sampling month (monthly farm rain coefficient). These figures were subsequently used to calculate the farm rain values for the each sampling in 2005 and 2006, by multiplying CATIE's 2005 and 2006 monthly rain values by each monthly farm rain coefficient.

4. Landscape context variables

The landscape context of each farm was examined using ArcGIS 9.1 and a 2005 land use map of the VCTBC. Buffers with radii of 100 and 500 m were drawn for each farm centroid. The area in coffee, pasture, forest and fallow within each buffer was calculated (Holland *et al.* 2004)

5. Statistical analyses

Normality and variance homogeneity assumptions for the response variables were verified using InfoStat Professional version 2007 (InfoStat 2007). Since assumptions were not met, rank transformations were performed. To determine differences between agroforestry system types, ANOVA were conducted using PROC MIXED, SAS version 8.2 (SAS Institute 2001). The autocorrelation between sampling observations was modeled by mean of different co-variance matrices: first order autoregressive (AR1), composed symmetry and unstructured models. Model fitting criteria (AIC and BIC) were used to select the best model. Composed symmetry models were selected for species richness and abundance. When the ANOVA was significant ($P = 0.05$), a Fisher LSD test for mean comparisons was conducted using the macro PDMIXED800 (Saxton 1998). To compare sharpshooter communities in each agroforestry treatment, discriminant function analysis, cluster analysis and principal components analysis were performed, using InfoStat Professional version 2007 (InfoStat 2007). A biplot of the principal components analysis of the abundances of sharpshooter species was constructed to interpret graphically the relationship between sharpshooter species abundances and with coffee agroforestry treatments. The effects of specific local and landscape variables were examined by correlation analysis, using InfoStat Professional version 2007 (InfoStat 2007).

Results

A total of 28,942 sharpshooter individuals belonging to 69 species were collected (Table 2.1). The conventional *E. poeppigiana* treatment had the highest sharpshooter abundance, and the organic *Cordia alliodora-Musa* spp.-*E.*

poeppigiana the lowest (Figure 2.2). However, no significant differences in sharpshooter abundance were found among treatments (Table 2.2). Additionally, there were no significant differences in species richness between agroforestry system types (Table 2.2; Figure 2.3). However, discriminant function analysis (using the abundance of each species as the discriminant variables) separated each agroforestry treatment as distinct sharpshooter community with an error of 4.7% (Figure 2.4).

Principal Components Analysis showed that many sharpshooter species were associated with a specific agroforestry treatment (Figure 5). This species idiosyncrasy was observed for the most abundant species (more than 1% of collected individuals), for which treatment had a significant effect (Table 2.3). For example, the most abundant species in the study, *Fusigonalia lativittata* Fowler, was more abundant in *E. poeppigiana*-only treatments (conventional and organic) than in the organic *C. alliodora-Musa* spp.-*E. poeppigiana* treatment, while *Ladoffa* sp.1, the second most abundant species, was more abundant in organic treatments than in conventional ones (Table 2.3). However, cluster analysis showed that sharpshooter communities are driven more by shade tree composition than by management (Figure 2.6). For many species, abundance in the organic *C. alliodora-Musa* spp.-*E. poeppigiana* treatment was significantly different from that in the conventional *E. poeppigiana*-only treatment (Table 2.3). Five species were more abundant on the OD type, and four species, in the CE type. Sharpshooters were usually not significantly different in the OE type and CD type (Table 2.3), suggesting these agroforestry system types are intermediate between the other two.. These two treatments had similar percentage of shade, temperature and coffee leaf resources, but differ in weed variables (Table 2.4).

Other local context variables affected sharpshooter abundance and species richness. The percentage of shade variable was negatively related to sharpshooter abundance (Table 2.5), and the abundance of several species (e.g. *F. lativittata, G. permagna*) (Table 2.6). However, percentage of shade positively affected the abundance of other species (e.g. *Ladoffa* sp. 1*, B. anita*). The abundance of *E. poeppigiana* trees had a similar effect on sharpshooter species abundance as percentage of shade (Table 2.66). Both local variables were correlated (r= 0.5; p<0.0001). Weed variables did not affect total sharpshooter abundance, but affected the abundance of individual species both negatively and positively (Table 2.6). Available coffee leaf resources positively affected species richness (Table 2.5), but had no effect on total abundance.

Landscape context variables also affected sharpshooter abundance and species richness. Abundance was affected positively by forest area at the 100m scale and negatively by pasture area at both scales studied (100m and 500m) (Table 2.5). Species richness was affected positively by fallow area at both scales (Table 2.5). Most species affected by landscape variables were affected at the 100m scale (Table 2.7). However, some land use types were more related to some sharpshooter species than to others, or affected them differently. For example, abundance of *B. anita* was positively correlated and abundance of *F. lativittata* was negatively correlated to surrounding area in pasture. Also, surrounding forest was positively correlated with the abundance of five species, but not with others (Table 2.7).

Sampling month significantly affected abundance and species richness, but there was no interaction between agroforestry treatment and sampling month (Table 2.2). Abundance was significantly higher in September of both sampling years, and species richness followed the same pattern (Figure 2.7a). Most species were also significantly more abundant in these sampling months (data not shown). Significantly less precipitation was recorded during September 2005 and 2006 than other months (Figure 2.7b), however neither abundance nor species richness were correlated with rainfall levels (data not shown).

Discussion

Even though sharpshooter species have similar feeding habits, they appear to be affected differently by abiotic and biotic elements of agroforestry systems and/or the landscapes these systems are embedded in. This disparity resulted in different sharpshooter communities in each coffee agroforestry system type, and no overall differences in species richness or abundance. This pattern has also been observed for coleopterans in coffee agroforestry systems of Ecuador (Richter *et al.* 2007). However, it is opposite to most studies of arthropod communities in coffee agroforestry sytems, which have reported higher species richness for most arthropod groups as coffee agroforestry systems become more diversified and shade increases (Perfecto and Armbrecht 2003).

Sharpshooter species responded to local context variables differently. Several coffee herbivores have higher abundances in less shaded agroforestry systems, as it has been observed for some spider mites (Teodoro *et al.* 2008), the leaf-cutting ant *Attta cephalotes* (Varón 2006) and mealybugs (Staver *et al.* 2001). In this study, several species were more abundant in the less shaded system (CE) and were negatively correlated to shade, such as *F. lativittata*, *G. permagna*, and *Graphocephala* sp. 1. Shade could negatively affect these species through bottom-up or top-down effects. First, shade can reduce food resources for sharpshooters. Shade reduces sap flow of coffee shrubs, especially midday sap flow peaks (van Kanten and Vaast 2006). Sharpshooters are known to feed more at this time of the day, when plant nutrient content and xylem tension are highest (Pérez 2007; Andersen *et al.* 1992). Second, shade may benefit natural enemies of sharpshooters, like parasitoids (density of shade trees, Sperber *et al.* 2004) and entomopathogenic fungi (through increased humidity, Griggs *et al*. 1999). However, in our studies shade positively affected other species, such as *Ladoffa* sp. 1, *B. anita* and *S. rufoapicata*. These species are more abundant in the forest than in coffee or pastures (Chapter 3), and potentially are more sensitive to the open sun.

Landscape context also influenced sharpshooter species idiosyncratically. Most species responded to landscape context more strongly at the scale of 100m. This may be related to the dispersal capabilities of sharpshooters. Although the dispersal capabilities of species in this region are not known, other sharpshooters are known to disperse within 90 and 155m from release sites (Asanzi *et al.* 1995, Blackmer *et al*. 2004). The two species (*G. permagna* and *M. ventralis*) that were affected by landscape context at the 500m scale may have larger dispersal capabilities. Surrounding forest habitats positively influenced the abundance of several species, suggesting this habitat may be a source of sharpshooters (Irwin *et al.* 2000; Chapter 3). Pasture and fallow habitats were important for two species (*B. anita* and *S. opaca,* respectively*)*, reflecting different landscape response strategies, as has been observed for other insects (Bianchi *et al.* 2006).

Seasonality was exhibited by most species, and most species were more abundant in September. In seasonal tropical regions, xylem feeders, like sharpshooters, are expected to show less seasonality than other insect groups because their generalist feeding habits allow them to change host plants as plants dry up (Young 1979). Also, the region where the study was conducted is tropical and “non-seasonal” (no dry season), where seasonality in insect populations is expected to be moderate (Young 1979). In this study, sharpshooters were more abundant when rains declined. This has been observed for *Cidadulina* species in Nigeria, which become more abundant at the end of the rainy season (Asanzi *et al.* 1994). However, in Panama, leafhopper species are more abundant in July (early rainy season), when most forest species are producing new leaves (Wolda 1979).

Alternatively, the pruning of *E. poeppigiana* shade trees could have driven the changes in sharpshooter abundance. Pruning of *E. poeppigiana* takes place twice a year, in January and October (data from interviews). Declines in abundance occur during these periods of time also. *Fusigonalia lativittata*, the most abundant species in our studies benefits from the presence of E. poeppigiana in conventional coffee farms, as it is less abundant in full sun (unshaded) coffee (Rojas *et al.* 2001). Pruning of shade trees in coffee agroforestry systems affects the abundance and distribution of ants that nest in shade trees, however, this effect vanishes after six months (Philpott 2005).

Although abundance and species richness of sharpshooters were not different among coffee agroforestry systems, sharpshooter community composition among systems was different. The difference in ecological attributes (at local and landscape scales) shown by sharpshooters in this study underscores the importance of identifying which sharpshooter species are more important vectors of *X. fastidiosa*. Management recommendations for “crespera” disease will be influenced by this. Host preference has been a critical characteristic of efficient *X. fastidiosa* vectors (Almeida *et al.* 2005). Previous studies in the VCTBC region have shown that several of the species that were more abundant in the CE treatments of this study, were usually found on coffee bushes (Rojas *et al*. 2001). Two of these species, *F. lativittata* and *G. permagna*, have been identified as carriers of *X. fastidiosa* (Godoy *et al.* 2005). Considering this and that most outbreaks of “crespera” disease have been observed in conventional coffee systems with reduced shade (Jacques Avelino, personal communication), diverse organic coffee agroforestry systems may be less prone to “crespera” disease outbreaks.

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Table 2.1. Total number of individuals collected for each species in each of four coffee agroforestry systems studied within the Volcánica Central-Talamanca Biological Corridor, Costa Rica.

Species	CD	CE	OD	OE	Total
1. *Fusigonalia lativitatta*	1707	3730	378	2287	8102
2. *Ladoffa* sp.1	804	303	1200	1336	3643
3. *Juliaca pulla*	571	1129	214	1358	3272
4. *Beirneola anita*	492	307	1201	698	2698
5. *Graphocephala permagna*	126	1517	0	228	1871
6. Morphospecies TR	367	509	92	324	1292
7. *Sibovia occatoria*	168	339	89	342	938
8. *Macugonalia testudinaria*	276	419	128	45	868
9. *Graphocephala* sp.1	73	639	4	61	777
10. *Stephanolla rufoapicata*	349	37	231	92	709
11. *Macunolla ventralis*	106	343	29	210	688
12. *Ladoffa* sp. 3	91	4	419	44	558
13. *Fusigonalia* sp.1	77	33	244	119	473
14. *Ladoffa* sp. 2	38	38	78	139	293
15. *Shildola opaca*	23	23	40	201	287
16. *Draeculacephala sp.*	15	47	55	93	210
17. *Microgoniella sociata*	31	90	3	83	207
18. *Graphocephala rufimargo*	28	117	2	44	191
19. *Oncometopia* sp. 7	49	67	23	48	187
20. *Oncometopia* sp.1	12	103	2	55	172
21. *Phera sp.*	13	108	15	35	171
22. *Hortensia similes*	6	63	10	71	150
23. Morphospecies 76	3	90	2	49	144
24. *Oncometopia sp.* 4	26	65	8	7	106
25. *Erythrogonia aerolata*	8	64	4	9	85
26. *Oncometopia sp. 3*	15	11	21	29	76
27. *Baleja flavoguttata*	11	16	12	31	70
28. Morphospecies 105	7	15	25	20	67
29. Morphospecies 77	8	33	0	25	66
30. *Mareja reticuliceps*	0	16	4	39	59
31. Morphospecies 42	11	21	8	16	56
32. Morphospecies 50	6	3	10	29	48
33. Morphospecies 118	2	1	2	39	44
34. Morphospecies 119	4	5	1	29	39
35. *Platygonia spatulata*	7	0	24	7	38

36. *Apogonalia fractinota*	7	5	6	10	28
37. *Tylozygus geometricus*	0	9	2	13	22
38. *Oncometopia* sp. 5	10	6	1	5	21
39. Morphospecies 131	0	3	0	18	20
40. *Chlorogonalia coeruluvitatta*	1	4	1	14	20
41. Morphospecies 60	4	7	1	8	18
42. Morphospecies 102	2	0	2	14	17
43. *Agrosoma pulchella*	2	14	0	1	15
44. *Oncometopia* sp. 8	1	6	2	6	14
45. *Graphocephala bivitatta*	1	1	0	12	14
46. Morphospecies 120	0	1	4	9	12
47. Morphospecies 1	2	3	2	5	10
48. Morphospecies 55	6	2	2	0	7
49. Morphospecies 113	0	0	5	2	6
50. Morphospecies 58	0	0	4	2	6
51. Morphospecies 124	0	0	0	6	5
52. Morphospecies 111	2	2	1	0	3
53. Morphospecies 67	0	1	1	1	3
54. Morphospecies 83	1	2	0	0	2
55. *Tylozygus fasciatus*	0	0	0	2	2
56. *Nilsonia sp.*	0	1	0	1	2
57. *Oncometopia sp. 2*	0	2	0	0	2
58. Morphospecies 14	1	0	1	0	2
59. Morphospecies 66	0	0	1	1	2
60. Morphospecies 130	0	0	1	1	2
61. Morphospecies 140	0	1	0	1	1
62. *Kapateira sp.*	0	1	0	0	1
63. Morphospecies 18	0	1	0	0	1
64. Morphospecies 65	0	0	1	0	1
65. Morphospecies 82	0	1	0	0	1
66. Morphospecies 90	0	1	0	0	1
67. Morphospecies 133	0	0	0	1	1
68. Morphospecies 135	0	0	0	1	1
69. Morphospecies 139	0	1	0	0	28942
Total	5570	10380	4616	8376	

[a] CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); CE is conventional management with *E. poeppigiana* shade; OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.), and OE is organic management with *E. poeppigiana* shade.

Table 2.2. ANOVA results (*P*-values) for species richness and abundance of sharpshooters on coffee agroforestry systems studied within the Volcánica Central-Talamanca Biological Corridor, Costa Rica.

Model Factor	Species richness	Abundance
Agroforestry system (AFS) type	0.4819	0.2243
Sampling month	<0.0001	<0.0001
AFS type* Sampling month	0.5331	0.7906

Table 2.3. Fisher LSD test results for mean comparison of abundances of the most abundant species (more than 1% of collected individuals) in the four coffee agroforestry systems studied within the Volcánica Central-Talamanca Biological Corridor, Costa Rica.

Species	CD	CE	OD	OE	*P*
F. lativitatta	AB	B	A	B	0.0126
Ladoffa sp.1	AB	A	B	B	0.0417
J. pulla	A	A	A	A	0.2254
B. anita	AB	A	B	AB	0.0508
G. permagna	AB	C	A	B	0.0007
Morphospecies TR	AB	B	A	AB	0.0905
S. occatoria	A	A	A	A	0.4504
M. testudinaria	B	B	AB	A	0.0646
Graphocephala sp.1	B	C	A	B	<0.0001
S. rufoapicata	B	A	B	A	0.0009
M. ventralis	A	A	A	A	0.1139
Ladoffa sp. 3	B	A	C	AB	0.0001
Fusigonalia sp.1	A	A	B	A	0.0056
Ladoffa sp. 2	A	A	A	A	0.1873
S. opaca	A	A	AB	B	0.0419

[a] CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); CE is conventional management with *E. poeppigiana* shade; OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.), and OE is organic management with *E. poeppigiana* shade.

Table 2.4. Mean values (± standard error) for abiotic and biotic variables for coffee agroforestry systems studied within the Volcánica Central-Talamanca Biological Corridor, Costa Rica.

Agroforestry system type[a]	Temperature (°C)	Shade (%)	Weed height (cm)	Weed cover (%)	Weed species richness	Coffee leaf resources
CD	27.6 ± 0.4 ab	52.7 ± 2.3 b	8.9 ± 1.4 a	21.2 ± 3.5 a	1.9 ± 0.3 a	102.5 ± 7.5 a
CE	27.9 ± 0.6 b	27.4 ± 2.1 a	9.3 ± 2.1 a	21.9 ± 4.6 a	1.3 ± 0.2 a	105.5 ± 8.1 a
OD	27.4 ± 0.5 ab	61.3 ± 1.4 c	24.9 ± 3.1 b	65.8 ± 7.0 b	4.0 ± 0.4 b	145.2 ± 3.3 b
OE	26.8 ± 0.5 a	50.0 ± 1.5 b	24.4 ± 3.0 b	61.6 ± 5.1 b	3.6 ± 0.4 b	111.8 ± 7.9 a
ANOVA P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[a] CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); CE is conventional management with *E. poeppigiana* shade; OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.), and OE is organic management with *E. poeppigiana* shade. Means within a column followed by different letters are significantly different according to Fisher's LSD test for mean comparison.

Table 2.5. Pearson's correlation coefficients for sharpshooter abundance and species richness on 19 coffee agroforestry systems (seven samplings) within the Volcánica Central-Talamanca Biological Corridor, Costa Rica, and local and landscape variables.

Variable	Abundance	Species Richness
Local context		
Temperature	0.204*	-0.062
Shade	-0.401***	-0.128
Weed species richness	-0.046	0.195*
Coffee resources	-0.070	-0.392***
Landscape context		
Coffee 100m	0.059	-0.231**
Pasture 100m	-0.176*	-0.066
Forest 100m	0.285**	0.205*
Fallow 100m	0.068	0.364***
Coffee 500m	0.180*	-0.036
Pasture 500m	-0.253**	-0.208*
Fallow 500m	0.128	0.398***

*Asterisks indicate significance: *P <0.05, ** P <0.01 and *** P <0.0001.

Table 2.6. Pearson's correlation coefficients for the most abundant species (more than 1% of collected individuals) and local variables on 19 coffee agroforestry systems (seven samplings) within the VCT Biological Corridor, Costa Rica.

Species	Shade (%)	Temp. (°C)	Weed cover (%)	Weed height (cm)	Weed spp. richness	No. of *E. poeppigiana*	No. of *C. alliodora*	Coffee resources
F. lativitatta	-0.560***	0.262**	-0.161	-0.255**	-0.155	-0.218*	0.003	0.019
Ladoffa sp.1	0.430***	-0.100	0.260**	0.280**	0.240**	0.140	0.090	0.100
J. pulla	-0.190*	0.080	-0.080	-0.210*	-0.100	-0.050	-0.230**	-0.140
B. anita	0.391***	-0.146	0.171*	0.232**	0.145	0.267**	0.062	0.019
G. permagna	-0.535***	0.108	-0.319**	-0.290**	-0.333***	-0.302**	-0.257**	0.127
Morphospecies TR	-0.360***	0.230**	-0.070	-0.170	-0.010	-0.240**	-0.010	-0.100
S. occatoria	-0.210*	0.003	0.180*	0.230**	0.110	-0.130	-0.220*	-0.290**
M. testudinaria	-0.280**	0.310**	-0.180*	-0.210*	-0.150	-0.210*	0.090	-0.270**
Graphocephala sp.1	-0.490***	0.280**	-0.210*	-0.200*	-0.190*	-0.250**	-0.120	-0.130
S. rufoapicata	0.410***	0.050	-0.005	-0.002	0.030	0.230**	0.260**	0.150
M. ventralis	-0.300**	0.070	0.120	0.070	0.070	-0.220*	-0.220*	-0.300**
Ladoffa sp. 3	0.280**	0.060	0.230**	0.070	0.290**	0.400***	0.510***	0.200*
Fusigonalia sp.1	0.270**	0.030	0.290**	0.210*	0.310***	0.330**	0.130	0.250**
Ladoffa sp. 2	0.230**	-0.080	0.250**	0.240**	0.260**	0.170	-0.120	-0.040
S. opaca	0.040	-0.270**	0.270**	0.190*	0.300**	0.110	-0.150	-0.160

Asterisks indicate significance: **P* <0.05, ** *P* <0.01 and *** *P* <0.0001.

Table 2.7. Pearson's correlation coefficients for the most abundant species (more than 1% of collected individuals) and landscape variables on 19 coffee agroforestry systems (seven samplings) within the VCT Biological Corridor, Costa Rica.

Species	Coffee 100m	Pasture 100m	Forest 100m	Fallow 100m	Coffee 500m	Pasture 500m	Forest 500m	Fallow 500m
F. lativitatta	0.246**	-0.333***	0.240**	-0.068	0.157	-0.185*	0.104	0.014
Ladoffa sp.1	-0.070	0.140	-0.070	0.100	0.180*	-0.160	-0.060	-0.050
J. pulla	0.200*	0.020	-0.060	-0.070	0.080	0.080	0.2*	0.180
B. anita	-0.327**	0.526***	-0.139	0.038	0.002	0.059	-0.076	-0.052
G. permagna	0.218**	-0.234**	0.047	-0.013	-0.035	-0.313**	0.492***	0.131
Morphospecies TR	0.200*	-0.230**	0.090	-0.110	0.260**	-0.110	-0.170	-0.010
S. occatoria	-0.100	-0.290**	0.550***	0.150	0.040	-0.280**	0.010	0.180*
M. testudinaria	-0.140	-0.200*	0.470***	0.060	0.160	-0.200*	-0.180*	0.080
Graphocephala sp.1	-0.100	-0.240**	0.490***	0.110	0.040	-0.170	-0.020	0.150
S. rufoapicata	-0.190*	0.250**	-0.130	-0.190*	-0.060	0.160	-0.140	-0.090
M. ventralis	-0.130	-0.260**	0.390***	0.190*	-0.010	-0.120	-0.090	0.350***
Ladoffa sp. 3	0.230**	-0.030	-0.140	-0.170	0.270**	0.140	-0.230**	-0.290**
Fusigonalia sp.1	-0.110	0.300**	-0.150	-0.040	0.090	0.240*	-0.230**	-0.170
Ladoffa sp. 2	-0.190*	0.210*	0.030	0.230**	0.020	0.030	0.030	0.130
S. opaca	-0.130	0.002	0.020	0.450***	-0.050	-0.090	0.160	0.240**

Asterisks indicate significance: *$P < 0.05$, ** $P < 0.01$ and *** $P < 0.0001$.

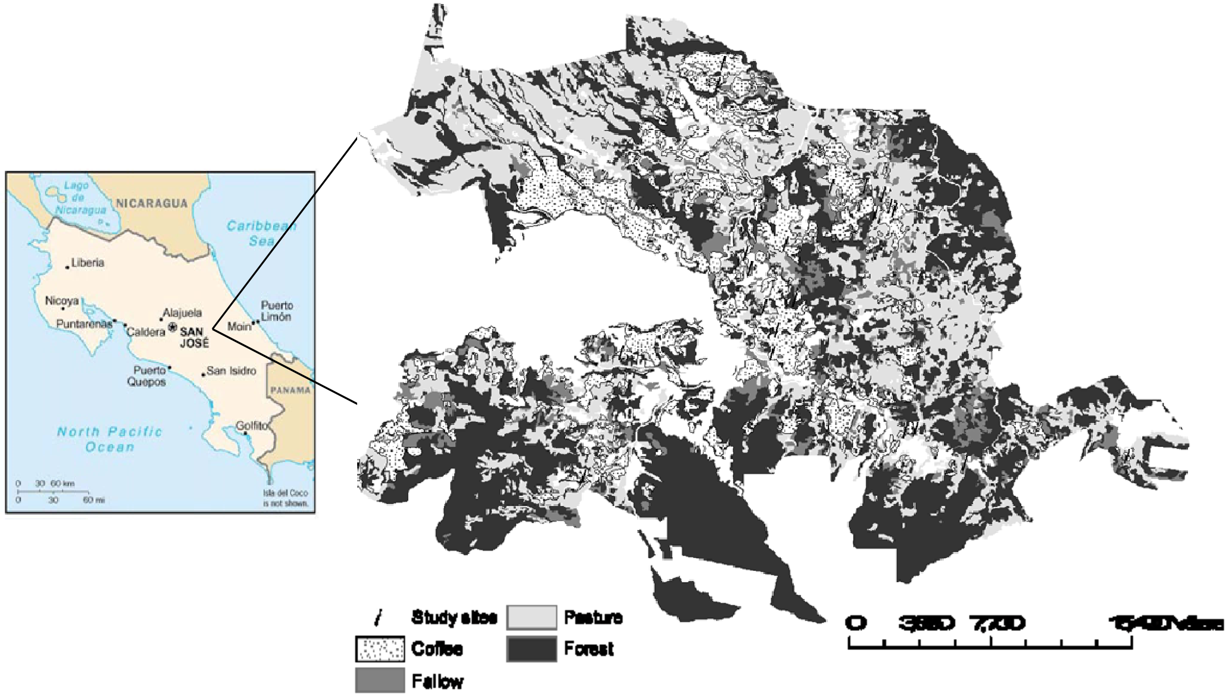

Figure 2.1. Location of study sites within the Volcánica Central-Talamanca Biological Corridor, Costa Rica.

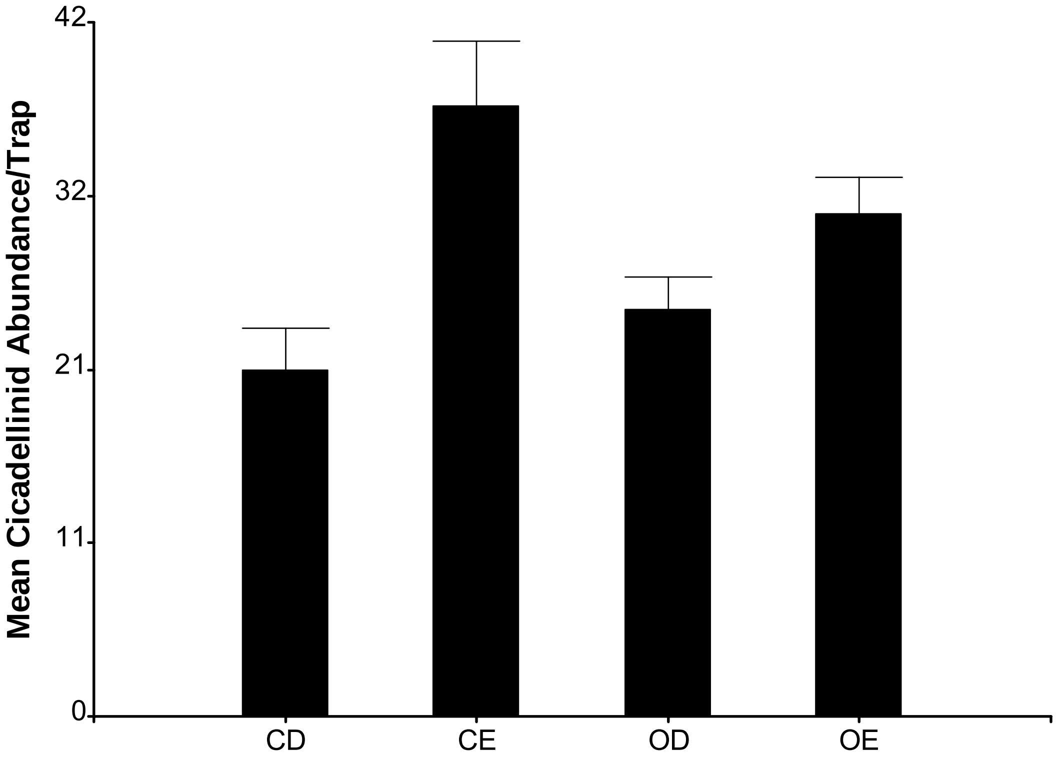

Figure 2.2. Mean abundance of sharpshooters collected per trap in each coffee agroforestry system type. CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); CE is conventional management with *E. poeppigiana* shade; OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); and OE is organic management with *E. poeppigiana* tree shade.

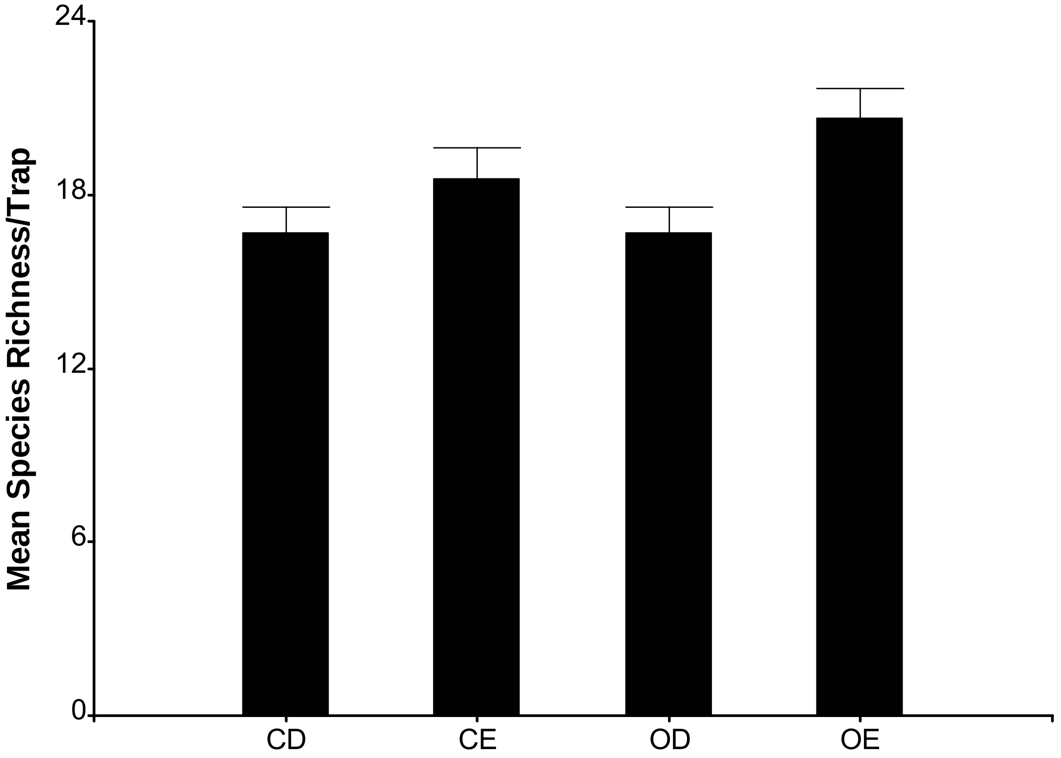

Figure 2.3. Mean species richness of sharpshooters collected per trap in each coffee agroforestry system type. CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); CE is conventional management with *E. poeppigiana* shade; OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); and OE is organic management with *E. poeppigiana* tree shade.

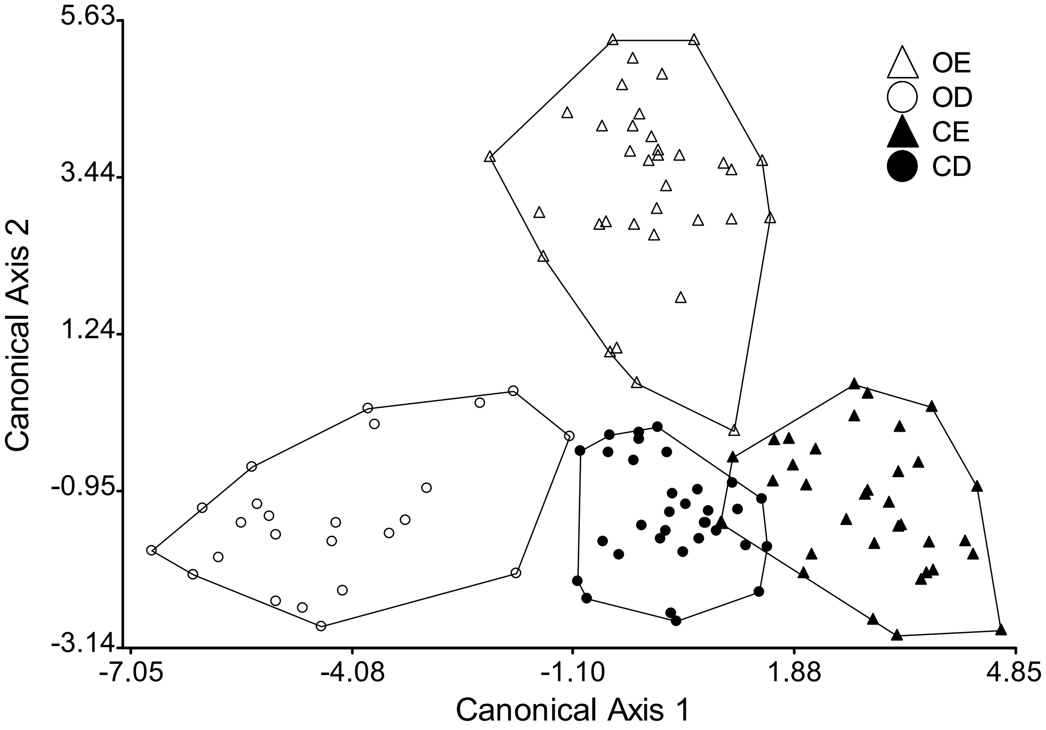

Figure 2.4. Scatter plot using the first two discriminant dimensions derived from sharpshooter community data. Triangles represent *E. poeppigiana* shade treatments and circles represent *C. alliodora-Musa* spp.-*E. poeppigiana* shade treatments. Empty symbols represent organic treatments and solid symbols, conventional ones.

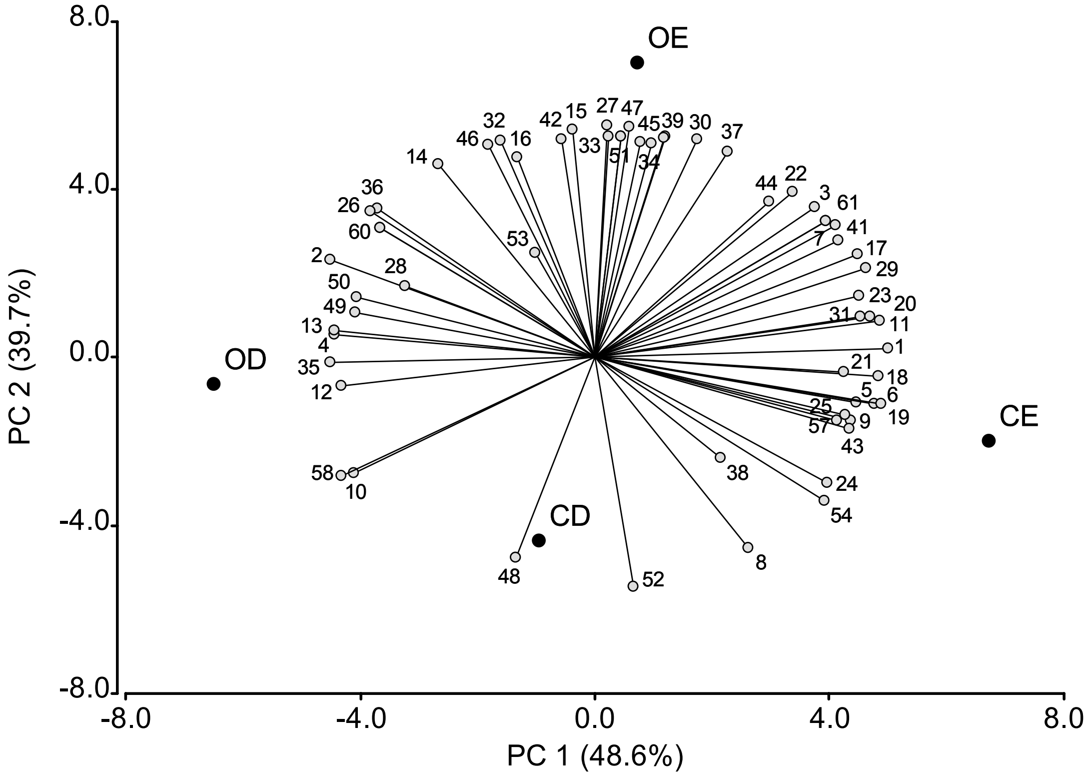

Figure 2.5. Biplot showing principle component analysis (PCA) results. Species are represented by numbers. Species names correspond to numbers in Table 2. Black circles represent coffee agroforestry system type and gray circles represent each sharpshooter species. CE is conventional management with *E. poeppigiana* tree shade; CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); OE is organic management with *E. poeppigiana* tree shade; and OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.*)*.

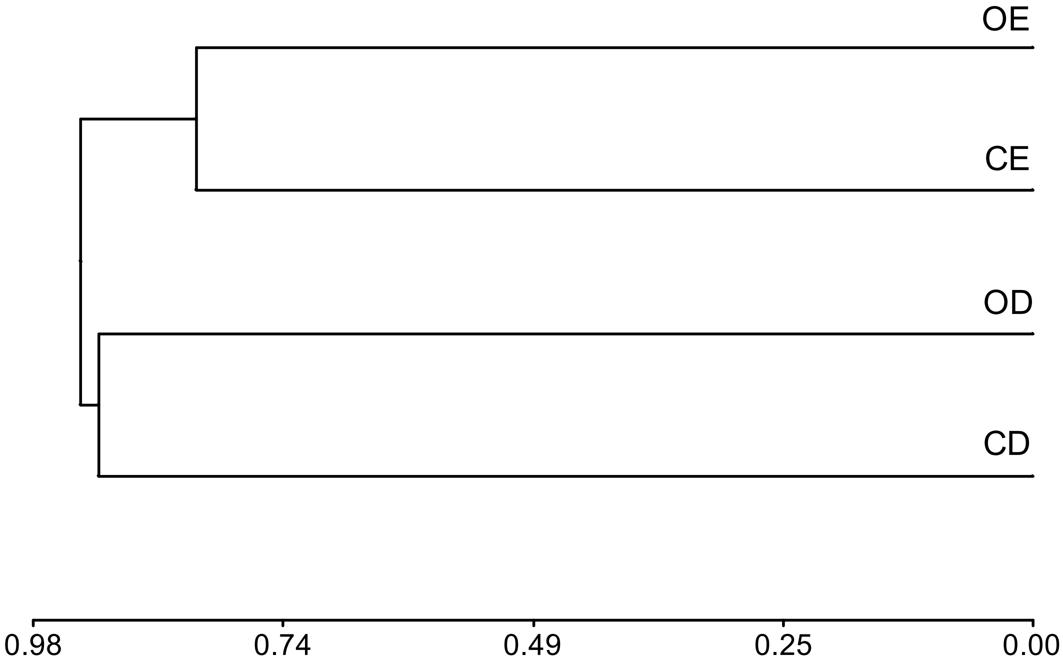

Figure 2.6. Cladogram showing cluster analysis results, when considering the abundance of each sharpshooter species at each coffee agroforestry system type. The x axis shows Jaccard's distance. CE is conventional management with *E. poeppigiana* tree shade; CD is conventional management with diverse shade (*C. alliodora*, *E. poeppigiana* and *Musa* spp.); OE is organic management with *E. poeppigiana* tree shade; and OD is organic management with diverse shade trees (*C. alliodora*, *E. poeppigiana* and *Musa* spp.*)*.

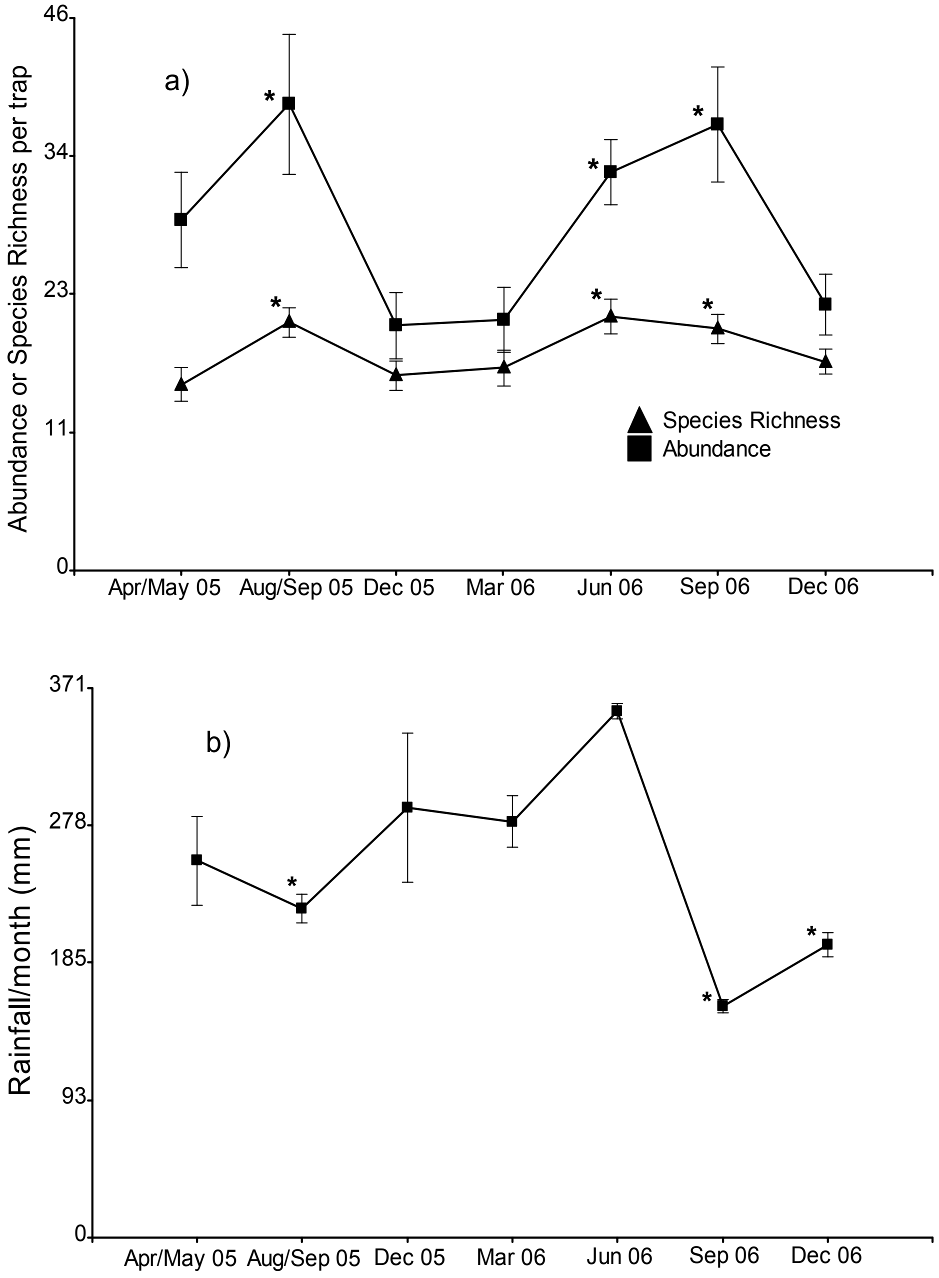

Figure 2.7. Mean abundance (squares) and species richness (triangles) of sharpshooters for the seven sampling times (a), as well as total precipitation (mm) (b) during sampling months. Asterisks represent significantly higher in (a) and significantly lower in (b), according to Fisher LSD test for mean comparison.

CHAPTER 3

Influence of adjacent pastures and forests on coffee leafhopper (Hemiptera: Cicadellinae) communities and *Xylella fastidiosa* incidence

Abstract

Sharpshooter species in the subfamily Cicadellinae are potential vectors of *Xylella fastidiosa*, the bacterial causal agent of “crespera” disease of coffee in Costa Rica and elsewhere. Sharpshooters are generalist xylem-sap feeders, and are known to move between different habitat types in a given landscape, potentially seeking complementary resources. The effect of adjacent forests and pastures on coffee sharpshooter communities and *X. fastidiosa* presence was studied in Turrialba, Costa Rica. Sharpshooters were sampled every other month in 2006 in three conventional coffee farms. Malaise traps were placed in the center of the farm and along farm edges neighboring forest and pasture. Yellow sticky cards were placed at the same locations, plus in adjacent forest fragments and pasture lands. For each farm, eight coffee plant samples per location (edge with forest, edge with pasture, and farm center) were tested for *X. fastidiosa* presence using ELISA. A total of 61 sharpshooter species was collected. Coffee sharpshooter communities were more similar to those in pasture than to those in forests, and sharpshooter abundance was higher at the farm edge adjacent to pasture than at other farm locations, suggesting complementary use of pasture and coffee resources. Sharpshooters were trapped equally moving into pasture from coffee and into coffee from pasture, whereas more sharpshooters were trapped moving from forest into coffee at forest edges. Sharpshooter patterns of abundance could not be related to *X. fastidiosa* presence, since all coffee plants sampled tested positive for this bacterium.

Keywords. Edge effects, ecotones, sharpshooters, coffee agroforestry systems, landscape, “crespera” disease, Costa Rica

Resumen

Algunos cicadelinos (Hemiptera: Cicadellinae) son los vectores potenciales de *Xylella fastidiosa*, bacteria que causa la “crespera” del café en Costa Rica. Los cicadelinos son generalistas, se alimentan exclusivamente del xilema, y potencialmente se desplazan entre hábitats, buscando recursos complementarios en el paisaje. Este estudio examinó el efecto de los bosques y las pastizales colindantes en las comunidades de cicadelinos y en la presencia de *X. fastidiosa* en fincas de café en Turrialba, Costa Rica. Los cicadelinos fueron muestreados cada dos meses en tres fincas, para un total de seis muestreos por finca en el 2006. Se colocaron trampas Malaise de migración en el centro y en los bordes (con bosque y pasturas) de cada finca. Además, se colocaron trampas amarillas en estas localidades y en el centro de los bosques y las pasturas. En cada uno de los puntos en las fincas donde se colocaron las trampas Malaise, se muestrearon ocho plantas de café para determinar la presencia de *X. fastidiosa* a través de ELISA. Se recolectó un total de 61 especies de cicadelinos. Las comunidades de cicadelinos del café fueron más parecidas a las comunidades de las pasturas que a las del bosque y la abundancia de cicadelinos fue mayor en el borde con la pastura, sugiriendo esto un uso complementario de los recursos de ambos sistemas. Los cicadelinos se movieron igualmente a la pastura y al café en el borde con la pastura, pero de forma unidireccional hacia el café en el borde con el bosque, lo cual sugiere que los bosques funcionan como fuentes de estos insectos en el paisaje. Los patrones de abundancia de los cicadelinos no se pudieron relacionar con los patrones de *X. fastidiosa*, ya que todas las plantas indicaron ser positivas a la bacteria.

Palabras clave: efecto de borde, ecotonos, sistemas agroforestales de café, paisaje, "crespera" del café, Costa Rica

Introduction

Some landscapes of Mesoamerica are a mosaic of forest fragments embedded in a matrix of agricultural land uses. Moreover, coffee agroforestry systems are the dominating agricultural land use in many of these landscapes. Coffee agroforestry systems have been investigated extensively, focusing on their shade component and the ecosystem services that the inclusion of shade can provide to both coffee systems (improved microclimate for production, soil conservation, natural pest control) and society as a whole (biodiversity conservation, watershed services, carbon sequestration) (Perfecto *et al.* 1996; Beer *et al.* 1998; Pérez-Nieto *et al*. 2005; Varón *et al.* 2007, Dossa *et al.* 2008). Nevertheless, the interaction of coffee agroforestry systems and their surrounding landscapes has been less studied, despite landscape factors can be important for local processes in coffee agroforestry systems and the services they provide.

A landscape perspective may be necessary to understand the service of natural insect pest control in coffee agroforestry systems, since several natural enemies and coffee insect herbivores respond to landscape elements. For example, proximity to forest affects both natural enemies and insect herbivores in coffee agroforestry systems. Natural enemies, like ants (Perfecto and Vandermeer 2003) and parasitoids (Klein *et al.* 2006), exhibit a decline in species richness with increasing distance from forest. Additionally, a decrease in parasitism of trap nesting hymenopterans is observed with increasing distance from forest (Klein *et al*. 2006). Leaf-cutting ants, an important coffee pest, also have a positive response to proximity to forest, having higher nest densities near edges with forest fragments (Varón 2006). In addition, landscape composition affects natural enemies and insect herbivores. Insectivorous birds, which are known to reduce coffee insect herbivore populations (Perfecto *et al.* 2004; Borkhataria *et al.* 2006), are influenced by the amount of forest cover surrounding coffee farms in 1km radii (Florian 2005).

Since some insect species can be vectors of plant pathogens, the study of such vectors, pathogens and the diseases they cause may also benefit from a landscape perspective. In the Neotropics, *X. fastidiosa,* a xylem-limited generalist bacterium, causes Coffee Leaf Scorch and Crespera disease in coffee (Berreta *et al*. 1996; Rodríguez *et al.* 2000). *Xylella fastidiosa* is also the pathogen responsible for diseases in many economically important plants, including grape (Pierce's disease), citrus (Citrus Variegated Chlorosis), almond (Almond Leaf Scorch) and ornamentals (Purcell 1997). *Xylella fastidiosa* is vectored by sharpshooters (Hemiptera: Cicadellidae: Cicadellinae) that are xylem-sap feeding specialists (Redak *et al.* 2004). Most Cicadellinae species tested in enough numbers have been proven to be carriers of *X. fastidiosa*, leaving vector behavior, vector host preference and distribution as the more important factors determining their role as vectors (Almeida *et al.* 2005). Since leafhoppers are generalists and can move between habitats (Irwin *et al.* 2000), local field sharpshooter abundance is potentially sensitive to other land uses present in the landscape. For example, sharpshooters colonize agricultural fields from surrounding vegetation fragments (Purcell 1974; Nestel and Klein 1995), which can result in higher disease incidence near these edges [Pierce's disease (Purcell 1974), Almond Leaf Scorch (Groves *et al*. 2005)].

Like its sharpshooter vectors (Godoy *et al.* 2005), *X. fastidiosa* strains of Costa Rica are believed to be native to the area, colonizing coffee when it was introduced (Montero-Astúa *et al.* 2007). Because forests are suspected as sources of leafhoppers in Costa Rica, while pastures are sinks (Irwin *et al.* 2000), forest fragments near coffee plantations may play a role in the distribution of *X. fastidiosa* and its sharpshooter vectors in farms. The response of sharpshooters to forest proximity may be a positive one, as described for temperate areas, or a negative one, considering that parasitoids and predators are positively affected by forest (Perfecto and Vandermeer 2003, Klein *et al.* 2006). In the case of pastures, Pierce's disease epidemics in California have been associated with neighboring irrigated pasture fields (Hewitt *et al.* 1942 *cited in* Almeida *et al.* 2005). Thus, while pastures are considered sinks for leafhoppers in Costa Rica (Irwin *et al.* 2000), this land use type may play also a role in the dynamics of the disease and its vectors. This might be particularly the case if we consider the presence in pastures of weed species (i.e. *Brachiaria* spp.) that carry *X. fastidiosa* (Lopes *et al*. 2001).

The present study sought to understand the effects of adjacent land uses on coffee sharpshooter communities and on the presence of *X. fastidiosa* in coffee plants within farms. A community level study was required since the most effective vectors in coffee have not been yet identified for Costa Rica, and all sharpshooter species tested thus far carry the bacteria (Godoy *et al*. 2005). Specifically, the present study examined: a) the effects of coffee farm edges with adjacent pasture or forest on sharpshooter communities, and b) the directionality in movement of sharpshooter at these edges. Forest and pasture were selected as adjacent land uses since they are frequently found next to coffee in landscapes of Costa Rica.

Materials and Methods

1. Site description

The study was conducted in the Southern part of the Volcánica Central-Talamanca Biological Corridor near Turrialba, Costa Rica (Figure 3.1). Three coffee farms with both forest and pasture adjacent land uses were selected. The farms were conventionally-managed, planted with var. Caturra and heavily-pruned *Erythrina poepiggiana* shade trees. Pastures were naturalized pastures currently being grazed by cows. Forest fragments were composed of secondary and primary forest species, including *Clarisia biflora, Ocotea nicaragüensis* and *Rollinia pittieri* (Murieta 2005).

2. Sharpshooter sampling

Sharpshooters were monitored every other month during 2006. To determine the potential directionality of movement from adjacent land uses to coffee and vice versa, 6m x 6m migration Malaise traps (Walker 1978) were used (Irwin *et al.* 2000). One trap was placed along each edge (with forest or with pasture) and in the coffee farm, approximately 100 m or more from the edges. Traps were placed twice per sampling month, each time for three days, for a total of six sampling days per sampling month. Sharpshooters collected on the two sides of the Malaise traps were kept and recorded separately. To compare the abundance of sharpshooters on the three land uses (coffee, forest and pasture) and the two farm edges (with pasture and with forest), yellow sticky traps (21.5 cm x 27.9 cm) were used. Two yellow sticky traps were placed in each of the five locations (pasture, forest, coffee, coffee edge with pasture, and coffee edge with forest) at a height of 120 cm, and collected after a week. Traps were set up once every sampling month.

Sharpshooter morphospecies were identified and counted in the laboratory, using a reference collection. Aid with species identification was provided by Carolina Godoy at Instituto Nacional de Biodiversidad (INBio), in Costa Rica. Species richness was determined by counting the number of species per trap side, and abundance by counting the total number of sharpshooter individuals in each morphospecies, per trap side. Shannon diversity indicex values were calculated using the biological diversity index function of InfoStat Professional version 2007 (InfoStat 2007).

3. *Xylella fastidiosa* sampling

Coffee plants were examined for presence of *X. fastidiosa* using ELISA (Rodríguez *et al*. 2001) to determine if its incidence was higher near edges or within the farm. In February 2007, eight coffee plants were selected randomly in each of the edges (forest and pasture) and in the coffee farm, at the same places where Malaise traps were set up, to collect plant samples (for a total of 24 samples per farm). For each coffee plant selected, the fourth pair of leaves of four basal branches (in the four cardinal directions) were collected and placed in a plastic bag. Samples were sent to the Centro de Investigación en Biología Celular y Molecular (CIBCM), Universidad de Costa Rica (UCR) for analysis.

4. Statistical Analyses

Normality and variance homogeneity assumptions for the response variables (sharpshooter species richness and abundance) were verified using InfoStat Professional version 2007 (InfoStat 2007). To determine differences between trap locations (i.e. coffee, forest, pasture, and edges) , ANOVA were conducted using PROC MIXED, SAS version 8.2 (SAS Institute 2001). The autocorrelation between weekly observations was modeled by mean of different co-variance matrices: autoregressive the first order (AR1), composed symmetry and unstructured models. AIC and BIC fitting criteria were used to select the best model. AR1 models were selected for species richness and abundance. When the ANOVA was significant ($P = 0.05$), a Fisher LSD test for mean comparison was carried out, using the macro PDMIXED800 (Saxton 1998). To determine if differences between trap sides of the migration Malaise trap at each edge were significant, a paired t-test was conducted using InfoStat Professional version 2007 (InfoStat 2007). To compare sharpshooter communities in each location, cluster analysis and principal components analysis were performed, using InfoStat Professional version 2007 (InfoStat 2007). A biplot of the principal components analysis of the abundances of sharpshooter species was constructed to interpret graphically the relationship between sharpshooter species abundances and with coffee agroforestry treatments.

Results

A total of 7,491 sharpshooter individuals belonging to 61 species was collected. Yellow sticky traps collected 4,587 individuals of 51 species (Table 3.1), wherareas Malaise traps collected 2,904 individuals of 52 species (Table 3.2). Yellow sticky traps captured more individuals at the coffee edge with forest than at the coffee edge with pasture. This difference was not detected with Malaise traps. Malaise traps were especially effective for collecting some species that were more abundant at the coffee edge with pasture, including *Sibovia occatoria, Macunolla ventralis, Hortensia similis, Draeculacephala sp.* and *Agrosoma pulchella*. These species were also present at the center of the coffee farm, but they were not as abundant.

Sharpshooter communities at the center of coffee farms were more similar to communities in pasture and coffee edge with pasture than to forest or coffee edge with forest communities (Figure 3.2). Species richness was significantly affected by location (Table 3.4). Yellow sticky trap data indicated that sharpshooter species richness was significantly higher at both coffee farm edges (with forest or pasture) than at the center of coffee farms, forests or pastures (Figure 3a). Malaise trap data showed higher species richness at the pasture edge only (Figure 3b). Coffee, pasture and coffee edge with pasture had higher sharpshooter diversity index values than forest and coffee edge with forest (Table 3.3).

Abundance of sharpshooters collected with yellow sticky traps was not significantly affected by location (Table 3.4), but there was a trend of higher abundance in the coffee edges with forest and pasture (Figure 3.4a) than in other locations. Malaise trap sharpshooter abundance was significantly affected by location (Table 3.4), and showed higher abundance in the coffee edge with pasture (Figure 3.4b). Although yellow trap overall sharpshooter abundance did not differ with location, individual species were associated with particular locations (Figure 3.5).

Sharpshooters appeared to move from forest sites to coffee fields, but not in the other direction. The abundance and species richness of sharpshooters from the two Malaise trap sides was significantly different at the forest edge (Table 3.5). Abundance (Figure 3.6) and species richness (Figure 3.7) were higher at the forest trap side than at the coffee side. No directionality of movement was observed at the pasture edge (Table 3.5). This could be due to the similarity of pasture sharpshooter communities to coffee sharpshooter communities (Figure 3.2). Both trap sides at the pasture edge showed higher means for abundance (pasture side mean = 38; coffee side mean = 45) and species richness (pasture side mean = 13; coffee side mean = 13) than the coffee trap side at the forest edge (Figure 3.6 and Figure 3.7). This was similar in all sampling months.

Known carriers of *X. fastidiosa,* such as *Fusigonalia lativitatta* (Fowler)*, Graphocephala permagna* (Nielson & Godoy) *and Hortensia similis* (Walker) (numbers 2, 18 and 34 in Figure 3.5, respectively) (Godoy *et al*. 2005) were associated with the pasture edge. *Xyllela fastidiosa* presence in coffee plants did not vary with location. All samples taken tested positive to the bacterium, even though coffee plants did not show symptoms of “crespera” disease.

Sampling time (month) significantly affected sharpshooter abundance (Table 3.4). Based on yellow sticky traps, sharpshooters were significantly more abundant in the June and August samplings (*P* = 0.05; Figure 3.8a). In contrast, Malaise trap data, although also showing a lower abundance during December and February, had a significantly higher abundance peak in April (*P* = 0.05; Figure 3.8b). April was the month with the lowest mean daily precipitation (Figure 3.9). Since Malaise traps are flight interception traps, sharpshooters appear to exhibit greater movement when there is less precipitation.

Discussion

Sharpshooters in coffee appear to colonize agricultural fields in a similar way to sharpshooters in temperate areas. Several studies in temperate areas have shown that sharpshooters colonize agricultural fields from adjacent forest fragments (including riparian forests), where they overwinter (Purcell 1975; Blua and Morgan 2003). In the present study, sharpshooters moved preferentially from forest to coffee, but not in the opposite direction. This has also been observed in other areas of Costa Rica, where leafhoppers moved preferentially from forest to pastures (Irwin *et al*. 2000). However, this directionality of movement did not result in higher abundance of sharpshooters at the coffee edge with forest. Instead, higher sharpshooter abundance was observed at the coffee edge with pasture.

Sharpshooters did not show directionality in movement at the coffee edge with pasture, but had higher abundance at this edge than at the edge with forest. Coffee sharpshooter communities are more similar to pasture than to forest sharpshooter communities, and sharpshooters potentially use coffee and pasture resources complementarily. Pasture and coffee sharpshooter communities also showed higher diversity index values than forest. This is expected if edges are considered ecotones, where community members of both habitats overlap (Speight *et al.* 1999). Also, the positive edge response of sharpshooter abundance at the coffee edge with pasture can be explained by Ries *et al.* (2004) model for edge effects in an edge between two equal quality habitats (in this case, coffee and pasture). A positive edge response is observed if there is either a) a use of complementary (different) resources in the two habitats, or b) a concentration of resources at the edge. The resources provided by coffee and pasture land uses are potentially complementary for sharpshooters, considering how the two land uses differ in vegetation composition and structure. The hypothesis of higher concentration of resources at the edge can apply, if livefences of pruned *E. poepegiana* are considered as a concentration of resources for sharpshooters. Many sharpshooter species are associated with *E. poepegiana* trees in coffee agroforestry systems (Rojas *et al.* 2001).

Malaise traps were better at detecting a difference between coffee edge with pasture and other locations. This was mainly due to increased catching of additional species (e.g. *Tylozygus geometricus*, *Hortensia similis,* and *Draeculacephala sp)* that apparently were not as attracted to yellow traps as other species. Yellow traps attract sharpshooters, while Malaise traps passively collect sharpshooters as they move through habitats (Missa *et al.* 2008). The difference in attraction to yellow traps could reflect attraction of these species to different plant resources, as different plant parts have different spectral reflectance (Chu *et al.* 2000). However, the trapping of these species in Malaise traps indicate they have flight activity at the coffee edge with pasture.

X. fastidiosa presence could not be related to sharpshooter patterns of abundance. *Xylella fastidiosa* was present in all coffee plants sampled. The bacterium might be present in a large proportion of coffee plants in the region, but plants do not express “crespera” symptoms*. Xylella* fastidiosa is an opportunistic pathogen that may live in the xylem of plants without causing disease symptoms (Purcell and Saunders 1999). Plant stress factors, especially water stress may trigger symptom appearance caused by *X. fastidiosa* (Paradela

Filho *et al*. 1999). In Costa Rica, higher incidence of Crespera disease has been observed in conventional farms with limited or no shade, located in areas (e.g. Tarrazú) where coffee plants may suffer water stress at least some part of the year (Jacques Avelino personal communication). In our study region, there is no distinct dry season, most farms have shade trees, and coffee plants typically do not suffer water stress (Benavides and Montoya 1974).

Sharpshooters communities in coffee agroforestry systems are affected differently by bordering land uses. Any future efforts to control or conserve sharpshooter species should consider edge effects, and forests as sources of sharpshooters in the landscape. More detailed studies on the development of Crespera disease in *X. fastidiosa*-infected coffee plants are needed to understand the role of sharpshooter ecology on the spread of the disease.

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Table 3.1. Total number of individuals collected for each species with yellow sticky traps per location. Numbers for the coffee location are averages of the two coffee trap locations.

Species	Coffee	Edge w/ Forest	Forest	Edge w/ Pasture	Pasture	Total
1. Beirneola anita	51.5	1134	540	51	4	1780.5
2. Fusigonalia lativitatta	293.5	55	0	329	27	704.5
3. Stephanolla rufoapicata	26.5	165	204	74	7	476.5
4. Juliaca pulla	76	69	6	56	4	211
5. Ladoffa sp.1	39.5	111	5	20	3	178.5
6. Macugonalia testudinaria	28.5	4	0	77	5	114.5
7. Sibovia occatoria	17	2	0	51	33	103
8. Erythrogonia aerolata	10	29	4	32	19	94
9. Fusigonalia sp.1	10	51	16	12	1	90
10. Macunolla ventralis	15	2	1	26	22	66
11. Ladoffa sp. 3	9.5	30	0	22	0	61.5
12. Morphospecies 105	1.5	19	31	2	2	55.5
13. Shildola opaca	6	15	3	14	15	53
14. Morphospecies 50	0	45	6	1	0	52
15. Graphocephala sp. 1	25.5	0	0	11	11	47.5
16. Morphospecies 42	9.5	12	5	12	2	40.5
17. Graphocephala rufimargo	0.5	0	0	18	21	39.5
18. Graphocephala permagna	22	2	0	14	1	39
19. Morphospecies TR	14.5	1	0	18	0	33.5
20. Oncometopia sp. 7	7	6	1	12	7	33
21. Morphospecies 76	0.5	0	0	7	22	29.5
22. Morphospecies 55	0.5	19	5	0	0	24.5
23. Phera sp.	3.5	0	0	10	11	24.5
24. Morphospecies 66	0.5	7	15	0	0	22.5
25. Oncometopia sp. 1	5	0	0	13	3	21
26. Morphospecies 60	0	0	21	0	0	21
27. Microgoniella sociata	4	0	0	11	2	17
28. Ladoffa sp. 2	3	8	2	2	1	16
29. Agrosoma pulchella	0.5	0	0	8	5	13.5
30. Oncometopia sp. 8	4.5	1	0	1	4	10.5
31. Morphospecies 65	0	9	0	1	0	10
32. Morphospecies 143	0.5	7	1	0	1	9.5
33. Draeculacephala sp.	1.5	1	0	4	3	9.5

34. Hortensia similis	1.5	0	0	4	4	9.5
35. Oncometopia sp. 4	1	0	0	5	3	9
36. Mareja reticuliceps	2.5	4	0	2	0	8.5
37. Morphospecies 200	0	7	1	0	0	8
38. Morphospecies 202	1.5	0	0	6	0	7.5
39. Morphospecies 77	1	0	1	2	3	7
40. Morphospecies 201	0	6	0	0	0	6
41. Morphospecies 67	0	2	4	0	0	6
42. Morphospecies 58	0	1	4	0	0	5
43. Oncocometopia sp.3	2.5	0	0	2	0	4.5
44. Tylozygus geometricus	0.5	0	0	2	0	2.5
45. Morphospecies 111	0	2	0	0	0	2
46. Morphospecies 203	0	2	0	0	0	2
47. Morphospecies 130	0	0	1	0	1	2
48. Apogonalia fractinota	0.5	1	0	0	0	1.5
49. Baleja flavoguttata	0.5	0	0	1	0	1.5
50. Morphospecies 120	0	0	1	0	0	1
51. Tylozygus fasciatus	0	0	0	1	0	1
Total Abundance	699	1829	878	934	247	4587

Table 3.2. Total number of individuals collected for each species with Malaise bi-directional traps per location.

Species	Coffee	Edge w/ Forest	Edge w/ Pasture	Total
Stephanolla rufoapicata	90	202	146	438
Tylozygus geometricus	111	50	206	367
Beirneola anita	16	188	33	237
Macunolla ventralis	66	10	149	225
Erythrogonia aerolata	45	17	138	200
Fusigonalia lativitatta	69	1	86	156
Oncometopia spp	40	21	92	153
Sibovia occatoria	29	17	105	151
Morphospecie*s 42*	32	12	52	96
Hortensia similis	9	3	83	95
Juliaca pulla	50	18	24	92
Ladoffa sp.1	15	38	34	87
Macugonalia testudinaria	29	5	50	84
Draeculacephala sp.	9	6	68	83
Agrosoma pulchella	6	0	55	61
Apogonalia fractinota	10	7	29	46
Fusigonalia sp.1	2	22	15	39
Ladoffa sp.3	5	11	15	31
Graphocephala permagna	13	0	9	22
Morphospecies *50*	0	20	0	20
Chlorogonalia coeruleovittata	1	2	16	19
Graphocephala sp. 1	8	1	10	19
Ladoffa sp.2	5	3	11	19
Morphospecies 55	0	19	0	19
Tylozygus fasciatus	3	0	13	16
Morphospecies 119	1	7	7	15
Morphospecies 58	0	12	0	12
Morphospecies 120	3	8	0	11
Morphospecies TR	4	1	6	11
Oncometopia sp.1	1	0	10	11
Shildola opaca	1	7	3	11
Phera sp.	0	0	9	9
Morphospecies 118	0	2	5	7
Morphospecies 65	0	4	1	5

Graphocephala rufimargo	1	0	3	4
Mareja reticuliceps	1	3	0	4
Microgoniella sociata	3	1	0	4
Morphospecies 201	1	1	1	3
Morphospecies 202	3	0	0	3
Morphospecies 66	0	1	2	3
Morphospecies 111	0	2	0	2
Morphospecies 130	0	2	0	2
Morphospecies 56	0	2	0	2
Morphospecies 76	0	0	2	2
Morphospecies 113	0	1	0	1
Morphospecies 143	0	1	0	1
Morphospecies 144	0	0	1	1
Morphospecies 203	0	0	1	1
Morphospecies 204	0	0	1	1
Morphospecies 205	0	1	0	1
Morphospecies 60	0	1	0	1
Shildola bivirga	0	1	0	1
Total Abundance	682	731	1491	2904

Table 3.3. Sharpshooter Shannon diversity index value ranges (minimum and maximum values) for the different locations.

Location	Shannon
Yellow sticky traps	
Coffee	2.13 – 2.36
Edge w/Forest	1.14 – 1.59
Forest	0.98 – 1.28
Edge w/Pasture	2.06 – 2.40
Pasture	2.23 – 2.43
Malaise traps	
Coffee	2.66 – 2.81
Edge w/Forest	2.37 – 2.57
Edge w/Pasture	2.88 – 2.97

Table 3.4. ANOVA results (*P*-values) for species richness and abundance of sharpshooters collected with yellow sticky traps and Malaise traps.

	Species Richness		Abundance	
Model factor	Yellow	Malaise	Yellow	Malaise
Site	0.1374	0.0338	0.5933	0.0243
Location	0.0028	0.0195	0.0675	0.0310
Sampling date	0.2039	0.0060	0.0006	<0.0001
Location*Sampling	0.0202	0.1993	0.2905	0.6770

Table 3.5. Paired t-test results (*P* values) comparing sharpshooter species richness and abundance, collected on both sides of Malaise traps located on forest and pasture edges.

Comparison	Species richness	Abundance
Edge: forest side/coffee side	0.0004	0.0016
Edge: pasture side/coffee side	0.3192	0.0618

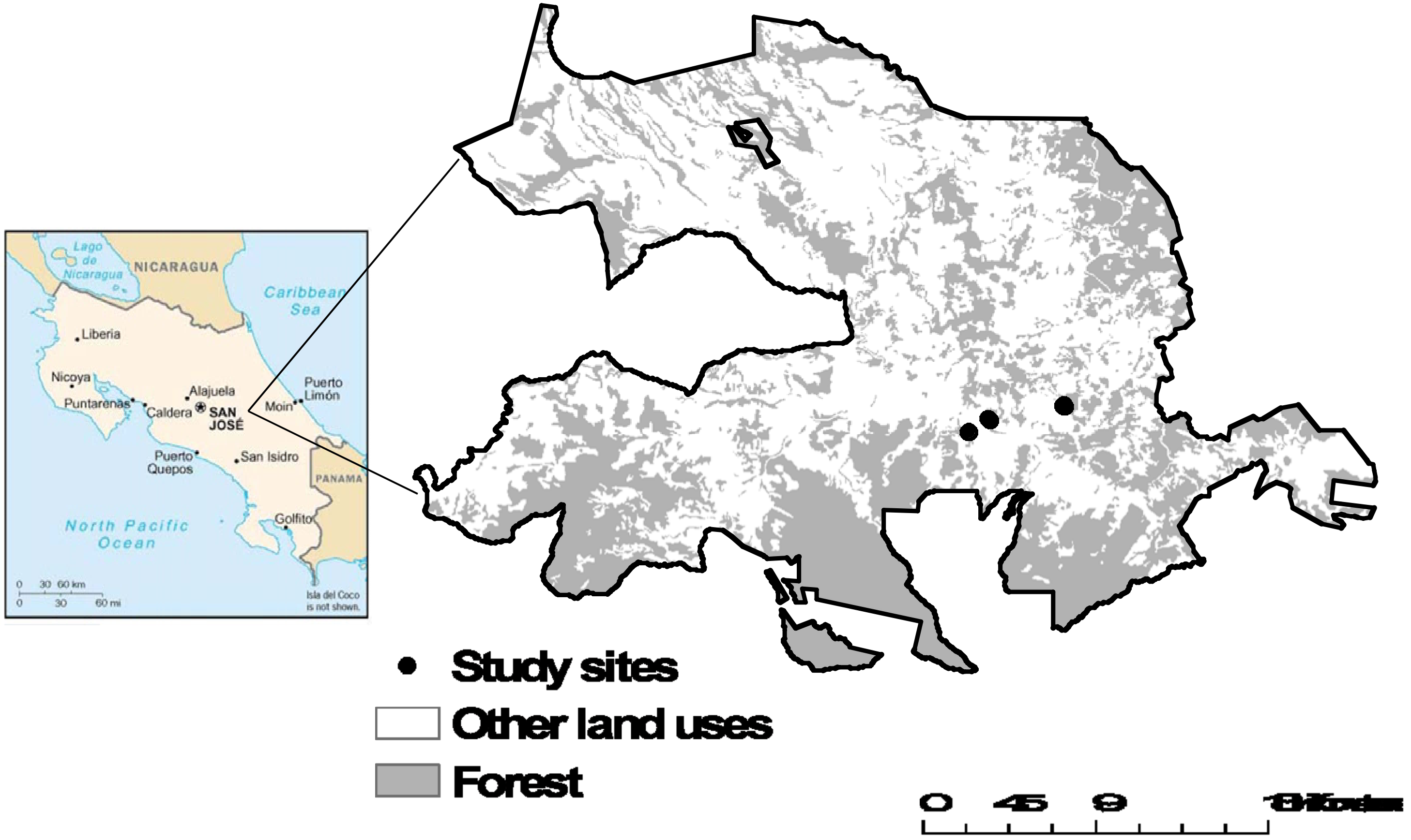


Figure 3.1. Location of study sites within the Volcánica Central-Talamanca Biological Corridor, Costa Rica

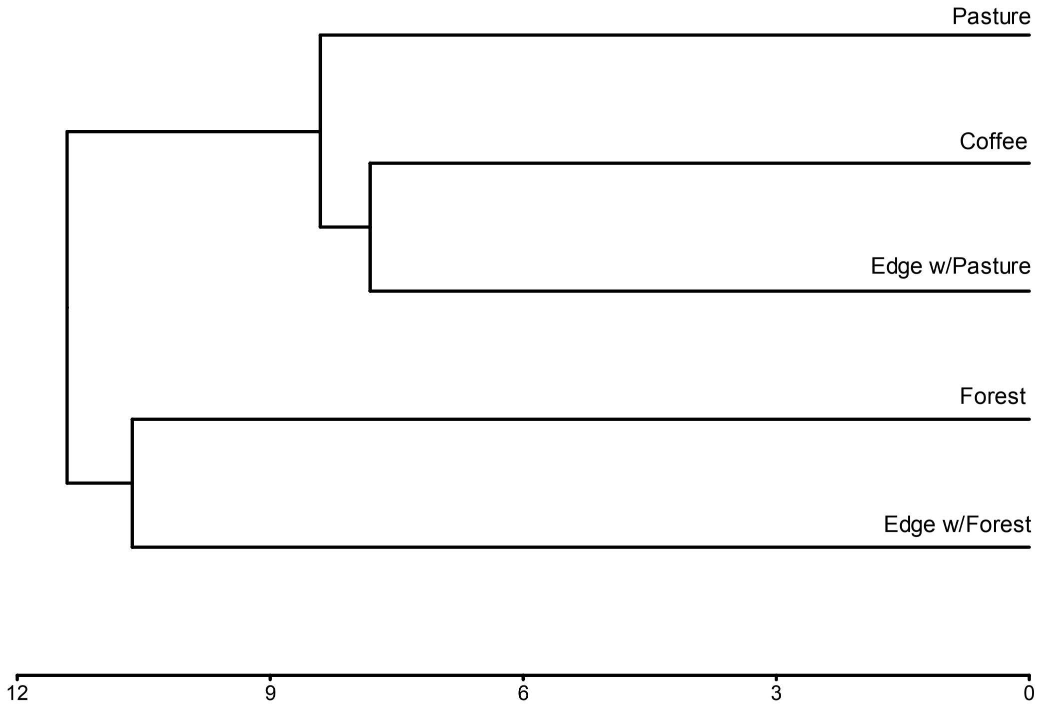
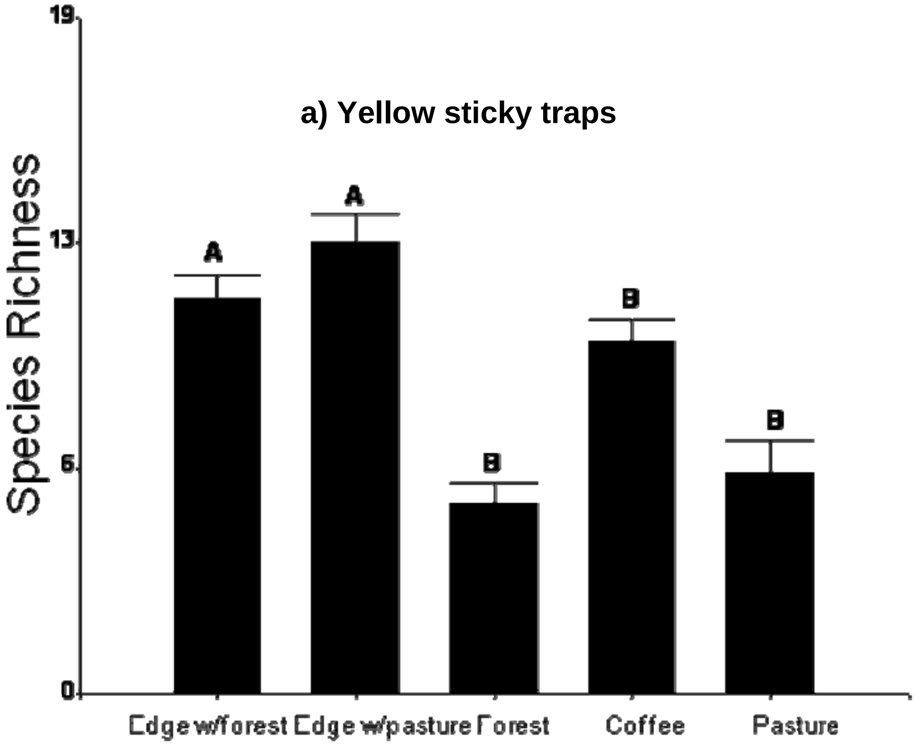
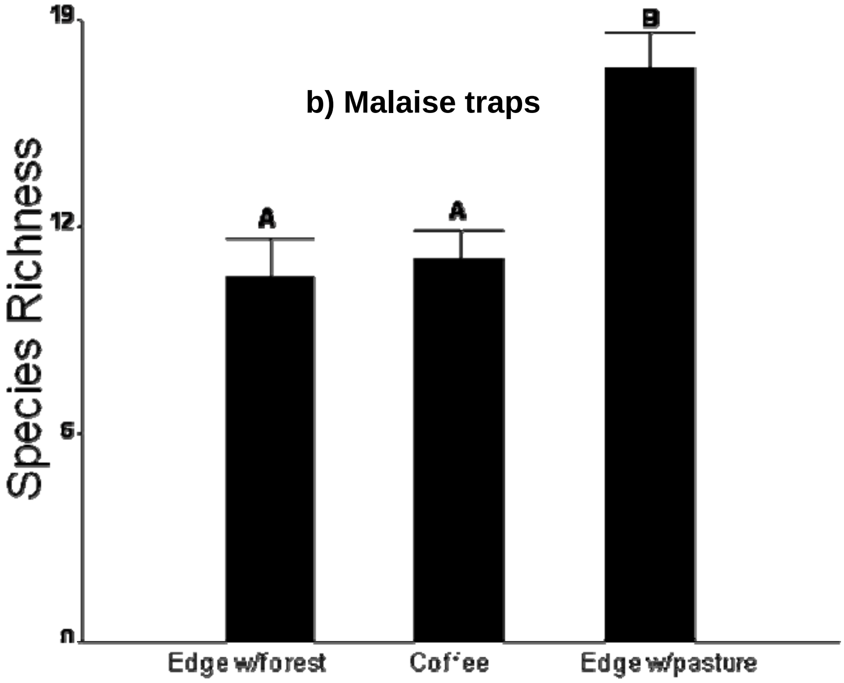


Figure 3.2. Cladogram showing cluster analysis results, when considering the abundance of each leafhopper species at each location. The x axis shows Jaccard's distance.



a) Yellow sticky traps



b) Malaise traps

Figure 3.3. Mean species richness of sharpshooters collected at each location with a) yellow sticky traps, and b) Malaise traps. Different letters indicate significant differences at $P = 0.05$.

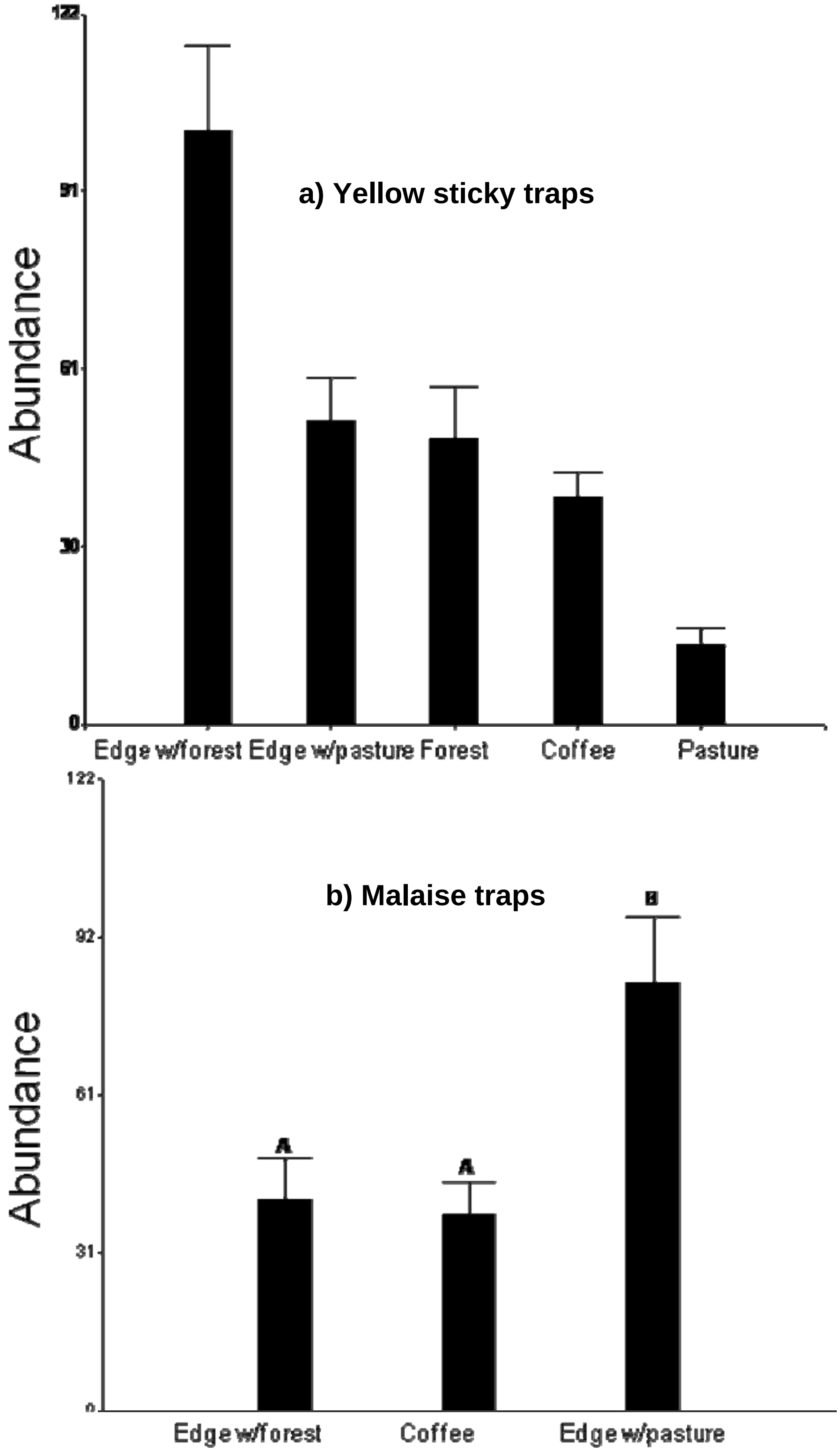

a) Yellow sticky traps
Abundance
122
91
61
30
0
Edge w/forest
Edge w/pasture
Forest
Coffee
Pasture
b) Malaise traps
Abundance
122
92
61
31
0
A
A
B
Edge w/forest
Coffee
Edge w/pasture

Figure 3.4. Mean abundance of sharpshooters collected per trap per sampling period in each farm location with a) yellow sticky traps, and b) Malaise traps. Different letters indicate significant differences at *P* = 0.05.

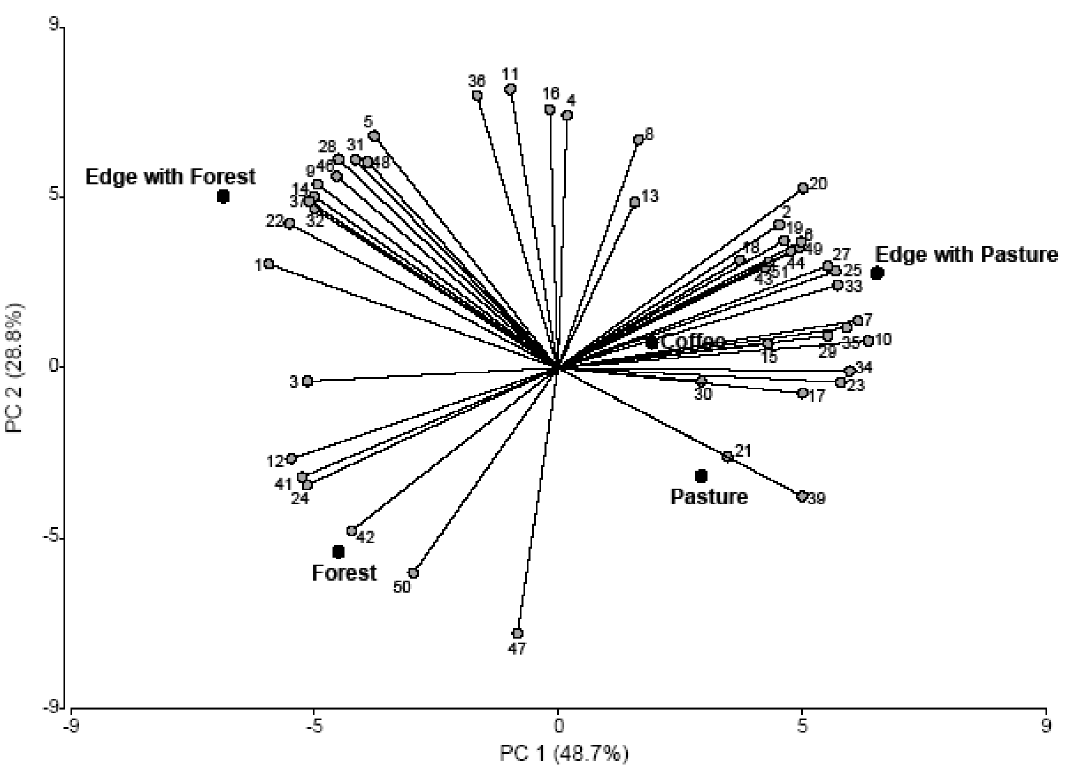


Figure 3.5. Biplot showing Principle Component Analysis (PCA) results from data collected with yellow sticky traps. Black circles represent locations and gray circles represent each leafhopper species, which are identified by the same numbers as in Table 1.

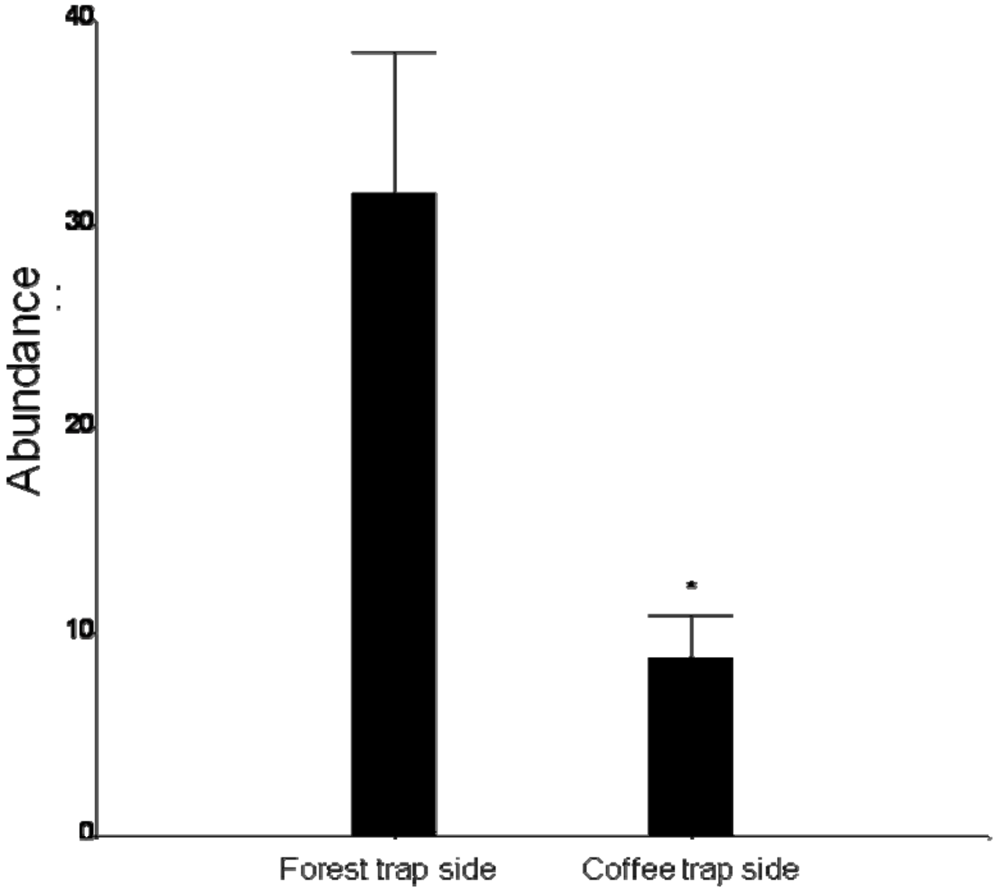


Figure 3.6. Mean abundance of sharpshooters collected in the two trap sides of the bi-directional Malaise trap at the forest edge per sampling. Asterisk indicates a significant difference at *P* < 0.05.

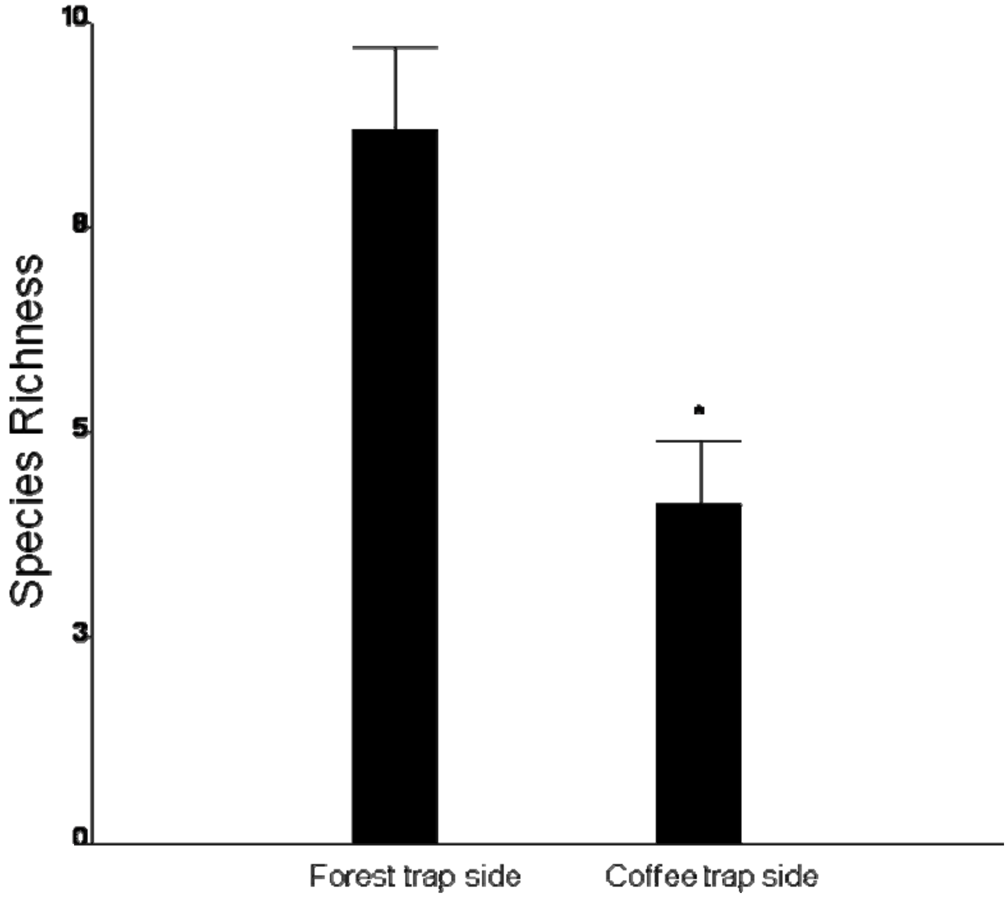
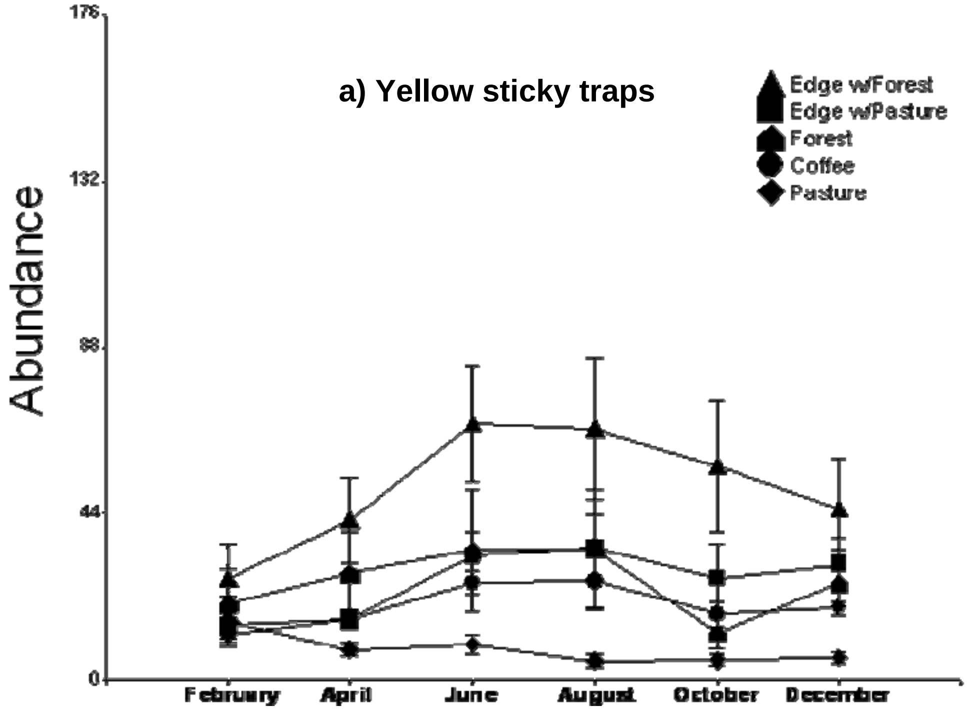


Figure 3.7. Mean species richness of sharpshooters collected in the two trap sides of the bi-directional Malaise trap at the forest edge per sampling. Asterisk indicates a significant difference at $P < 0.05$.


a) Yellow sticky traps
Edge w/Forest
Edge w/Pasture
Forest
Coffee
Pasture
Abundance
176
132
88
44
0
February
April
June
August
October
December

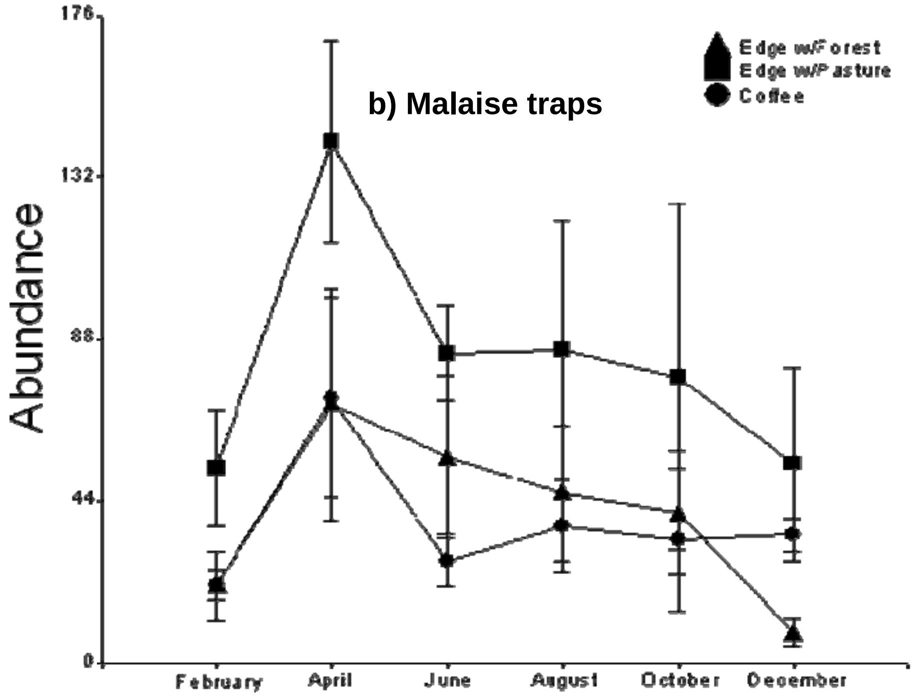

b) Malaise traps
Edge w/Forest
Edge w/Pasture
Coffee
Abundance
176
132
88
44
0
February
April
June
August
October
December

Figure 3.8. Mean abundance of sharpshooters in each location collected with a) yellow sticky traps and b) Malaise traps in the six sampling periods.

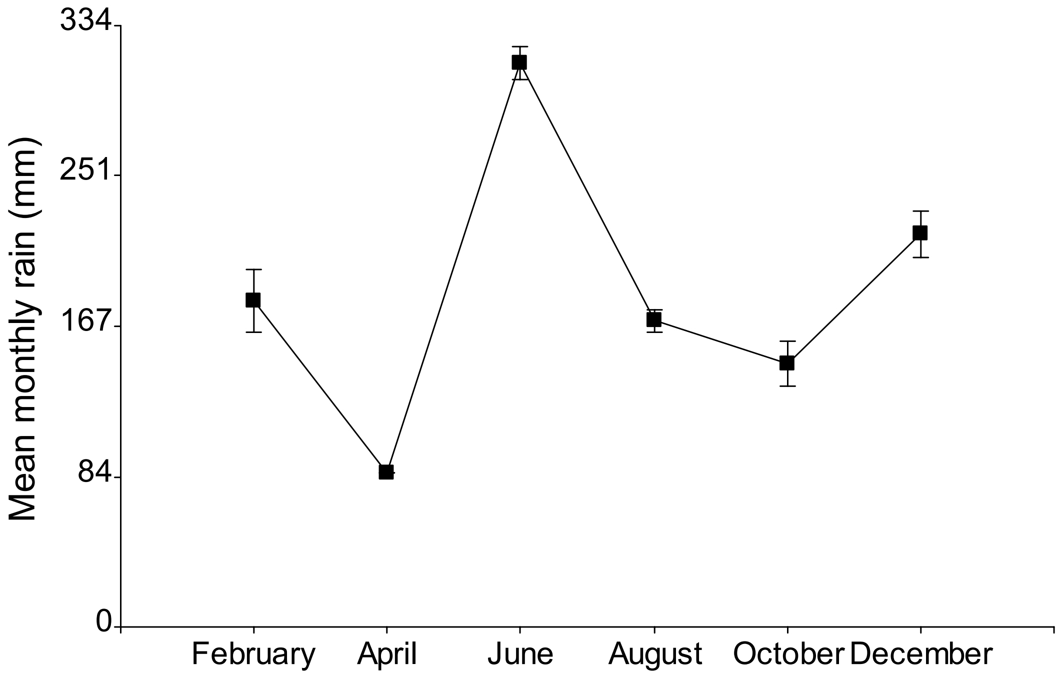


Figure 3.9. Mean monthly precipitation (mm) during sharpshooter samplings in 2006.

CHAPTER 4

The effect of coffee farm weed management on leafhopper communities (Hemiptera: Cicadellinae), including potential vectors of *Xylella fastidiosa*

Abstract

Weed management is an economically important practice in coffee agroforestry systems of Costa Rica. Weed management is known to affect herbivore populations in other agroecosystems. This study examined the effect of weed management practices on sharpshooter communities in coffee agroforestry systems. Sharpshooters are the potential vectors of *Xylella fastidiosa*, the causal agent of crespera coffee disease in Costa Rica. Two experiments were conducted: the first from November 2005 to January 2006, and the second from September 2006 to November 2006. Experiments were designed as Randomized Complete Block Designs with five blocks and three weed management treatments (herbicide control, mechanical control and no weed control). Sharpshooters were collected weekly using yellow sticky traps for eight weeks after treatment application. Sharpshooter abundance and species richness did not differ among treatments. Sharpshooter abundance and species richness, however, were affected by trap height and sampling period. On the temporal and spatial scale of this study, sharpshooter communities in coffee agroforestry systems appear to be affected by factors other than weed management.

Keywords. Coffee agroforestry systems, sharpshooters, agroecology, habitat management, insect vectors of pathogens

Resumen

El manejo de las malezas es una práctica de importancia económica en los sistemas agroforestales de Costa Rica. El manejo de las malezas afecta las poblaciones de herbívoros en otros agroecosistemas. Este estudio examinó el efecto del manejo de malezas en las comunidades de cicadelinos en sistemas agroforestales de café. Los cicadelinos son los vectores potenciales de *Xylella fastidiosa*, la bacteria que causa la crespera del café. Se realizaron dos experimentos. Un experimento se llevó a cabo entre noviembre de 2005 y enero de 2006, y el otro, entre septiembre de 2006 y noviembre de 2006. Se siguió un diseño de parcelas completamente aleatorizadas con tres tratamientos de manejo (control con herbicida, control con machete y ningún control) y cinco parcelas. Los cicadelinos fueron muestreados semanalmente, por ocho semanas, utilizando trampas amarillas pegajosas. No hubo diferencias en abundancia o riqueza de especies entre tratamientos. Sin embargo, hubo diferencias debido a la altura de la trampa y al tiempo de muestreo. Las comunidades de cicadelinos en sistemas agroforestales de café aparentan no ser afectados por las prácticas de manejo de malezas en las escalas temporales y espaciales utilizadas en este estudio.

Palabras clave: Sistemas agroforestales de café, chicharritas, agroecología, manejo de hábitat, insectos vectores de patógenos

Introduction

Coffee (*Coffea arabica)* agroforestry systems are known to provide ecosystem services such as maintaining biodiversity, watershed services, and reducing insect pest populations (Perfecto *et al.* 1996, Sommariba *et al.* 2004, Pérez-Nieto *et al.* 2005, Varón *et al.* 2007). The capacity of coffee agroforestry systems to provide these services is driven in part by the higher plant diversity coffee agroforestry systems have compared to coffee monocultures. In conventional coffee agroforestry systems that employ herbicide for weed control, shade trees provide plant diversity, while in organic coffee agroforestry systems, weeds also contribute to agroecosystem plant diversity.

Weed vegetation can be important for the ecosystem service of natural insect pest control. The presence of weeds has been associated with lower insect pest populations in some agroecosystems (Norris and Kogan 2000). Because herbicides are not toxic to insects, the effect of weed management practices on insect pests is indirect; it is mediated via the impact of management practices on weed plants that serve as hosts for insects (Norris and Kogan 2005). Both top-down and bottom-up mechanisms could be responsible for this effect. Weeds can provide resources for natural enemies of insect pests, like floral rewards for parasitoids (e. g. Damon *et al.* 1999) and alternative prey for predators (e. g. Lykouressis *et al.* 2008). This may result in higher abundance of natural enemies and control of insect pests. This is referred as to the natural enemy hypothesis (Root 1973). Alternatively, the effect of weed presence on insect pests could be due to bottom-up mechanisms, in which weeds reduce the concentration of the crop species, making it harder for herbivores to find the crop species. This is known as the resource concentration hypothesis (Root 1973). Additionally, weeds have a diluting effect, in which herbivores attack the crop species less because they feed on the weeds (Varón *et al.* 2007).

Several studies have examined the ecosystem service of natural insect pest control, directly (predation, Perfecto *et al*. 2004) or indirectly [abundance of natural enemies, e. g. ants Perfecto *et al.* (2002), and parasitoid wasps, Klein *et al.* (2006)] in coffee agroforestry systems. Because most studies have examined the effect of a particular coffee agroforestry system type, it is difficult to discern if the presence of weeds had an effect on the abundance of insects (herbivores or natural enemies). The only study that experimentally examined the effect of coffee farm weed management practices on arthropod communities showed that insects present in the soil, coffee or shade trees were not affected by weed management (Suárez *et al.* 1998). Also, in coffee agroforestry systems of

Mexico, ground ant foraging activity was not affected by weed biomass (Nestel and Dickenschen 1990). It is possible to observe the potential effect of weeds on insect abundance in the few studies that have compared insect abundance between abandoned and organic coffee agroforestry systems. The main difference of these two farm typologies is that in organic systems weed vegetation is disturbed by coffee collectors and by mechanical management practices while in abandoned coffee agroforestry systems these disturbances are not present. Abandoned coffee agroforestry systems have higher abundances of natural enemies (arachnid predators), but also of herbivores (Richter *et al.* 2007).

Weed management in coffee agroforestry systems of Costa Rica ranges from no weed control to intense mechanical control (i.e., four control events using a machete/year) in organic farms, to combined machete and chemical control (three control events with machete and two glyphosate-oxyfluorfen applications/year), or exclusive chemical control (six glyphosate-oxyfluorfen applications/year) in conventional farms (Mora-Delgado and Acosta Arce 2001, Cárdenas 2008). Producers dedicate approximately 30% of farm expenses to activities associated to weed control (Cárdenas 2008). Weeds compete with coffee plants, causing a reduction in stem diameter and primary branch growth (Friessleben *et al.* 1991), and yield reductions might reach up to 60% (Pereira and Jones 1954). The effect of weeds on coffee yield is significant during the first year of plantation establishment, but decreases as coffee trees and shade trees grow (Aguilar *et al.* 2003). Weeds are also a nuisance for coffee berry collectors (e.g. they limit their ability to see poisonous snakes) and interfere with coffee berry borer, *Hypothenemus hampei*, management (e.g. limit the ability to collect infected coffee berries from the ground).

The objective of this study was to determine the effect of coffee farm weed management practices on xylem-feeding leafhopper (Hemiptera: Cicadellinae) communities. Sharpshooters are mainly Neotropical (90% of species) and some species within this subfamily are vectors of *Xylella fastidiosa* (Redak *et al.* 2004), the bacterium that causes Crespera disease in coffee, a recently discovered disease in Costa Rica (Rodríguez *et al.* 2001). Sharpshooters are generally abundant on weedy vegetation (Redak *et al.* 2004), are known to feed and oviposit on weed species in the Atlantic slope of Costa Rica (Pérez 2007), and weeds are hosts of *X. fastidiosa* (Lopes *et al.* 2003). Hence, weed management may play an important role in the epidemiology of Crespera disease in coffee. In this study, the effect of common weed management practices in coffee agroforestry systems of Turrialba, Costa Rica on sharpshooter communities was experimentally examined.

Materials and Methods

1. Site description

The study was conducted on the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) commercial farm, located in Turrialba, Costa

Rica. The farm of 640 hectares includes coffee agroforestry systems (conventional and organic, with different shade trees), pastures, sugarcane fields, forest plantations and natural forest. It has an approximate mean elevation of 550m and an annual rainfall of 2960mm (mean of 2005 and 2006). The farm falls within the Volcánica Central-Talamanca Biological Corridor, a local initiative to promote the conservation of biological and ecosystem diversity in the region, while promoting sustainable social and economic development (Canet 2003).

Five areas planted with coffee (variety Caturra) and *Erythrina poepegiana* shade trees were selected. The five areas had conventional management before our experiments, consisting of intensive pruning of the shade trees, and synthetic fertilizer (complete formula) and herbicide (glyphosate and oxyfluorfen) applications. Common weed species were *Impatiens balsamina*, *Spermacoce latifolia*, the vine *Cissus biformifolia* and several Poaceae species (e.g. *Panicum* spp., *Cynodon* spp. and *Digitaria* spp.).

2. Experimental Design

Two experiments were conducted; the first from November 2005- to January 2006, and the second from September to November 2006. Experiments were arranged as Randomized Complete Block Designs (RCBD) with the five areas mentioned above serving as blocks or repetitions. Each block was composed of three weed management treatments: mechanical control with machete, chemical control with herbicides (see below for rates), and no weed control. For both experiments, treatments were applied randomly to one of three

15m x 15m plots in each block. Treatment plots were separated from each other by 5m x 15m no-treatment buffers on the West and East sides to reduce interplot interference. In addition, there were 65m x 10m no-treatment buffers on the North and South sides of each block.

3. Application of treatments

Treatments were applied once in November 2005 for the first experiment, and once in September 2006 for the second experiment. No weed control was conducted in the five experimental blocks for at least two months before treatment application. The three treatments were applied to one block on the same day. Plots receiving herbicide treatment were evenly sprayed with 486 g of glyphosate/ha (Monsanto Company, St. Louis, MO) and 80g of oxyfluorfen/ha (Rohm and Hass Company, Philadelphia, PA), a rate similar to that used by farmers in the region. Weeds on plots receiving machete treatment were cut using a machete. On the first experiment, the machete treatment was “chapeado”, which in the region indicates that weeds are not completely killed and some ground cover is left, and in the second experiment, it was “lumbrado”, which means that no ground cover is left.

4. Sharpshooter sampling

Leafhoppers in the subfamily Cicadellinae (sharpshooters) were sampled one week before the application of treatments and every week thereafter for eight weeks. Sampling was conducted using 14cm x 22cm double-sided yellow sticky traps and traps were left in the field for one week before being replaced. Since sharpshooters might move at various heights within a field, one trap was placed at each of two heights (10cm and 120cm) in each trap position. Trap positions were: a) center of treatment plot (4 traps), and b) edges of treatment plots (two traps per edge, for a total of 8 traps). Traps were placed at the different positions to better determine the effect of weed management treatments, as center traps were surrounded by a larger treated area than the edges, and the latter could be influenced by closer proximity to non-treated weedy areas. Traps were placed by clipping them to two wood sticks. Additionally, 4 clear sticky traps of the same size were hung in coffee bushes in the center of the treatment plot to assess the abundance of sharpshooters on coffee plants. All samples were taken to the Entomology Laboratory at CATIE, where sharpshooters were identified using a reference collection and counted. Aid with species identification was provided by Carolina Godoy at Instituto Nacional de Biodiversidad (INBio), in Costa Rica. Species richness was determined by counting the number of species per trap side, and abundance by counting the total number of sharpshooter individuals per trap side. Shannon and Simpson diversity indices were calculated using the biological diversity index function of InfoStat Professional version 2007 (InfoStat 2007).

5. Weed monitoring

Weed communities in all treatment plots were monitored one week before and every week after the application of treatments for eight weeks. A 1m x 1m frame was placed in the center of each plot. Within the $1m^2$ frame, number of weed species and individuals, height of weeds, and percentage of the ground covered by weeds were recorded. Weed species were identified by J. González at the Organization of Tropical Studies and J. Gómez at the University of Costa Rica.

6. Statistical analyses

Sharpshooter data were recorded by trap side. Since there was no difference between trap sides, averages per trap side were calculated for the response variables of interest (abundance and species richness). For center traps, averages were calculated over four trap sides and for side traps over eight trap sides. Normality and variance homogeneity assumptions for the response variables were verified using InfoStat Professional version 2007 (InfoStat 2007). Since assumptions were not met, rank transformations were performed. Using PROC MIXED, SAS version 8.2 (SAS Institute 2001), an ANOVA was conducted for a model that included the effect of block, treatment, trap height, trap position, and time (week). The autocorrelation between weekly observations was modeled by mean of different co-variance matrices: autoregressive the first order (AR1), composed symmetry and unstructured models. To select the best model, Akaike (AIC) and Bayesian (BIC) information criteria criteria were used. Composed symmetry models were selected for number of species and *F. lativitatta* abundance, and unstructured model for abundance. When the ANOVA was significant ($\alpha=0.05$), Fisher LSD test for mean comparison was conducted, using the macro PDMIXED800 (Saxton 1998). To test that applied treatments were effective, an ANOVA was carried out with plant height as the indicator of treatment effectiveness (response variable).

Results

Weed control treatments were effective at reducing weeds in both experiments (Table 4.1). After treatment application, weeds were greatly reduced in machete and herbicide treatments in both experiments (Figure 4.1). Weeds started to regrow earlier in the machete than in the herbicide treatment. This was more evident in experiment 2, where the type of machete control utilized was “lumbrado”. In this experiment, weeds started to regrow on the fourth week (two weeks after treatment application) in the machete-weeded plots, compared to the sixth week on the herbicide-treated plots. As weeds regrew, weed species composition was similar across treatments.

No sharpshooters were collected on clear sticky traps hung from coffee plants. On yellow traps, a total of 26 sharpshooter species was collected in both experiments. Twenty-six sharpshooter species were collected in experiment 1 and 22 species, in experiment 2 (Table 4.2). Machete treatments exhibited lower sharpshooter abundance in both experiments than other control treatments (Table 4.2), however this difference was not significant (Table 4.3). *Fusigonalia lativitatta* was the most abundant species across treatments, followed by Morphospecies TR, *Stephanolla rufoapicata* and *Ladoffa* sp. 1. Species richness of sharpshooters did not differ significantly among treatments (Table 4.3). However, diversity indices of sharpshooters were higher in machete than in other treatments (Table 4. 4).

Sharpshooter abundance and species richness were affected by trap height and sampling time (Table 4.3). Traps placed at 10cm above the ground had significantly lower abundances and species richness than traps at 120cm (Figure 4.2). Sharpshooter abundance declined weekly in both experiments (Figure 4.3). Abundance declined in all treatments equally, and no interaction between treatment and week was detected (Table 4.3). However, there were differences in sharpshooter abundance between experiments (Table 4.3). Abundances were higher in experiment 2 than in experiment 1 (Figure 4.3). Ending abundances for experiment 2 were similar to mean starting abundances in experiment 1. Experiment 1 was conducted from November 2005 to January 2006, while experiment 2 was conducted from September through November 2006. Experiment 2 was conducted at a time with lower precipitation than experiment 1 (Figure 4.4). Species richness was also significantly lower in experiment 1 (mean=1.10 species per trap side) than in experiment 2 (mean=1.58 species per trap side) and declined weekly (data not shown).

Discussion

Sharpshooters are frequently more abundant in grassy areas of agricultural fields (Redak *et al.* 2004) and preferentially use weeds than crops (Ott *et al.* 2006). The limited literature on the subject shows that leafhoppers are affected by weed management practices in various agroecosystems such as rice and alfalfa fields. Leafhoppers are more abundant in non-weeded than in weeded plots in rice (Afun *et al.* 1999), but are less abundant in weedy alfalfa plots (Oloumi-Sadeghi *et al.* 1987). In coffee agroforestry systems, weed removal by mechanical (machete) or chemical practices does not have an impact on sharpshooter communities. Results from this study suggest that these sharpshooters are not dependant on weed resources. Sharpshooters were less abundant at 10cm height than at 120cm, indicating a higher activity at this height. Even though clear sticky traps were not effective in collecting sharpshooters, previous studies have found sharpshooters in coffee bushes (Rojas *et al.* 2001).

Sharpshooters are polyphagous. For example, the glassy wing sharpshooter, *Homalodisca coagulata*, one of the most studied sharpshooters, can feed on hundreds of different, taxonomically unrelated host plants (Redak *et al.* 2004). Weeds are primary producers in the food web and can serve as an alternative food for sharpshooters (bottom-up effect). Potentially, sharpshooters use weeds in coffee agroforestry systems, but can use other resources after weed removal. Although in our experiments abundance of sharpshooters was not significantly different between treatments, machete treatments had lower abundances of *F. lativitatta* than herbicide or no weed control treatments. This could reflect the effect of immediate removal of weed species (machete) versus the effect of a slower weed death and maintenance of weed structure (herbicide).

Weeds may also contribute to sharpshooter control by providing food for their natural enemies (top-down effect). Egg parasitoids are important natural enemies of sharpshooters (Tryapitsyn *et al.* 1998). Egg parasitoids benefit by the presence of weeds, as weeds provide alternative prey when the crop and sharpshooter hosts are not available (Doutt and Nakata 1973). The indirect effect of weeds on sharpshooters through augmentation of their natural enemies, were potentially not observed due to the length of our study. Alternatively, sharpshooters in our study sites were not under regulation by natural enemies, although they are in ornamental plantations of Costa Rica (Prado 2006). Longer-term studies that also monitor the abundance and richness of sharpshooter natural enemies would help clarify our findings.

Weed communities change over time due to management and shade increase (Aguilar *et al.* 2003). Weed communities in organic shaded systems are dominated by Commelinaceae species, while conventional unshaded systems are dominated by Poaceae species (Nestel and Altieri 1992). Different weed communities may support different arthropod communities. In this study, weed community species composition did not differ among treatments after the effect of the treatment ended. This suggests that differences in weed and arthropod communities between areas subjected to diverse weed management practices may take longer to become manifest in coffee agroforestry systems, than the duration of this study.

Weeds may also contribute to insect pest control through altered habitat conditions (Norris and Kogan 2005). Altered habitat conditions (modified field microclimate that can affect arthropod fitness) provided by weeds may be important in annual crops, where weeds dominate the canopy part of the year. Coffee agroforestry systems are perennial agroecosystems (i.e. shade trees and coffee bushes are present throughout the year). Weeds present in coffee agroforestry systems, may only dominate the canopy of the system during plantation establishment, an event that is very uncommon in the current Turrialba landscape (most farms are 15 years or older in the region). Additionally, in most farms of the region, weeds are not present throughout the year, because of heavy weed management. In our experiments, coffee bushes dominated the canopy, even in the no weed control treatment.

Sharpshooters may be affected by weed management at larger spatial scales than those examined in this study. Several insect groups have shown a positive response to landscape complexity, increasing species richness with higher percentage of perennial grassy habitats in the region (Bianchi *et al.* 2006). Sharpshooters are known to disperse from field margins and near land uses (forest fragments, riparian forests, citrus groves) to crop fields (Irvin *et al.* 2001, Redak *et al*. 2004) and are more abundant near edges (Blua and Morgan 2003). Mark-recapture studies have shown that *H. coagulata* can disperse at least 90m from a release site (Blackmer *et al.* 2004).

Seasonality in the abundance of sharpshooters was observed in this study. Sharpshooter abundance was higher during September and lower in the following months. This could be due to differences in rainfall patterns. Although xylem feeders are expected to show less seasonality because their generalist feeding habits allow them to change host plants as plants dry up (Young 1979), seasonality in leafhoppers has been observed in other studies. In Panama, leafhopper species are more abundant in July (early rainy season), when most forest species are producing new leaves (Wolda 1979). In Nigeria, *Cidadulina* species were more abundant at the end of the rainy season (Asanzi *et al.* 1994). Higher abundances during August-September and declines in the subsequent months were observed in other studies conducted in the Turrialba area (Chapters 2 and 3).

Other components of coffee agroforestry systems, including their management or the landscapes they lay in, appear to affect the abundance of sharpshooters in such systems. Currently, limited information exists about sharpshooter natural history and ecology in the Neotropics to draw conclusions. Of the approximately 1,450 species of sharpshooter present in the Neotropics, only a few *X. fastidiosa* vectors have been studied. It is important to devote more attention to this group of insects, considering that most sharpshooter species have the potential to be vectors of *X. fastidiosa* (Redak *et al.* 2004), and that this is a generalist bacterium that can cause disease in many plant species (Purcell 1997), including Crespera in coffee. For small-scale coffee producers of Costa Rica, efforts to control Crespera disease should explore other components of farm management that could affect the epidemiology of the disease.

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Table 4.1. ANOVA results for weed height.

Factor	p-value
Experiment	0.4921
Block	<0.0001
Treatment	<0.0001
Week	<0.0001

Table 4.2. Number of individuals of Cicadellinae species collected from different weed treatments in coffee fields in Turrialba, Costa Rica, 2006-2007.

Species	Experiment 1			Experiment 2			Total
	C	M	H	C	M	H	
1. *Fusigonalia lativitatta**	867	519	806	2528	1872	2511	9103
2. Morphospecies TR	414	324	371	852	749	951	3661
3. *Stephanolla rufoapicata*	265	376	355	228	382	246	1852
4. *Ladoffa sp.1*	35	30	33	350	346	289	1083
5. *Sibovia occatoria*	188	107	111	169	84	104	763
6. *Macunolla ventralis*	144	120	123	78	66	109	640
7.*Macugonalia testudinaria*	42	61	67	76	179	147	572
8. *Microgoniella sociata*	57	37	66	165	93	129	547
9. *Beirneola anita*	35	49	45	44	96	42	311
10. *Draeculacephala sp.*	34	24	23	54	34	46	215
11. *Ladoffa sp. 3*	10	12	18	44	65	23	172
12. *Erythrogonia aerolata*	20	23	21	14	11	1	90
13. *Fusigonalia sp.1*	8	18	9	9	10	8	62
14. *Apogonalia fractinota*	1	0	2	15	15	22	55

15. *Agrosoma pulchella*	16	14	7	5	1	3	46
16. *Graphocephala permagna**	7	12	11	0	4	9	43
17. *Shildola opaca*	2	6	17	3	4	2	34
18. Morphospecies 42	2	8	9	3	2	4	28
19. *Phera sp.*	5	10	7	0	0	0	22
20. Morphospecies 105	1	1	0	3	7	4	16
21. *Ladoffa sp. 2*	3	1	2	0	2	2	10
22. *Baleja flavoguttata*	0	1	1	2	2	3	9
23. *Juliaca pulla*	1	0	0	0	3	0	4
24. *Hortensia similes**	0	1	1	0	0	0	2
25. *Chlorogonalia coerulvitatatta*	0	1	1	0	0	0	2
26. *Platygonia spatulata*	0	0	1	0	0	0	1
Total	2157	1755	2107	4642	4027	4655	19343

[a] "C" stands for control treatments, "M" for machete treatments and "H" for herbicide treatments. Potential vectors that tested positive for *X. fastidiosa* (Godoy *et al.* 2005) are marked with an asterisk. Experiment 1 was conducted from November 2005-January 2006, and Experiment 2 from September 2006-November 2006.

Table 4.3. ANOVA results (p-values) for: a) number of sharpshooter species collected and b) sharpshooter abundance.

Factor	Number of species	Abundance
Experiment	<0.0001	<0.0001
Block	0.0009	0.0362
Treatment	0.8039	0.5971
Position (Center or edge)	0.1033	0.1292
Treatment*Position	0.6006	0.1759
Height	<0.0001	<0.0001
Treatment*Height	0.4986	0.8262
Position*Height	0.8443	0.5494
Week	<0.0001	<0.0001
Experiment*Week	<0.0001	<0.0001

Table 4.4. Sharpshooter Shannon diversity index value range for the three weed control treatments in coffee fields in Turrialba, Costa Rica, 2006-2007.

Treatment	Experiment 1	Experiment 2
Control	1.78 – 1.90	1.50 – 1.61
Machete	2.00 – 2.14	1.67 – 1.77
Herbicide	1.86 – 1.97	1.53 – 1.63

Experiment 1 was conducted from November 2005-January 2006, and Experiment 2 from September 2006-November 2006.

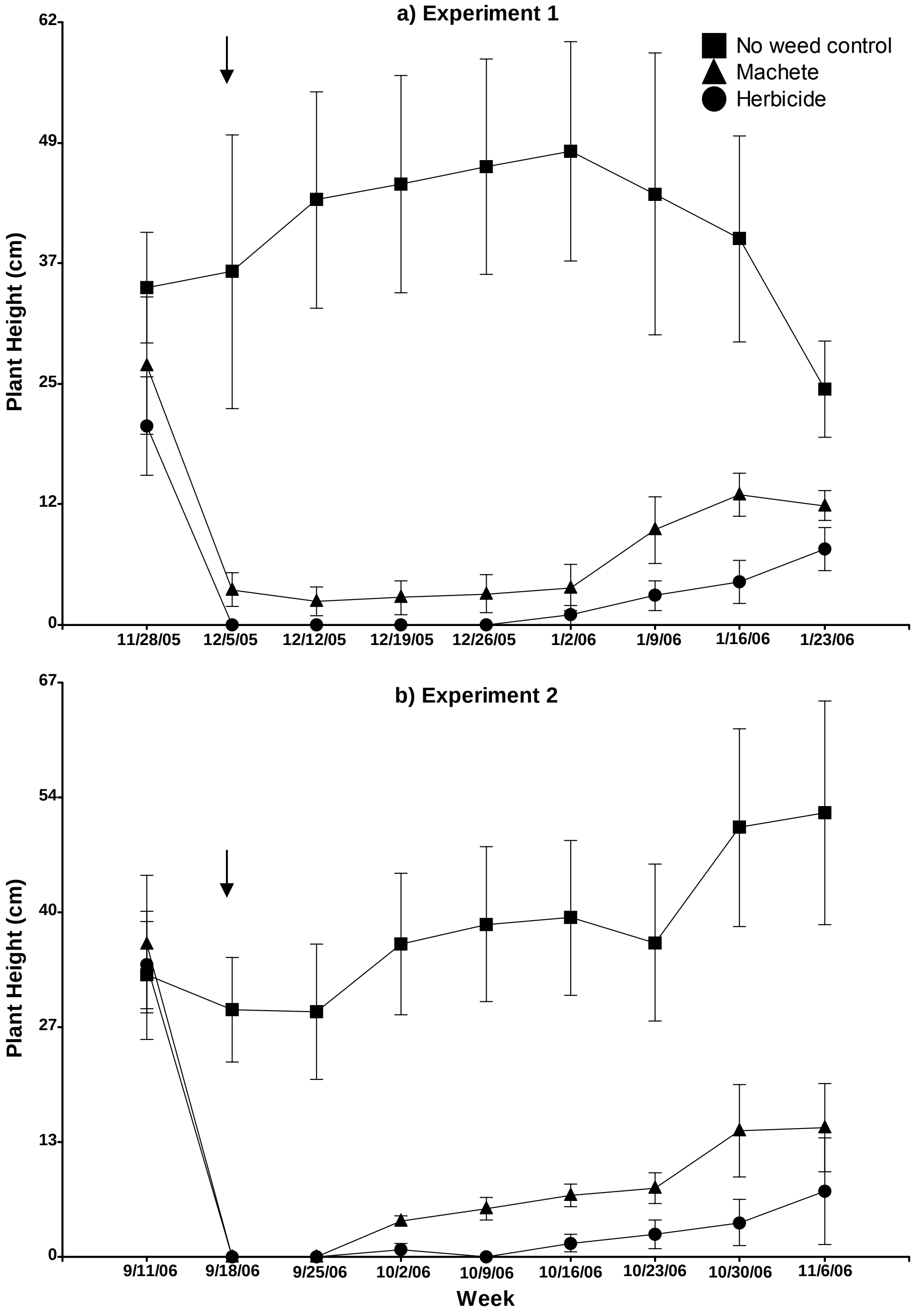


Figure 4.1. Change in weed height (cm) after treatment application (vertical arrow) and eight weeks thereafter in: (a) experiment 1 and (b) experiment 2 in coffee fields in Turrialba, Costa Rica, 2006-2007.

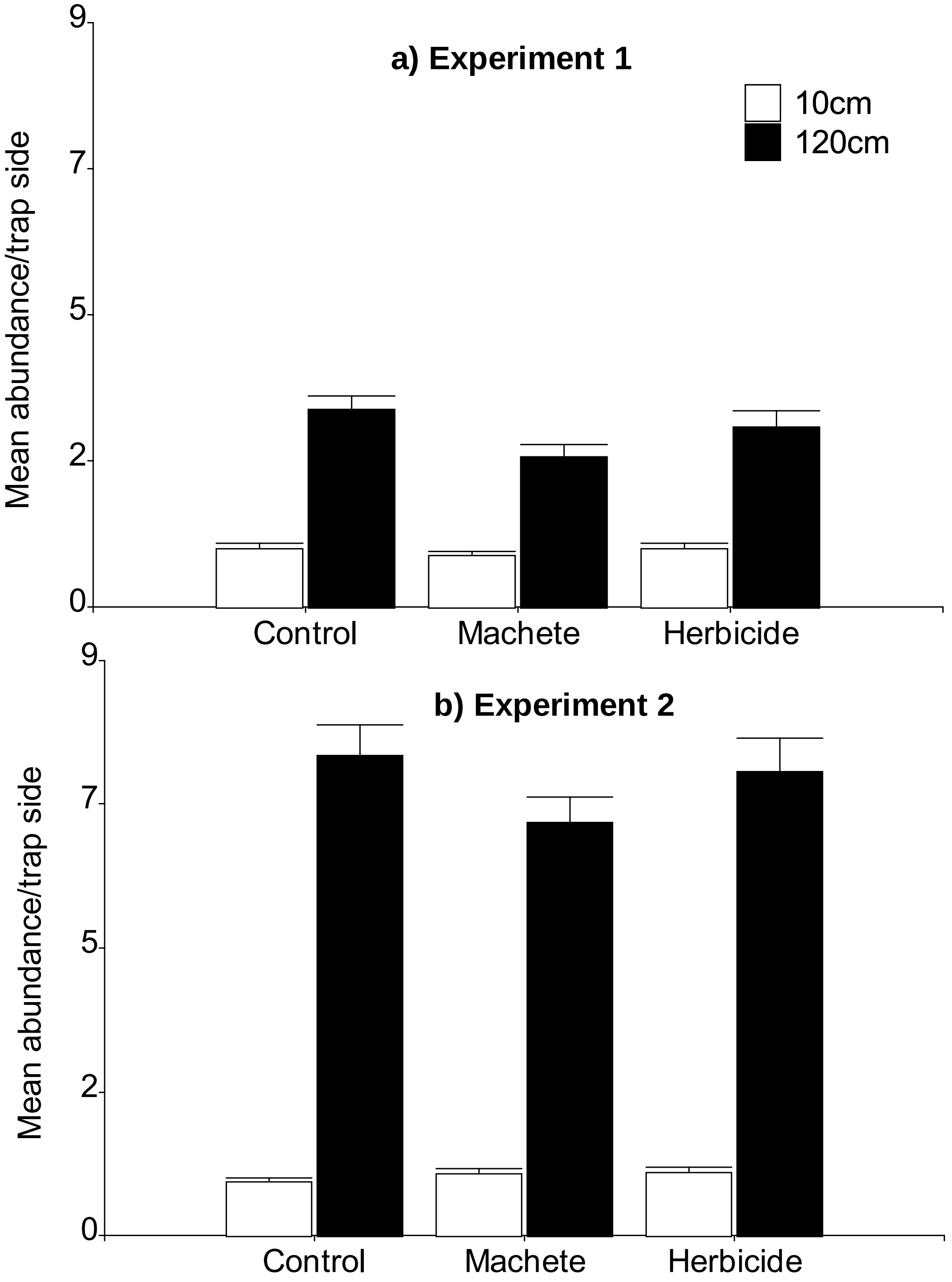
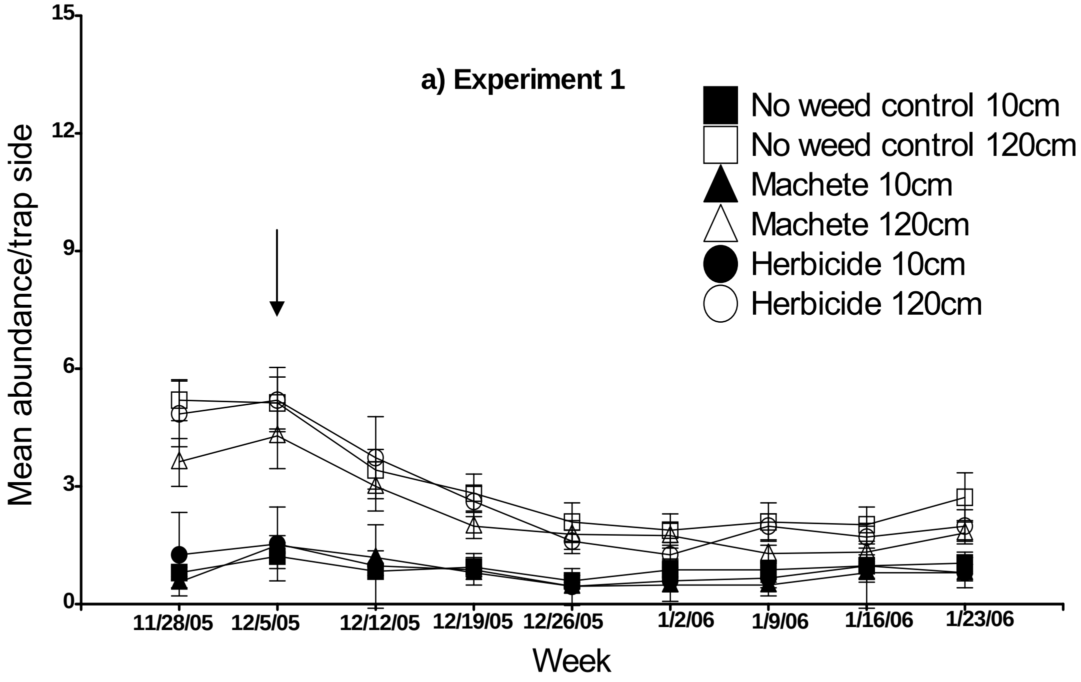

a) Experiment 1
10cm
120cm
Mean abundance/trap side
9
7
5
2
0
Control
Machete
Herbicide
b) Experiment 2
Mean abundance/trap side
9
7
5
2
0
Control
Machete
Herbicide

Figure 4.2. Mean sharpshooter abundance per trap side at two traps heights (10cm in white and 120cm in black) in the three weed control treatments in a) experiment 1 and b) experiment 2 in coffee fields in Turrialba, Costa Rica, 2006-2007.


a) Experiment 1
No weed control 10cm
No weed control 120cm
Machete 10cm
Machete 120cm
Herbicide 10cm
Herbicide 120cm
Mean abundance/trap side
15
12
9
6
3
0
11/28/05
12/5/05
12/12/05
12/19/05
12/26/05
1/2/06
1/9/06
1/16/06
1/23/06
Week

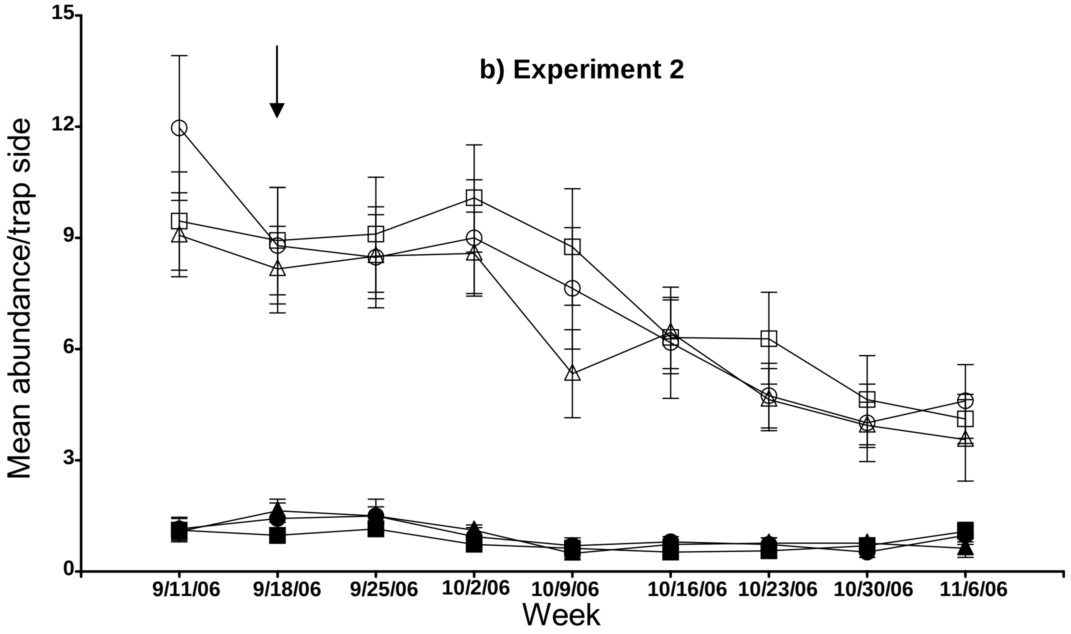

b) Experiment 2
Mean abundance/trap side
15
12
9
6
3
0
9/11/06
9/18/06
9/25/06
10/2/06
10/9/06
10/16/06
10/23/06
10/30/06
11/6/06
Week

Figure 4.3. Change in mean abundance per trap side after treatment application (vertical arrow) and eight weeks thereafter in: (a) experiment 1 and (b) experiment 2 in coffee fields in Turrialba, Costa Rica, 2006-2007.

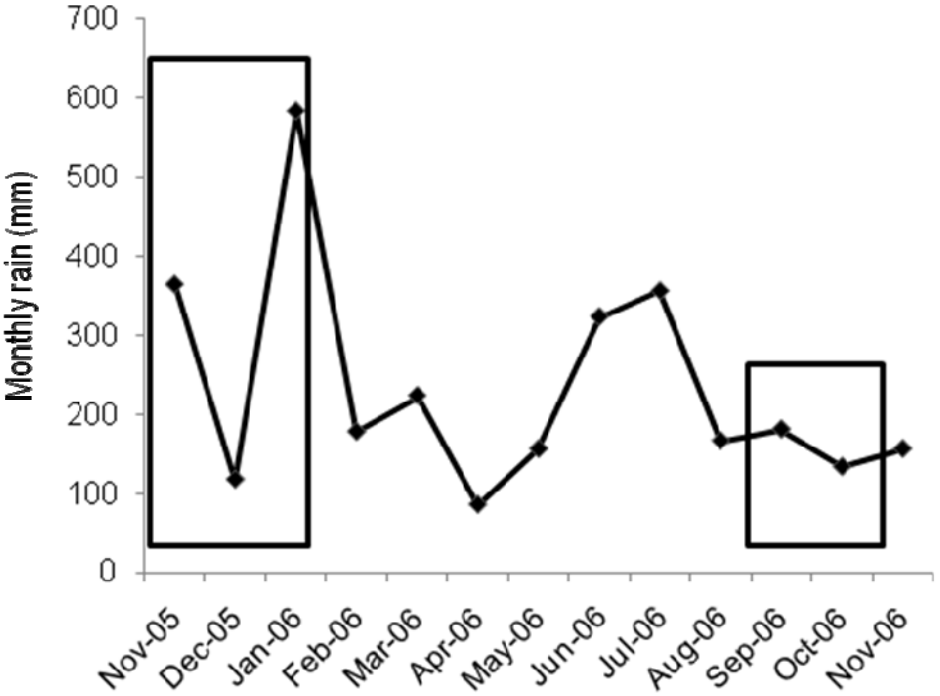


Figure 4.4. Total monthly precipitation during experiments conducted in in coffee fields in Turrialba, Costa Rica. Months when experiments were conducted are marked with a rectangle.

CHAPTER 5

Integrating decision maker preferences and ecosystem services of coffee agroforestry systems within the Volcánica Central-Talamanca Biological Corridor, Costa Rica

Abstract

In landscapes of Mesoamerica, long-term conservation of biodiversity is more likely to be achieved if it is combined with sustainable agricultural productivity, sustainable rural livelihoods, and the provision of ecosystem services. Agroforestry practices can improve the potential of agricultural areas to provide important ecosystem services. The Volcánica Central-Talamanca Biological Corridor (VCTBC) in Costa Rica is a local initiative designed to promote sustainable social and economic development, while connecting protected areas through management of the agricultural matrix, restoration and reforestation. The objectives of this study were to: a) characterize the distribution of coffee agroforestry systems (CAFS) within the VCTBC and a current structural connectivity network; b) select areas with the highest density of CAFS within this connectivity network; c) evaluate the overlap of three ecosystem services (watershed services, biodiversity and natural pest reduction) for these CAFS high density areas; d) understand how decision makers involved in the VCTBC implementation perceived and valued ecosystem services provided by CAFS; and e) provide GIS-based ecosystem service information for the prioritization of

areas within the VCTBC. We used an existing coffee farm database and performed a georeferenced census of all certified organic coffee farms within the VCTBC. Most of the coffee growing within the VCTBC is planted under the shade of trees (91.5%); the most common CAFS were those with only *Erythrina poeppigiana* (33% of all coffee), or with a combination of *Erythrina poeppigiana* and *Cordia alliodora* (30% of all coffee); and less than 1% of CAFS were certified organic. Using ArcGIS 9.1, we created a 1km buffer for an existing connectivity network and selected the 10 areas with the highest density of CAFS. We modeled the level of ecosystem services provided by CAFS within the VCTBC using information from existing data from previous studies that examined several ecosystem services, a digital elevation model, a land use cover map, a coffee database, a soils map, and a hydrological database. The amount of land in ecosystem service overlap was determined for each of the 10 areas selected. The perception of decision makers (VCTBC Committee members) about ecosystem services was evaluated by semi-structured interviews, ranking of different ecosystem services based on pair-wise comparisons by the decision makers, and a workshop that included a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. All the information generated in this study was also presented at the workshop to be used for the prioritization of three of the ten areas for resource allocation. Maximum overlap of ecosystem services provided by CAFS was reached when lower values of all ecosystem services were included. If values of 50 or more for all ecosystem services were not included,

almost no land of the corridor had overlap of the three ecosystem services. High values of ecosystem services were considered a strength of CAFS by decision makers. While certain CAFS areas were prioritized because of specific environmental services, the corridor committee included location within the corridor, and organizational infrastructure, and opportunities for tourism as other important themes for prioritization.

Keywords. Coffee, ecosystem services, biodiversity, watershed services, natural pest control, prioritization, preferences, GIS

Introduction

Biological corridors are important areas for conservation (Chetkiewicz *et al.* 2006). The purpose of corridors is to connect similar patches (structural connectivity), to increase the flow of organisms in a landscape (functional connectivity; Turner *et al.* 2001), or both. While linear, forested corridors might be easier to establish in a landscape (by government or non-governmental organizations), the efficacy of this type of corridor has been questioned (Rosenberg *et al.* 1997). Landscape heterogeneity can play an important role in the flow of organisms (Gustafson and Gardener 1996). Additionally, in the developing world, corridors are increasingly viewed not only as biophysically defined areas, but also as socioeconomic and political tools for sustainable development (Zimmerer *et al.* 2004). The Mesoamerican Biological Corridor

(MBC) initiative aims to achieve biodiversity conservation and sustainable economic development, recognizing that the sustainability of corridors will be strongly dependent on the wellbeing of its inhabitants. To integrate economic development with biodiversity conservation, the MBC initiative recognizes four land categories (Core Zones, Buffer Zones, Corridor Zones and Multiple-Use Zones); sustainable economic activities are explicitly promoted in the last two of these categories (Miller *et al.* 2001).

Agriculture is the most common economic activity within national corridors participating in the MBC initiative (Godoy Herrera 2003). Research has shown that specific agricultural practices, especially agroforestry practices, can increase ecosystem services (i.e. “conditions and processes through which natural ecosystems sustain and fulfill human life”, Daily 1997) provided by those productive systems, while supporting productive activities (Harvey *et al.* 2005). Agroforestry systems are formed when at least one woody perennial interacts biologically with another plant species, and at least one of them is managed for production (Somarriba 1992). Agroforestry systems have been recognized as key for biodiversity conservation (Scroth *et al.* 2004) and carbon sequestration (ICRAF 2006) in tropical landscapes. Currently agroforestry systems are included in payments for environmental services in Costa Rica (Wünscher *et al.* 2008) and under sustainable production certification schemes (e.g. Rainforest Alliance certification, Raynolds *et al.* 2007).

Much attention has been given to coffee agroforestry systems (CAFS) as a potential sustainable land use. Because of their shade tree component, CAFS can provide ecosystem services such as maintaining biodiversity, reduction of erosion, reduction of water contamination by agrichemicals, and reducing pest populations, depending on their structure and management (Perfecto *et al.* 1996; Somarriba *et al.* 2004; Pérez Nieto *et al.* 2005; Varón 2006; Varón *et al*. 2007). In addition, CAFS are near critical areas for conservation in many areas, including Southern Mexico (Moguel and Toledo 1999) and the Volcánica Central-Talamanca Biological Corridor in Costa Rica. Although CAFS have potential as a sustainable economic activity within corridors, it is unknown how decision makers involved in corridor design and implementation value these systems and the ecosystem services they provide.

Researchers and policy makers are now beginning to understand the importance of landowner and stakeholder perspectives, and local knowledge to inform conservation project design (Russell and Harshbarger 2003). Historically, conservation planning efforts have relied heavily on assessing systems from a biophysical perspective. Rarely have these efforts included the perceptions and values of local people, or if so, only afterwards rather than during the planning process (Brown *et al.* 2004). Scientists' understanding of the biological processes occurring in a particular area can be improved by drawing upon local knowledge (Brown *et al*. 2004). Also, the inclusion of decision makers can result in conservation plans that are scientifically sound but also publicly supported (Meo *et al*. 2002; Russell and Harshbarger 2003).

The objectives of this study were to: a) characterize the distribution of coffee agroforestry systems (CAFS) within the VCTBC and a current structural connectivity network; b) select areas with the highest density of CAFS within this connectivity network; c) evaluate the overlap of three ecosystem services (watershed services, biodiversity and natural pest reduction) for these areas with highest CAFS density; d) understand how decision makers involved in the VCTBC implementation perceived and valued ecosystem services provided by CAFS; and e) provide GIS-based ecosystem service information for the prioritization of areas within the VCTBC. The VCTBC was chosen for this case study because of the available existing information on ecosystem services provided by CAFS in the region, and the interest of decision makers in prioritizing areas for resource allocation.

Materials and Methods

1. Case study area

The VCTBC is located on the Atlantic slope of Costa Rica and covers approximately 72,000 hectares. The VCTBC is dominated by agricultural production (28% pasture, 14% coffee, 6% sugarcane and 3% other crops), with 40% of its area under a highly fragmented forest cover. The VCTBC is a local initiative, designed to promote sustainable social and economic development, while connecting protected areas through management of the agricultural matrix, restoration and reforestation (Canet 2003). It is part of the Mesoamerican Biological Corridor (MCB) Project, which seeks to connect protected areas throughout Mesoamerica (Miller *et al.* 2001).

The VCTBC Committee is responsible for the coordination of VCTBC activities and corridor implementation. It represents a shift from top-down conservation to a more representative process that incorporates non-conservation stakeholder perspectives. The committee includes members of international institutions (International Model Forest), Costa Rica's Ministry of the Environment (MINAE), CATIE faculty, Institute of Coffee (ICAFE), an organic farmers' association (APOT), and representatives of several local communities.

2. Characterization of the distribution of coffee agroforestry systems (CAFS) within the VCTBC

Using the Costa Rican Coffee Institute (ICAFE) GIS farm database, a land use map for the VCTBC and ArcGIS 9.1, the total area in coffee and in the different shade typologies was calculated. Also, GIS layers of the different coffee farm shade typologies were developed. To determine the area under organic coffee production, a census of all members of the Turrialba Association of Organic Producers (APOT) was conducted on February 2005. All certified organic coffee farms, were visited, georeferenced and rapidly characterized by: 1) crop and shade tree species present, 2) height of coffee (in categories), 3) number of strata, 4) farm homogeneity and 5) slope (in categories). This was done in coordination with the Association of Organic Producers of Turrialba (APOT).

3. Selection of areas with highest CAFS density within the VCTBC

An existing structural connectivity network (Murieta 2005) was used to select the areas of the VCTBC with highest density of CAFS and in critical locations for the connectivity of the corridor. This existing connectivity network was used by the VCTBC Committee as a base for their future activities. It was built by considering the different contributions of land uses to structural connectivity, based on information from the literature, field observations and expert knowledge (Murieta 2005). A buffer of 1 km of this connectivity network was created using ArcGIS 9.1. Then, a layer of the different densities (in hectares) of CAFS within this buffer was developed. The areas with the highest CAFS density were selected, for a total of ten areas selected.

4. GIS layer development of ecosystem services

a) Watershed services

The hydrology of the VCTBC was simulated using the Soil Moisture Routing (SMR) model (Brooks *et al.* 2006). The risk, or probability, of each 30-m raster cell in the VCTBC was determined using monthly simulations produced by the SMR model. A 5-yr daily SMR simulation was run to identify consistently saturated areas, which were the primary factor in determining the probability of saturation (p_{sat}). The combination of p_{sat}, runoff depth, and slope was combined using the raster calculator to determine the areas of highest erosion potential and pollutant loading zones. Finally, a GIS layer was developed within ArcGIS to indicate areas from zero probability to the highest probability of erosion and pollution potential consistent with saturation. The values were converted to a zero-to-100 scale, with higher levels of erosion/pollution having the lowest watershed ecosystem service levels.

b) Biodiversity

The biodiversity map was developed by combining in Arc GIS 9.1 two habitat suitability raster GIS layers that were available for coffee agroforestry systems within the VCTBC (Florian *et al.* unpublished). The first map was an avian diversity GIS layer that represented the species richness of birds based on CAFS vegetation structure and proximity to forest. The second map was a forest sharpshooter habitat suitability GIS layer that represented the abundance of forest sharpshooter species based on CAFS vegetation structure, CAFS organic management and proximity to forest. The layers were summed using the Raster Calculator, and the resulting layer was normalized to a zero-to-100 scale, with highest values representing highest levels of the ecosystem service of biodiversity conservation.

c) Natural pest control

The natural pest control map was developed by combining in Arc GIS 9.1 two insect pest habitat suitability raster GIS layers that were available for coffee agroforestry systems within the VCTBC (Ramos *et al.* unpublished). The first map was a leaf-cutting ant (*Atta cephalotes*) habitat suitability GIS layer that represented the abundance of *A. cephalotes* nests based on CAFS vegetation structure, CAFS organic management and proximity to forest. *A. cephalotes* is an important pest of coffee in the region (Varón *et al.* 2007). The second map was a *Xylella fastidiosa* potential vector GIS layer that estimated the abundance of potential *X. fastidiosa* sharpshooter vectors based on CAFS vegetation structure, CAFS organic management and proximity to pasture. *Xylella fastidiosa* is the bacterial causal agent of “crespera” coffee disease in Costa Rica (Rodríguez *et al.* 2001). First, each pest layer was transformed to represent the ecosystem service of CAFS in terms of realized natural pest control (i.e. the inverse of the pest abundance estimates). Then, the two layers were summed using the Raster Calculator, and the resulting layer was normalized to a zero-to-100 scale, with higher values representing the highest levels of the ecosystem service of natural pest control.

3. Overlap of ecosystem services GIS layers

Overlapping or “bundling” of ecosystem services is necessary in order to maximize benefits to society and to prevent the creation of pervasive incentives (Heredia Declaration 2007). The methodology proposed by Wendland *et al.* (in press) was used to overlap the three ecosystem service layers (water, biodiversity and pest control) for each of the 10 areas with highest density of CAFS. The *z*-normalization procedure (Wünscher *et al.* 2008) was not necessary, since all layers were already normalized to a zero-to-100 scale. Using the raster calculator, all CAFS areas with each of the three ecosystem services with values higher than 10 (out of 100) were identified. This was similarly done for all ecosystem service values greater than 20, 30, 40, 50, 60, 70 and 90. The objective was to understand how excluding lower values of ecosystem services restricted the amount of overlap between the three ecosystem services. Additionally, areas in overlap of pairs of ecosystem services (i.e. water-biodiversity, water-pest control and biodiversity-pest control) were calculated following the same methodology. All ecosystem services received equal weights in the overlapping.

4. Interviews and ranking of ecosystem services by TVCBC committee members

Semi-structured interviews were administered to the VCTBC administration committee (13 subjects, comprising a portion of the committee) in November 2006. These interviews aimed to gain knowledge from each decision maker concerning the prioritization of the institution he or she represented on the committee, regarding CAFS in the context of the VCTBC. The first part of the interview was designed to elicit information about institutional goals, interests within the corridor, existing projects within the corridor, and type of prioritization desired (restoration vs. conservation). The second part of the interview was designed to determine preferences by the committee member’s institution concerning the ecosystem services provided by different CAFS. To prioritize ecosystem services provided by CAFS, the committee members made pair-wise comparisons of ecosystem services. The pair-wise comparisons of the ecosystem services were analyzed using the Analytical Hierarchy Process (AHP) and Inconsistency Index (Mendoza *et al.* 1999) to assign final weights to each ecosystem service. The AHP is a multi-criteria analysis (MCA) characterized by its mathematical ability to analyze complex decision problems with multiple criteria (Saaty 1977, 1980).

5. Workshop (SWOT Analysis, prioritization of areas and open discussion)

On April 2007, a workshop was conducted with the 13 VCTBC committee members who participated in interviews and four others, for a total of 17. The workshop objectives were to a) evaluate how the VCTBC perceived ecosystem services, b) identify and prioritize three of the 10 areas with high density of CAFS within the corridor, and c) understand why they prioritized those areas. Maps provided to the participants in the workshop represented the forest fragments present and the level of overlapping ecosystem services provided by CAFS (Figure 5.1).

The Strengths, Weaknesses, Opportunities and Threats (Team Action Management 2007) for each of the 10 with high density of CAFS were assessed. Strengths and weaknesses assess the internal elements affecting the area. Strengths were defined as the primary attributes and unique resources of the area and weaknesses were considered things about that area that are lacking or could be improved. Opportunities and threats were considered external factors impacting the areas. Opportunities were considered elements that were especially interesting or advantageous to workshop participants while threats were potential challenges participants may face working in areas (Mindtools 2007). Workshop participants worked collaboratively on the SWOT for approximately one hour. After completing the SWOT exercise, participants reviewed the generated information for each of the 10 areas. Participants were then given three labels and asked to place only one label in each map of their top three priority CAFS areas for resource allocation. Votes were counted and results were presented to the participants. An open discussion proceeded to discuss why they chose particular areas and what they thought about the voting results.

Results

1. Coffee agroforestry systems (CAFS) within the VCTBC

Most of the coffee growing within the VCTBC is planted under the shade of trees (91.5%). The most common CAFS were those with only *Erythrina poeppigiana* (33% of all coffee), or with a combination of *Erythrina poeppigiana* and *Cordia alliodora* (30% of all coffee). Less than 1% of CAFS within the VCTBC were certified organic.

2. Overlap of ecosystem services

The ten areas with the highest density of CAFS (also used for the SWOT analysis) covered 68% of the total VCTBC coffee area and differed in the amount of land in coffee (Table 5.1). Areas 2, 3 and 4 had the greatest amount of land in coffee. Overlapping of the three ecosystem services revealed that if low values of ecosystem services are included, a high percentage of each of the 10 areas land (hectares) has overlapping of the three ecosystem services. However, if low values (less than 50) for the three ecosystem services are not included in the overlap of services, spatial overlap of the three services is largely reduced in all areas (Table 5.1). Areas 3, 4 and 10 had the highest amount of land with overlapping of the three services at services values of 50 or higher. At service values of 50 or higher, areas 3 and 4 also exhibited the highest amount of land in ecosystem service overlap for pairs of ecosystem services (Tables 5.2, 5.3 and 5.4). Areas 3 and 4 showed a greater proportion of land in overlapping watershed and natural pest control services than all of the other ecosystem service combinations.

3. Decision maker interest

Analytical hierarchy process analysis of decision-maker preference (weighting) for ecosystem services detected differences among all six services evaluated (Table 5.5). Connectivity received the highest rating (25%), while sharpshooter diversity received the lowest (12%). The pest management surrogates were second in terms of preference, while erosion and water pollution risk was third.

Analysis using SWOT showed that higher levels of ecosystem services were considered as strengths, although lower values of ecosystem services were not considered frequently as weaknesses (Table 5.6). Other topics related to the ecosystem services studied were mentioned by participants. Strengths identified included proximity to forest (which affects the services of biodiversity conservation and natural pest control) and coffee certifications (Rainforest Alliance and Organic; which may also affect the services of biodiversity conservation and natural pest control). Erosion and pollution (which affect watershed services) were mentioned as threats. In addition to these topics, employment, level of organization and tourism were considered important aspects for the prioritization of areas within the VCTBC (Table 5.6).

Participants prioritized areas 2, 3, 4 and 9 for resource allocation (Figure 5.2). The first three areas are also the largest ones. Areas 3 and 4 had the highest amount of land in which there was overlap of all three ecosystem services with values of 50 or higher. Area 9 had almost no overlap of the three services at levels of 30% or higher. In the open discussion after the prioritization process, it was shown that participants selected areas primarily based on either their location within the VCTBC (area 2), the proportion of small-scale CAFS present (areas 3 and 4), or the proportion of forest (area 9) (data not shown). Although ecosystem services provided by CAFS were mentioned in the SWOT, they were not mentioned as reason for selecting areas in the following open discussion.

Discussion

Although biological corridors have been designed since 1999 in Mesoamerica, especially in Costa Rica (34 initiatives), most of these corridors have had problems with their actual implementation on the ground and in the achievement of their original biodiversity conservation purposes (Canet 2007). Implementing corridors requires public interest and participation and monetary resources (Hilty *et al.* 2006). Since biodiversity conservation is an ecosystem service that benefits society, payments that promote conservation efforts, like biological corridors, should exist. However, it is currently difficult to monetize or to get local beneficiaries to pay for biodiversity directly (Chomitz *et al.* 1999). Bundling (overlapping) of biodiversity conservation with other ecosystem services may bring more interest (and monetary resources) to preserve ecosystems that provide these services.

Our study shows that overlapping of ecosystem services is possible for coffee agroforestry systems within the VCTBC. Coffee agroforestry systems dominate coffee production in the VCTBC, and most land in CAFS is located in key places for the structural connectivity of the corridor. However, overlapping is only possible if low and medium values of ecosystem services are included. For high values of ecosystem services, payment efforts should focus on specific services. Preference for a particular ecosystem service was only clear in the case of structural connectivity. Other services received similar weights. This could reflect the diversity of the committee, which includes representatives of local communities, international organizations, the national hydroelectric company, and others.

Decision makers can use a variety of knowledge and experience when prioritizing CAFS areas for resource allocation. The SWOT analysis indicated that ecosystem services in general were important to the decision makers. For three of the four areas identified as highest priority for directing resources to improve the VCTBC, values of ecosystem services from medium to high were explicitly mentioned as strengths. In addition, to ecosystem services, the important internal strengths of areas were current resources and the level of organizational infrastructure found in the area (e.g. what is already happening, what is the possibility of synergy of activities). Among the important weaknesses noted, the threat of land use change was often noted, implying that decision makers are seek stability and some insurance that their resources will have a lasting effect.

Payments for ecosystem services already exist in Costa Rica, and include agroforestry systems as a qualifying land uses for payments (Wünscher *et al.* 2008). Also, several sustainable production certification schemes exist for coffee (Raynolds *et al.* 2007), which pay indirectly for the ecosystem services CAFS provide. Some CAFS within the VCTBC are already under sustainable production certification schemes (organic and Rainforest Alliance), but most are not. Helping owners of CAFS in critical locations of the VCTBC acquire some of these certifications could aid in the maintenance of these ecosystem services within the corridor. Committee members also identified the potential of eco and agro-tourism development as opportunities. Although committee members saw high values of ecosystem services as strengths for many areas, more attention should be given to ecosystem service bundling as a tool for achieving corridor goals.

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Table 5.1. Land in overlapping (bundling) ecosystem services (ES) (water, biodiversity and pest control) at different levels of ecosystem services in each area selected for the SWOT analysis. For each area, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each area's land in ecosystem bundling.

VCTBC Area Name	Land (ha) in Overlap of Ecosystem Services								
Value of ES	>10	>20	>30	>40	>50	>60	>70	>80	>90
1. Guayabo (65.3 ha)	53.2	51.0	15.0	15.0	0.8	0.0	0.0	0.0	0.0
	81%	78%	23%	23%	1%	0%	0%	0%	0%
2. Aquiares (792.0 ha)	672.0	592.5	538.2	340.1	0.5	0.5	0.5	0.0	0.0
	85%	75%	68%	43%	0%	0%	0%	0%	0%
3. Tres Equis (459.1 ha)	396.2	381.2	288.5	280.6	19.3	1.8	1.5	0.7	0.0
	86%	83%	63%	61%	4%	0%	0%	0%	0%
4. Pavones (518.4 ha)	442.2	377.1	125.8	125.8	14.9	9.2	9.1	0.0	0.0
	85%	73%	24%	24%	3%	2%	2%	0%	0%
5. Florencia (276.5 ha)	219.9	219.8	16.8	16.5	0.1	0.0	0.0	0.0	0.0
	80%	79%	6%	6%	0%	0%	0%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	19.7	19.7	2.6	2.6	2.6	0.0	0.0
	81%	78%	15%	15%	2%	2%	2%	0%	0%
7. Tuis (328.7 ha)	263.7	210.5	106.9	106.3	1.6	0.2	0.2	0.0	0.0
	80%	64%	33%	32%	0%	0%	0%	0%	0%
8. Tucurrique (104.0 ha)	82.2	68.3	4.5	4.1	0.0	0.0	0.0	0.0	0.0
	79%	66%	4%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	0.5	0.5	0.0	0.0	0.0	0.0	0.0
	86%	57%	0%	0%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	10.8	10.8	4.6	2.9	2.0	0.0	0.0
	78%	71%	14%	14%	6%	4%	3%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 5.2. Land in overlapping (bundling) ecosystem services (ES) (water and biodiversity) at different levels of ecosystem services in each area selected for the SWOT analysis. For each area, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each area's land in ecosystem bundling.

VCTBC Area Name	Land (ha) in Overlap of Ecosystem Services								
Value of ES	>10	>20	>30	>40	>50	>60	>70	>80	>90
1. Guayabo (65.3 ha)	53.2	53.2	19.4	16.1	1.9	1.1	0.6	0.5	0.0
	81%	81%	30%	25%	3%	2%	1%	1%	0%
2. Aquiares (792.0 ha)	672.0	594.5	540.3	340.1	0.5	0.5	0.5	0.5	0.0
	85%	75%	68%	43%	0%	0%	0%	0%	0%
3. Tres Equis (459.1 ha)	396.18	385.4	294.84	284.4	22.68	5.22	3.6	3.06	0
	86%	84%	64%	62%	5%	1%	1%	1%	0%
4. Pavones (518.4 ha)	442.2	397.9	138.1	132.5	21.2	15.1	10.6	6.3	0.0
	85%	77%	27%	26%	4%	3%	2%	1%	0%
5. Florencia (276.5 ha)	219.87	219.9	24.66	22.5	6.1	6.12	3.69	0	0
	80%	80%	9%	8%	2%	2%	1%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	21.6	21.6	4.5	4.5	4.5	2.6	0.0
	81%	78%	17%	17%	4%	4%	4%	2%	0%
7. Tuis (328.7 ha)	263.7	239.9	130.9	111.4	6.9	5.5	3.1	0.2	0.0
	80%	73%	40%	34%	2%	2%	1%	0%	0%
8. Tucurrique (104.0 ha)	82.2	72.5	7.0	4.1	0.1	0.1	0.1	0.0	0.0
	79%	70%	7%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	11.5	7.4	0.0	0.0	0.0	0.0	0.0
	86%	57%	10%	6%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	60.7	11.5	10.8	4.6	2.9	2.0	2.0	0.0
	78%	78%	15%	14%	6%	4%	3%	3%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 5.3. Land in overlapping (bundling) ecosystem services (ES) (water and pest control) at different levels of ecosystem services in each area selected for the SWOT analysis. For each area, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each area's land in ecosystem bundling.

VCTBC Area Name	Land (ha) in Overlap of Ecosystem Services								
Value of ES	>10	>20	>30	>40	>50	>60	>70	>80	>90
1. Guayabo (65.3 ha)	53.2	51.0	15.3	15.2	15.2	11.1	6.0	0.2	0.0
	81%	78%	23%	23%	23%	17%	9%	0%	0%
2. Aquiares (792.0 ha)	672.0	592.5	544.1	345.9	149.9	149.7	137.8	29.8	29.8
	85%	75%	69%	44%	19%	19%	17%	4%	4%
3. Tres Equis (459.1 ha)	396.2	381.2	290.0	282.1	263.0	236.3	193.0	18.3	18.3
	86%	83%	63%	61%	57%	51%	42%	4%	4%
4. Pavones (518.4 ha)	442.2	377.1	139.1	138.9	126.7	116.8	102.6	9.4	4.2
	85%	73%	27%	27%	24%	23%	20%	2%	1%
5. Florencia (276.5 ha)	219.9	219.8	31.1	30.7	24.9	10.6	10.6	0.0	0.0
	80%	79%	11%	11%	9%	4%	4%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	81.5	54.0	19.7	19.7	18.0	0.0	0.0
	81%	78%	64%	42%	15%	15%	14%	0%	0%
7. Tuis (328.7 ha)	263.7	210.5	119.0	118.4	106.6	105.7	74.8	2.3	2.3
	80%	64%	36%	36%	32%	32%	23%	1%	1%
8. Tucurrique (104.0 ha)	82.2	68.3	10.1	6.7	4.1	3.9	3.8	0.0	0.0
	79%	66%	10%	6%	4%	4%	4%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	4.5	4.5	0.0	0.0	0.0	0.0	0.0
	86%	57%	4%	4%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	14.2	14.2	10.8	10.8	7.9	0.0	0.0
	78%	71%	18%	18%	14%	14%	10%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 5.4. Land in overlapping (bundling) ecosystem services (ES) (biodiversity and pest control) at different levels of ecosystem services in each area selected for the SWOT analysis. For each area, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each area's land in ecosystem bundling.

VCTBC Area Name	Land (ha) in Overlap of Ecosystem Services								
Value of ES	>10	>20	>30	>40	>50	>60	>70	>80	>90
1. Guayabo (65.3 ha)	53.2	51.0	15.0	15.0	0.8	0.0	0.0	0.0	0.0
	81%	78%	23%	23%	1%	0%	0%	0%	0%
2. Aquiares (792.0 ha)	672.0	670.1	612.1	612.1	15.8	15.8	15.8	0.3	0.0
	85%	85%	77%	77%	2%	2%	2%	0%	0%
3. Tres Equis (459.1 ha)	396.2	392.0	298.6	298.6	29.3	10.3	10.3	0.7	0.0
	86%	85%	65%	65%	6%	2%	2%	0%	0%
4. Pavones (518.4 ha)	442.2	420.0	126.4	126.4	16.0	9.8	9.8	0.0	0.0
	85%	81%	24%	24%	3%	2%	2%	0%	0%
5. Florencia (276.5 ha)	219.9	219.8	16.9	16.9	0.1	0.0	0.0	0.0	0.0
	80%	79%	6%	6%	0%	0%	0%	0%	0%
6. Cruzada (127.9 ha)	104.0	104.0	19.7	19.7	2.6	2.6	2.6	0.0	0.0
	81%	81%	15%	15%	2%	2%	2%	0%	0%
7. Tuis (328.7 ha)	263.7	233.8	106.9	106.9	1.6	0.2	0.2	0.0	0.0
	80%	71%	33%	33%	0%	0%	0%	0%	0%
8. Tucurrique (104.0 ha)	82.2	77.7	4.5	4.5	0.0	0.0	0.0	0.0	0.0
	79%	75%	4%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	103.7	0.5	0.5	0.0	0.0	0.0	0.0	0.0
	86%	86%	0%	0%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	10.8	10.8	4.6	2.9	2.9	0.0	0.0
	78%	71%	14%	14%	6%	4%	4%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 5.5. Decision-maker weighting of ecosystem service surrogates.

General ecosystem service	Specific ecosystem service evaluated	Weighting (of a maximum weight of 100 and a neutral of 16)
Watershed services	Erosion and water pollution	16
Biodiversity	Connectivity	25
	Sharpshooter diversity	12
	Avian diversity	13
Natural pest control	Leaf-cutting ants	17
	X. fastidiosa potential vectors	17

Table 5.6. Topics mentioned for VCTBC areas in the SWOT analysis.

Topic	SWOT	Areas mentioned
Values of overlapping ecosystem services provided by CAFS	Strength (high*)	2, 3, 4, 7
	Weakness (low)	8
Related to ecosystem services studied		
Pollution	Weakness	2, 3, 5, 9
	Threat	4, 8, 9, 10
Proximity/presence of forest	Strength	2, 3, 4, 7, 5, 9
	Weakness (low)	6, 8,10
Land use change	Threat	2, 4, 6, 7, 8
Intensive/ monoculture agriculture	Weakness	2, 5, 8
	Threat	3, 4, 7
Erosion	Weakness	9
	Threat	1, 3, 4
ES payments/ coffee certifications	Strength (existing)	5, 2, 4
	Opportunity (potential for)	6, 7, 3
Social aspects		
Community organizations/ participation	Strength	1, 2, 3, 4, 8, 10
	Opportunity	4, 5
	Weakness (lack of)	6, 7
Institutional presence/support	Strength	5, 8, 9
Employment	Opportunity	2, 3, 4
	Weakness (low)	1, 5, 6, 7
Tourism	Strength	1, 6, 8, 9
	Opportunity	1, 3, 4, 5, 8, 9

*Information in parenthesis describes how committee members actually referred to the topic.
VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica
SWOT = Strengths, weaknesses, opportunities and threats
ES = Ecosystem service

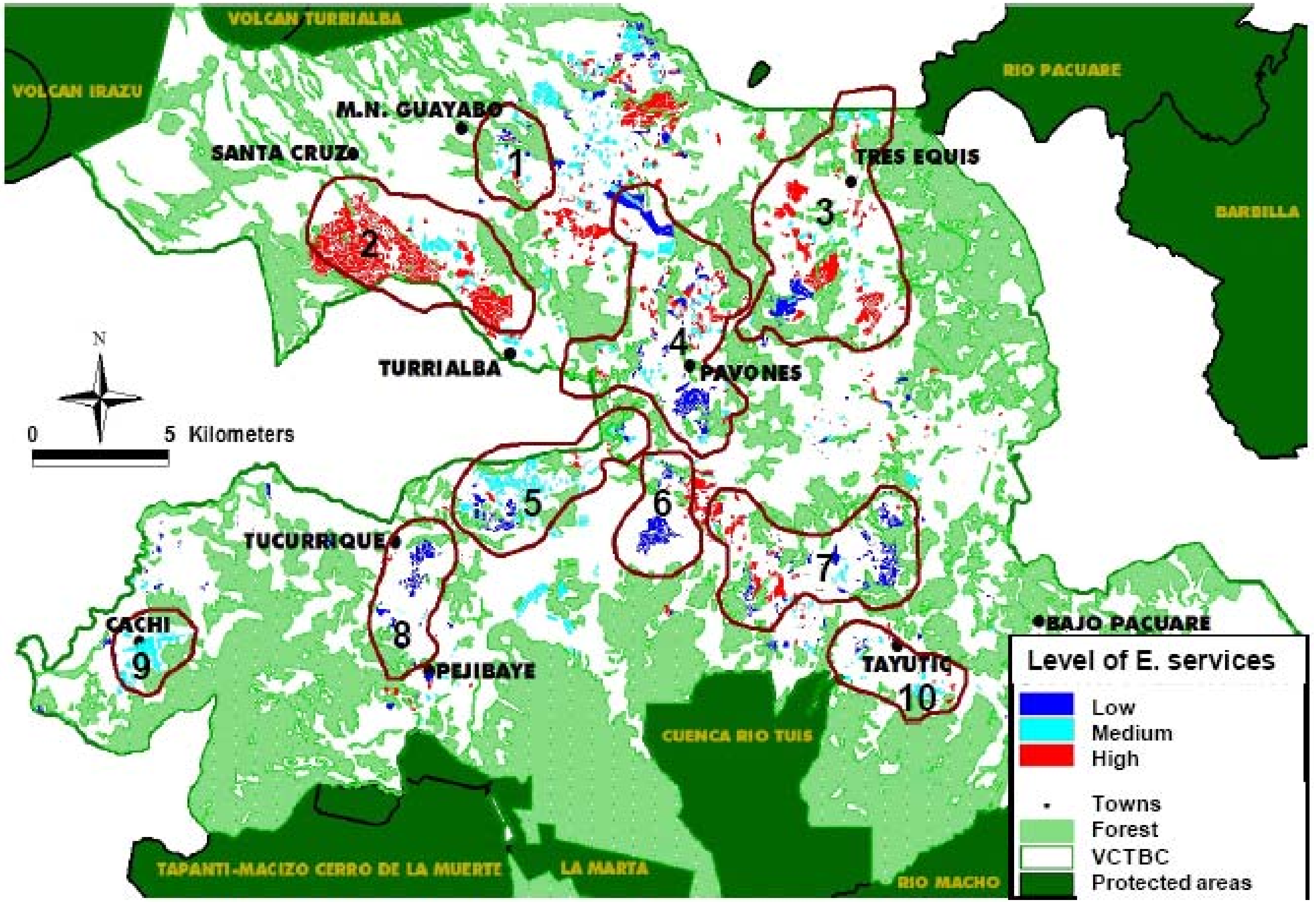

Figure 5.1. VCTBC coffee agroforestry areas evaluated in decision-maker workshop. E. Services are ecosystem services.

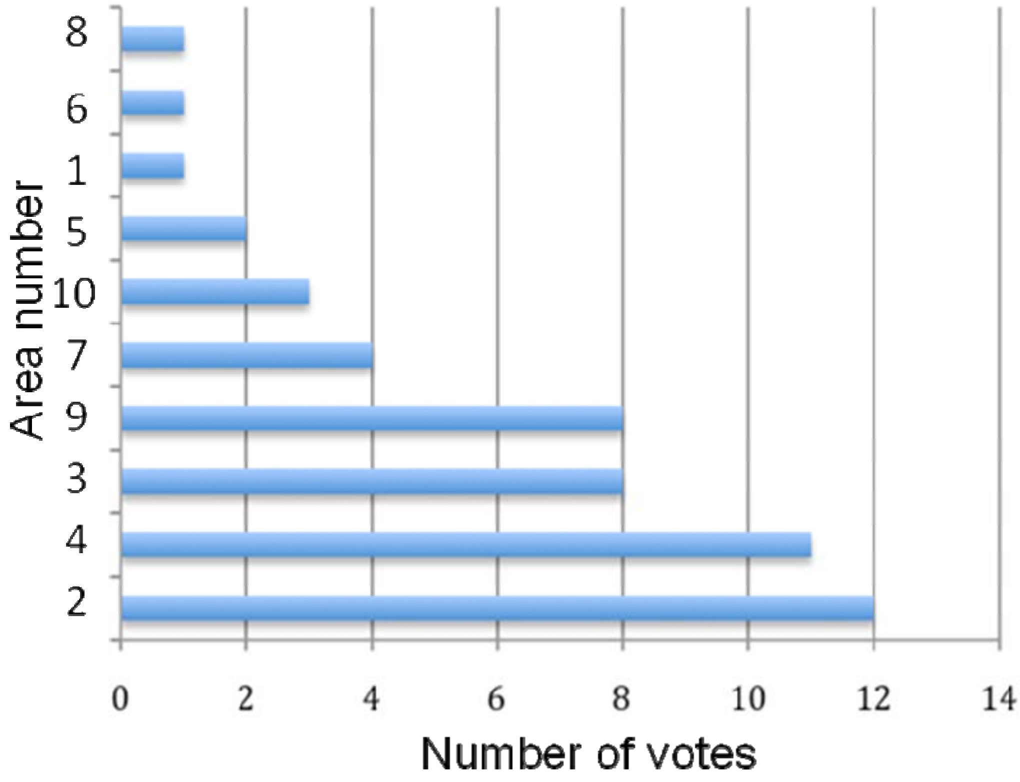

Figure 5.2. VCTBC committee votes for the prioritization of areas with high density of CAFS within the corridor.

CHAPTER 6

Concluding chapter

Introduction

Approximately 73 species of sharpshooters (Hemiptera: Cicadellidae: Cicadellinae) are found in coffee agroforestry systems within the Volcánica Central-Talamanca Biological Corridor (VCTBC), Costa Rica. Three of these species, *Fusigonalia lativitatta, Graphocephala permagna* and *Hortensia similes*, have tested positive for *Xylella fastidiosa*, the bacterium that causes crespera disease in coffee (Godoy *et al.* 2005). However, of the species present in the region, only these three species have been tested, and it is likely that more sharpshooter species could be vectoring *X. fastidiosa* in coffee agroforestry sytems within the VCTBC. *Xylella fastidiosa* is a generalist xylem-limited bacterium that causes disease in many crops, and its vectors, sharpshooters are also generalists that feed on xylem fluids (Redak *et al*. 2004). Most sharpshooters tested for *X. fastidiosa* exhibit positive results (Almeida *et al.* 2005), leaving sharpshooter vector ecology as key for the spread of *X. fastidiosa* (Purcell 1985).

Due to the recent discovery of *X. fastidiosa* as the cause of crespera disease in Costa Rica (Rodríguez *et al*. 2001), many questions remain unanswered about the epidemiology of crespera. Current research being conducted at the Centro de Investigación en Biología Celular y Molecular

(CIBCM), Costa Rica, is trying to discern which *X. fastidiosa* strains are pathogenic to coffee (A. L. Moreira personal communication). Researchers there already determined that *X. fastidiosa* isolates present in coffee are native to Costa Rica, and that they probably colonized coffee when it was introduced into the country (Montero-Astúa *et al.* 2007). Additionally, researchers at CIBCM have tested several sharpshooter species that are present in coffee farms in the Central Valley region of Costa Rica (Godoy *et al.* 2005). Current research at CATIE, is examining how the amount of *X. fastidiosa* present in coffee plants is related to crespera disease presence (J. Avelino personal communication).

Due to the importance of vector ecology in *X. fastidiosa* transmission, this dissertation sought to discern how ecological factors that are considered important in agroforestry systems and fragmented landscapes affected sharpshooter communities. The dissertation focused on communities due to the high diversity of cicadellind sharpshooters in the area, the potential of all species to transmit X*. fastiodiosa*, and as first step in determining which species might be important for crespera epidemiology. The most common agroforestry systems types within the VCTBC were selected for all studies conducted. This was part of an interdisciplinary team effort of several M.Sc. and Ph.D. students conducting research in agroforestry systems of the region as part of the IGERT Turrialba Team. The most common agroforestry systems encountered were those with only *Erythrina poeppigiana* and those with *E. poeppigiana* and *Cordia alliodora* as shade trees. Conventional management (more than 3,000 farms) was vastly more dominant than organic management (80 farms) in the corridor. However, organic systems and management practices were studied due to the growing consumption of organic products globally, especially organic coffee.

Principal findings

1. Effect of weed management on ciadellinid sharpshooter communities

   Weed communities are different in coffee agroforestry sytems with different shade structure and management (Nestel and Altieri 1992, Aguilar *et al.* 2003). Our findings indicate that weed management practices do not affect sharpshooter communities on the short term. This could be due to the fact that weeds are not the dominant structural component of coffee agroforestry systems, varying in presence throughout the year due to weed management. Sharpshooter species, being polyphagous, may change to other coffee agroforestry system plant components when weeds are not available.

2. Effect of local and landscape context on sharpshooter communities in coffee agroforestry sytems

   Recent studies have shown that local patterns of insect abundance and species richness could be due to local or to landscape factors (reviewed in Bianchi *et al.* 2006). We found that sharpshooters are affected by both. Sharpshooter abundance was negatively affected by local shade, but its relation to landscape factors was weaker. However, species richness was equally affected by local (negatively by farm coffee resources) and landscape factors (positively by surrounding area in fallow). Even though local factors were important, no differences in abundance or species richness of sharpshooters were observed among coffee agroforestry types. This was probably due to the different abundances of each sharpshooter species in the different coffee agroforestry systems. This individual species differences were also observed in the effect of landscape factors.

3. Effect of forests and pastures on sharpshooter communities and on patterns of *X. fastidiosa* presence in coffee agroforestry systems

Sharpshooters are known to colonize agricultural areas from forest fragments (Irwin *et al.* 2000), and in California, this is related to patterns of *X. fastidiosa* infection and Pierce's disease (higher incidence of Pierce's disease near forests, Purcell 1974). Our findings indicate that in the VCTBC, Costa Rica, sharpshooters also appear to move from forest fragments to coffee agroforestry systems. However, *X. fastidiosa* presence in coffee plants was not higher near forests; it was present in all sampled coffee plants. Sharpshooters had a positive response to edges, especially at pasture/coffee edge, indicating complementary use of resources in both pastures and coffee agroforestry systems. Coffee sharpshooter communities were more similar to pasture than to forest sharpshooter communities.

4. Coffee agroforestry systems as habitat for sharpshooters

Although all sharpshooter species have similar feeding habits, they have different habitat requirements. For example, we found that *Beirneola anita*, a species that is more abundant in forests, is affected positively by shade and is more abundant in organic diverse coffee agroforestry systems than in conventional ones with only *E. poeppigiana* shade trees. This was also observed for *Ladoffa* sp. 3 and *Fusigonalia* sp. 1, which were more abundant in edges. *Stephanolla rufoapicata*, which was more abundant in forests, was also positively affected by shade and was more abundant in diverse coffee agroforestry systems, both organic and conventional. *Graphocephala permagna* and *Graphocephala* sp. 1 were negatively affected by shade and more abundant in conventional coffee agroforestry systems with only *E. poeppigiana* shade trees. These species were more abundant in coffee than in forest or pasture. *Fusigonalia lativitatta* was the most abundant species in this study. It was negatively affected by shade and was more abundant in coffee agroforestry systems with only *E. poeppigiana* shade trees, both organic and conventional. It was more abundant in coffee and in edges with pasture.

5. Seasonality of sharpshooters in coffee agroforestry systems

Sharpshooters in coffee agroforestry sytems within the VCTBC were more abundant from June to September and declined afterwards. However, they showed increased movement in April, one of the driest months in the region. Although no direct relationship was found between rain and abundance, this has been a factor reported to influence sharpshooters in other regions (Wolda 1979, Asanzi *et al.* 1994).

6. Perception of decision makers of ecosystem services, including those that involve sharpshooters

The natural control of sharpshooters was perceived as a more important ecosystem service than the conservation of forest sharpshooter species. In fact, natural pest control in general was more important for decision makers than all other services except connectivity.

Final remarks and future research

Although research is needed on the epidemiology of *X. fastidiosa* on coffee, this study contributed significantly to the knowledge of sharpshooter ecology in coffee agroforestry systems. Previously, it was known that Auchenorrhycha communities differed among some CAFS (Rojas *et al.* 2001 a and b), but specific local and landscape variables that affected sharpshooter species were not known. This study revealed the negative effect of shade for sharpshooter communities in general, and the insignificance of weed management in them. Also, it brought attention to the importance of considering landscape elements (forest as sources and higher abundance near edges) when discussing sharpshooter communities. This information can not only be valuable for future management of “crespera” disease, but showed to be important already for decision-makers involved in corridor design and who consider ecosystem services provided by CAFS in their prioritization activities.

Future research should examine more aspects of sharpshooter ecology and their interactions with *X. fastidiosa*. Which are the host plants of the most common sharpshooters should be investigated. Similar studies have been conducted for leafhoppers in ornamental plantations, and have revealed the importance of spontaneous vegetation for leafhoppers (Pérez 2007). The effect of shade tree management practices should be further explored, as the decline in sharpshooters appears to be in the same months as pruning occurs. Mark-recapture studies should be conducted to explore further the movement of sharpshooters between land uses.

Leafhoppers are the 10th largest insect family (Tipping and Mizell 2004), contributing significantly to the world's biodiversity. Their greatest diversity is thought to be in tropical rain forests (Dietrich 2004), one of the world's most threatened ecosystems. In addition, leafhoppers are important plant disease vectors, including viruses (Nault 1997), phytoplasmas (Hill and Sinclair 2000) and bacteria, and their saliva and plant injury can cause hopper burn (Backus *et al.* 2005). Finally, leafhoppers are a fascinating insect group with exceptional behaviors, like long distance migration, acoustic communication (through plant surfaces), and brochosome powdering of their eggs. More attention should be given to them.

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