BIOLOGY AND MANAGEMENT OF THE BANANA WEEVIL (*COSMOPOLITES SORDIDUS* GERMAR) IN THE SOCIOECONOMIC AND AGROECOLOGICAL CONTEXT OF THE INDIGENOUS TERRITORIES OF TALAMANCA, COSTA RICA

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by

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AUTHORIZATION TO SUBMIT DISSERTATION

This dissertation of Ruth Dahlquist submitted for the degree of Doctor of Philosophy with a major in Entomology and titled "Biology and management of the banana weevil (*Cosmopolites sordidus* Germar) in the socioeconomic and agroecological context of the indigenous territories of Talamanca, 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

The banana weevil is a pest on bananas and plantains throughout the tropics. No published studies exist on the banana weevil in smallholder banana and plantain systems within the Bribri-Cabécar Indigenous Territories in Talamanca, Costa Rica. These include monoculture plantain and organic banana in agroforestry systems. Concerns exist over pesticide use in plantain and conversion of agroforestry systems to monoculture plantain. Alternatives to pesticides in plantain and improved pest management in organic banana to increase profitability of agroforestry systems are needed. Such efforts must be undertaken with an understanding of the socioeconomic and agroecological context of the indigenous territories. We conducted a livelihoods analysis of cacao agroforestry systems comparing cacao to plantain and organic banana. Existing production data was integrated with data from household interviews to identify factors in the decline of cacao agroforestry systems. We also conducted a rapid rural appraisal with plantain and organic banana producers. Semi-structured interviews with 75 farmers examined current pest management practices and perceptions of pest status and biology. In plantain, 63% of farmers used combination nematicide-insecticides for banana weevil control. Most organic banana farmers (61%) did not use banana weevil management practices. We assessed banana weevil damage levels and yield in 21 organic banana agroforestry farms. Yield was correlated with damage in the banana corm cortex, and 94.7% of damage was in the cortex. To determine efficacy of pheromone traps for banana weevil management in smallholder plantain farms, we evaluated weevil damage and yield before and after 58 weeks of trapping. Traps were placed in six farms at recommended rates, and six farms without traps were controls. Weevil damage decreased by 33% in farms with traps, and did not decrease in control farms. There was no reduction in trap catches, indicating that damage reduction can occur without reduction of weevil populations. We evaluated movement patterns of banana weevils in response to host plant volatiles at 1 and 2 m distances in the field. Weevils were tagged, released, and relocated using harmonic radar. Weevils oriented to host plant volatiles at 1 m but not 2 m, and displayed positive orthokinesis at both distances.

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Introduction

The banana weevil (*Cosmopolites sordidus* Germar) is an important pest on bananas and plantains (*Musa* spp.) in Talamanca (E. Somarriba pers. comm.) and throughout the tropics (Gold et al. 2001). While the banana weevil is not considered a major problem in commercial banana plantations, it has eluded control in smallholder production systems. Damage is caused by the larvae, which tunnel into the banana corm. Banana weevil damage can reduce yield and plantation life, and heavy infestation can lead to crop failure in newly planted fields (Gold et al. 2001). Farmers use various control measures, but not all have been evaluated widely for their efficacy or potential integration with other practices (Karamura and Gold 2000). These measures include cultural controls such as clean planting material, intercropping, destruction of residue after harvest, and pseudostem traps. Other possibilities for control include biological control with myrmicine ants (Castineiras and Ponce 1991) or entomopathogens (Pena et al. 1995), botanical or synthetic pesticides (Gold et al. 2001), and mass trapping with pheromone lures (Tinzaara et al. 2002).

The pest status of the banana weevil can vary depending on local agroecological conditions and *Musa* cultivars (Gold et al. 2001). Consequently, it is necessary to evaluate banana weevil damage levels and effects on yield in smallholder systems to determine pest status and appropriate management practices. No previous published studies exist on the banana weevil in the cropping systems of the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica, where bananas and plantains are important cash crops for many small- and medium-scale farmers. Plantain grown in monoculture is the dominant economic activity in both the Bribri-Cabécar Indigenous Reserve (Villalobos and Borge 1998) and the adjacent Sixaola Valley (Segleau and Mora 1989, Somarriba 1993). Organic banana is also an essential source of income for indigenous farmers, and is grown in mixed agroforestry systems that range from cacao and banana cultivated with one or two shade tree species to traditional systems with a diverse canopy of forest species (Somarriba and Harvey 2003). Agroforestry systems, which incorporate perennial crops such as coffee or cacao with shade trees, have been noted for their ability to provide both habitat for forest species and economic benefits to producers

(Perfecto et al. 1996, Somarriba and Harvey 2003). Cacao agroforestry systems are of particular interest for conservation (Rice and Greenberg 2000). Diversified agroforestry systems in which cash crops are grown along with timber and/or fruit trees can provide a stable source of income to producers and cushion the impact of market fluctuations or crop failure. They can also provide a diversity of potential habitat types to native species, and can serve as buffers outside protected areas or as movement corridors for species between protected areas (Pandey 2002).

The Talamanca region contains several protected areas, including La Amistad International Park, Chirripó National Park, Hitoy-Cerere Biological Reserve, Gandoca-Manzanillo Wildlife Refuge, and a number of smaller private reserves (Boza 1986). These protected areas are part of the Talamanca-Caribbean Biological Corridor (CBTC), otherwise known as Fila Carbón, which ranges from the Atlantic coast to the upper slopes of the Talamanca mountain range. The Talamanca region also contains several indigenous reserves, including those of the Bribri and Cabécar. These communities are located within the CBTC, and their stewardship has contributed to the high conservation value of the land. The various agroforestry systems within the indigenous territories have been evaluated for their conservation value and function as habitats supporting biodiversity (Somarriba and Harvey 2003). In contrast to monoculture banana and plantain plantations in the area, which displace the regional flora and fauna, these traditional agroforestry systems under forest cover may provide complementary biodiversity conservation and ecosystem services to adjacent protected areas (Gámez and Ugalde 1988).

Talamanca is the poorest canton of Costa Rica, and indigenous peoples in the area have been highly marginalized in Costa Rican society (Gómez 2001). Agricultural production in the Bribri-Cabécar Indigenous Reserve is an essential source of household income. There is some concern that economic pressures to increase income may drive the conversion of traditional, diverse agroforestry systems to more intensive, less diverse agriculture (Villalobos and Borge 1998, CATIE 2000). Improving productivity of crops grown in agroforestry systems through better management practices is necessary in order to strengthen the economic stability of diversified production in the region. Insect, nematode, and fungal pests can significantly reduce banana yields. Improved management of the banana weevil could contribute to the economic stability of the diversified systems in Talamanca, which might also decrease the likelihood of their conversion to plantain monoculture. Additionally, there is a need for alternatives to the organophosphate pesticides used in conventional plantain due to their toxicity to humans and wildlife. The efficacy of pesticides used to control the banana weevil has been questioned, as pesticides that are not systemic will not kill the larvae unless they remain effective until the adults emerge and contact the soil (Sponagel et al. 1995), and banana weevil populations resistant to insecticides have developed in some areas (Collins et al. 1991, Gold et al. 1999a).

Before work on a strategy for improved banana weevil management can begin, basic information on the banana weevil in Talamanca is needed; in fact, farmers in the Bribri-Cabécar Indigenous Reserve have expressed interest in an evaluation of banana weevil populations in their farms (E. Somarriba and M. Villalobos, pers. comm.). Damage levels in smallholder plantain and organic banana farms are unknown, as well as management practices currently in use by indigenous farmers and farmer knowledge and perceptions of banana weevil biology and management. Management practices for the banana weevil within the indigenous reserve are thought to include pesticide use in plantain and various cultural practices, but have not been documented. Additionally, it is necessary to understand the social and economic factors involved in land use and pest management decisions before recommending appropriate pest management alternatives.

One possibility for improved banana weevil control is mass trapping with pheromone lures. An aggregation pheromone of the banana weevil is commercially produced in Costa Rica (Ndiege et al. 1996). Use of this pheromone has been shown to increase the efficiency of trapping adult weevils in banana plantations (Jayaraman et al. 1997). Recommendations exist for use of pitfall traps with pheromone lures in commercial banana and plantain plantations in Costa Rica (Alpízar et al. 1999). However, further evaluation of pheromone trapping under different agroecological conditions is needed (Tinzaara et al. 2002), and the efficacy of pheromone traps in smallholder plantain farms has not been determined.

Banana weevils are able to move between farms (Gold and Bagabe 1997, Gold et al. 2002). Movement of banana weevils into a farm from adjacent areas could affect the efficacy of any management strategy. A study evaluating the efficacy of pseudostem traps found that they were much less effective in plots surrounded by banana farms, and more effective in one farm which was isolated by other vegetation such as coffee and bush fallow (Gold et al. 2002). The distance at which weevils can respond to stimuli used in host finding may be important for understanding the movement of the banana weevil in a heterogeneous landscape such as Talamanca, where small farms are often adjacent to other farms that could act as sources of banana weevils. The banana weevil is thought to fly rarely or never, and moves mainly by crawling. Estimates of movement range from 15 m in a night to 10 m over several months. Some studies have found very little movement; one mark-recapture experiment in which weevils were released into experimental plots found less than 3% of marked weevils in a plot other than their release plot after 3 years (Gold et al. 1999b). However, other studies have found greater rates of movement: a similar mark-recapture experiment found that 60% of marked weevils had moved more than 10 m in a two-week period (Gold and Kagezi unpublished data, cited in Gold et al. 2001). Adult banana weevils have been shown to orient to both host plant volatiles and their aggregation pheromone (Tinzaara et al. 2003), but the distance over which they can sense the volatiles and orient towards the host plant in the field is unknown (Gold et al. 1999b).

Research on the banana weevil in the context of the indigenous territories of Talamanca was conducted with the following objectives: 1) evaluate cacao, banana, and plantain production using a livelihoods framework, 2) determine banana weevil management practices currently in use and farmer perceptions of banana weevil biology and management, 3) assess banana weevil damage levels and banana yield in organic banana agroforestry systems, 4) evaluate the efficacy of pheromone traps in smallholder plantain farms, 5) evaluate responses of the banana weevil to host plant volatiles in the field, and 6) provide the results of research to the indigenous communities of Talamanca.

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Chapter 1: Incorporating livelihoods in biodiversity conservation: a case study of cacao agroforestry systems in Talamanca, Costa Rica

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Abstract

Over the past two decades, various organizations have promoted cacao agroforestry systems as a tool for biodiversity conservation in the Bribri-Cabécar indigenous territories of Talamanca, Costa Rica. Despite these efforts, cacao production is declining and is being replaced by less diverse systems that have lower biodiversity value. Understanding the factors that influence household land use is essential in order to promote cacao agroforestry systems as a viable livelihood strategy. We incorporate elements of livelihoods analyses and socioeconomic data to examine cacao agroforestry systems as a livelihood strategy compared with other crops in Talamanca. Several factors help to explain the abandonment of cacao agroforestry systems and their conversion to other land uses. These factors include shocks and trends beyond the control of households such as crop disease and population growth and concentration, as well as structures and processes such as the shift from a subsistence to a cash-based economy, relative prices of cacao and other cash crops, and the availability of market and government support for agriculture. We argue that a livelihoods approach provides a useful framework to examine the decline of cacao agroforestry systems and generates insights on how to stem the rate of their conversion to less diverse land uses.

Key words: banana, cocoa, Bribri, Cabécar, indigenous peoples, institutional support, land-use decisions, Meso-American Biological Corridor, *Musa,* monoculture, organic agriculture, plantain, *Theobroma cacao*

Introduction

Land-use change, including the expansion of intensive agriculture, is one of the most cited explanations for biodiversity loss worldwide (Sala et al. 2000). Rates of forest conversion have been especially rapid in the American tropics, where estimates of net deforestation range from 22,000 to 44,000 km^2 per year (Wright and Muller-Landau 2006). In response, researchers in conservation biology seek to promote less intensive agriculture such as multistrata agroforestry systems that provide farmers with income while protecting biodiversity (McNeely and Scherr 2003; Schroth et al. 2004). Cacao (*Theobroma cacao*) agroforestry systems demonstrate great potential to fulfill these goals due to their ability to maintain avian, mammalian, and other forms of biodiversity amidst the increasing international demand for cocoa beans and chocolate-based products (Rice and Greenberg 2000). Multistrata cacao agroforestry systems that include timber, fruit, and native forest species contribute to biodiversity conservation by providing habitat for species, enhancing landscape connectivity, and reducing edge effects between forest and agricultural land (Johns 1999; Guiracocha et al. 2001; Reitsma et al. 2001; Harvey et al. 2006). These systems can also benefit farming households. The shade provided by agroforestry systems can help preserve soil temperature and moisture regimes that allow nutrient cycling to occur and can increase nutrient-use efficiency of the system (Young 1999). Fruit and timber species can provide alternative and supplemental sources of income to households and buffer them for greater economic security in times of low prices (Rice and Greenberg 2000).

Given their potential benefits to both biodiversity and farming households, cacao agroforestry systems have been promoted as an alternative to more intensive land uses. However, the continued presence of cacao agroforestry systems depends upon land-use decisions at the household level. Since smallholder production accounts for between 70 and

90% of world cacao production (CABI 2001), understanding the factors influencing farmer decisions is crucial if cacao agroforestry systems are to be successfully promoted. While the importance of including socioeconomic factors in agroforestry research is increasingly recognized (Schroth et al. 2004; Shapiro and Rosenquist 2004; Montambault and Alavalapati 2005), agroforestry research in general has focused more on biophysical aspects of agroforestry systems than socioeconomic factors (Mercer and Miller 1998; Nair 1998). Similarly, research on the conservation value of cacao agroforestry systems has primarily focused on their contribution to on-farm and landscape-level biodiversity, although wider perspectives exist on this issue (see Schroth et al. 2004).

We employ components of a livelihoods approach in order to identify socioeconomic factors affecting cacao agroforestry systems. A livelihood consists of a household's capabilities, assets, and activities required for a means to a living (Chambers and Conway 1991; Carney et al. 1999). Originally developed in the 1980s in the context of Farming Systems Research and Education, the framework for a livelihoods approach arose as an effort to develop more effective poverty reduction strategies by including household decision-making and constraints on farming households within analyses (Carney 1998). This approach has also been used to link conservation and rural development (Boyd et al. 1999; Hulme and Muphree 2001), as it provides a methodology for examining the economic, social, and institutional factors that influence household land use. Livelihoods analyses include the vulnerability context of the household, household assets described as five types of capital, and the structures and processes that mediate household livelihood strategies (Department for International Development 2003). In this paper, we will focus on two aspects of the livelihoods approach: the vulnerability context, which consists of trends and shocks that are largely outside the immediate control of households, and structures and processes, which include socioeconomic and institutional factors that are both endogenous and exogenous to the social world in which households participate (Ellis 2000; Department for International Development 2003).

Talamanca case study

We present the Bribri and Cabécar indigenous territories of Talamanca, Costa Rica as a case study of an area in which cacao agroforestry systems have declined since the late 1970s despite numerous interventions (Acuña 2002) and in which the inclusion of livelihoods analyses in conservation projects could help mitigate the conversion of land to less diverse, more intensive agricultural systems such as monoculture plantain (*Musa* AAB). Cacao grown in Talamanca is sold only to organic markets and is produced without agrochemical inputs. Comparisons of land uses in the territories have found higher mammal and beetle species richness in cacao and banana (*Musa* spp.) agroforestry systems than in monoculture plantain (Harvey et al. 2006) and avian species richness in both managed and abandoned cacao farms that is slightly higher than that of forest (Reitsma et al. 2001). The greater diversity found in cacao agroforestry systems can approximate the structural and floristic complexity of the previous forest (Somarriba and Harvey 2003; Suatunce et al. 2003). The position of cacao agroforestry systems within the larger agricultural matrix of Talamanca may also contribute to biodiversity conservation (Harvey et al. 2006), since cacao agroforestry systems can serve as a buffer zone between monoculture agriculture and protected areas (Gamez and Ugalde 1988).

In contrast to cacao, plantain in Talamanca is grown primarily in monoculture with very few shade or fruit trees and with application of agrochemicals in varying amounts and frequencies (Polidoro and Dahlquist unpublished data). The effects of these agricultural practices on on-farm biodiversity include reduced habitat quality and connectivity, increased fragmentation and deforestation, and species loss due to toxic agrochemical use (Henriques et al. 1997; The Nature Conservancy 2005). Agrochemicals can also negatively affect biodiversity in off-farm areas through movement to and pollution of nearby aquatic and coastal resources (Castillo et al. 1997; Castillo et al. 2000; Lowrance et al. 2001). In Talamanca, monoculture plantain is grown on floodplain soils, where previous research has linked the loss of native riparian vegetation to decreased aquatic habitat and water quality

(Pringle et al. 2000), as well as increased flooding events, soil erosion, and landscape instability (Sanchez-Azofeifa et al. 2002; Thoms 2003). Given the negative consequences of monoculture systems for biodiversity in Talamanca, researchers and conservation planners continue to promote cacao agroforestry systems for their conservation value. However, conversion of land to less diverse systems continues in areas where plantain can be cultivated.

Recognizing the factors that encourage the spread of less diverse agricultural systems and the corresponding decrease of more diverse systems, such as cacao agroforestry systems, can benefit conservation efforts. The objectives of this study are to: 1) examine factors influencing the presence of cacao agroforestry systems in the landscape of Talamanca within a livelihoods framework, and 2) identify strategies to mitigate abandonment of cacao agroforestry systems in Talamanca, with potential applications for other regions where cacao is grown. We use a combination of methods including compilation of economic and production data, review of gray literature produced in Talamanca, interviews with local stakeholders, and triangulation to assess these factors and their implications for conservation.

Site Description

Indigenous territories

The Bribri and Cabécar indigenous territories of Costa Rica are located in southeastern Costa Rica in the canton of Talamanca within the Meso-American Biological Corridor, which comprises the largest remaining tract of contiguous forest in Central America (Palminteri et al. 1999). The landscape within the territories includes the floodplain of the Talamanca Valley, surrounded by undulating foothills that give way to the high montane regions of the Talamanca mountain range. The Atlantic slopes of the Talamanca range encompass both humid tropical forest and premontane wet forest life zones (Holdridge 1967). Annual precipitation increases with altitude from approximately 2,600 mm of rain at 40 masl to 6,400 mm at 1,000 masl (Borge and Castillo 1997). Within the Talamanca region, the Bribri and Cabécar indigenous territories are considered extremely valuable for biodiversity conservation, as they are surrounded by several national and international protected areas (Palminteri et al. 1999).

The Bribri and Cabécar indigenous territories support a population of about 10,000 inhabitants (Municipality of Talamanca 2003) and contain 43,690 ha and 22,729 ha, respectively (Borge and Castillo 1997). Talamanca is the poorest canton in Costa Rica, with more than a third of the population unemployed or under-employed and the highest concentration of poverty occurring within the indigenous territories (Municipality of Talamanca 2003). Indigenous peoples have been historically marginalized in Costa Rica, and the territories have limited access to health care, education, infrastructure, and road access (Gómez Valenzuela 2001). The major sources of income in the territories are plantain, organic banana, organic cacao, and wage labor. Currently, the Talamanca region is responsible for 95% of Costa Rican cacao production, 52% of plantain production, and 90% of organic banana production (Municipality of Talamanca 2003). Cacao in Talamanca long predates the Spanish colonial presence, and the Bribri and Cabécar used it historically for a ceremonial drink (Villalobos and Borge 1998; Somarriba and Beer 1999). The cacao tree figures prominently in Bribri and Cabécar narratives of origin (Murillo and Segura 2003), and some within the indigenous population still consider cacao sacred.

Landscape attributes

Topographical and geomorphological variations contribute to distinct land-use patterns in the landscape of the indigenous territories. An estimated 17,000 ha of agricultural land exists within the territories, 60% of which is located within the Talamanca Valley (Borge and Castillo 1997). The valley contains highly variable, fertile soils that have high base status and organic matter content, classified as Entisols (Polidoro et al. in press). In contrast, the foothills are a mosaic of acidic, low-fertility soils with high clay content, classified as Ultisols, intermixed with less acidic, slightly more fertile soils, classified as Inceptisols (Winowiecki unpublished data). Although cacao natively grows on floodplain soils in the

Amazon basin and was cultivated in the Talamanca Valley by the United Fruit Company (UFC), it can also grow on steep slopes and low-fertility soils. Despite this ability, research indicates that low-pH soils with high aluminum saturation greatly inhibit cacao yields (Baligar and Fageria 2005). In contrast to cacao, plantain and organic banana production for commercial purposes is limited to well-drained, sandy-textured soils on low-gradient slopes (Robinson 1996) such as those in the floodplain of the Talamanca Valley. Attempts to grow plantain in the foothills have been unsuccessful after one harvest (Winowiecki and Whelan unpublished data). These variations in soil type and slope have contributed to the current pattern: banana and plantain dominate the valley, while cacao remains the major cash crop that can be widely produced on the low-fertility soils of the foothill slopes. It is important to note that this variation in landscape and corresponding soil characteristics is responsible in part for the distribution of land uses within the territories (Fig 1.1).

Description of farms

Household landholdings in the indigenous territories can include multiple plots of land with different land uses (Whelan 2005). Cacao is managed at a low intensity, and canopies of cacao agroforestry systems in the territories vary in tree species composition and amount of shade. These include systems with scattered shade trees of only one species, intercropped systems with a variety of timber and fruit species including banana, and 'rustic' systems in which cacao is grown under thinned forest trees (Somarriba and Harvey 2003).The canopy of banana agroforestry systems often contains remnant trees of the original forest or naturally regenerated laurel (*Cordia alliodora*), and is generally less floristically diverse than that of cacao (Guiracocha et al. 2001; Suárez Islas 2001). Households often intercrop cacao and banana in agroforestry systems, since they are both compatible as organic cash crops and can grow under shade. These systems may emphasize one crop over the other. Plantain grown without agrochemical inputs can also be included in agroforestry systems, either for household consumption or for sale as low-quality produce. While much of the valley is cultivated for plantain or organic banana production, cacao agroforestry systems still exist in valley communities, particularly in those closer to the foothills. Household landholdings in the valley are generally much smaller than those in the foothills (Morera et al. 1999; Whelan 2005). Foothill farms tend to be more diversified, with areas dedicated to shifting cultivation of annual crops and fallows, as well as primary forest and cacao and banana agroforestry systems (Somarriba et al. 2003).

Methods

Integration of local and national information

Much of the information on the indigenous territories is unpublished or gray literature, such as theses or project reports of government agencies, non-governmental organizations (NGOs), and private consultants. In the absence of systematic and comprehensive research in this area, we compiled this information on Talamanca along with national and international data on price, production, and export trends in cacao and plantain in Costa Rica in order to identify and characterize trends affecting cacao in Talamanca. These data include yield and land use statistics obtained from the Asociación de Pequeños Productores de Talamanca (APPTA), cacao prices obtained from the International Cacao Organization (ICCO), land use, yield, trade, and price information obtained from FAO databases (http://fao.faostat.org), and comparisons of production systems within the indigenous territories (Deugd 2001; Hinojosa Sardan 2002; Municipality of Talamanca 2003; Yepez 1999). Although we cannot conduct additional analyses from these sources, we employ these secondary data as the relevant and available cases related to our regional analysis. In addition, several authors of this paper have conducted participatory research projects in both the biophysical and social sciences in the indigenous territories over the past two years (2004-2006), in land uses including cacao, banana, plantain, and basic grains. Although anecdotal, our own experiences and participant observation in the indigenous territories provide context for our analysis of factors influencing cacao production.

Household and key informant interviews

Thirty exploratory semi-structured interviews were conducted with regional key informants, which included staff of government agencies and NGOs, Bribri and Cabécar local extensionists, and residents. Semi-structured interviews were based on an interview guide of open-ended questions which gave respondents latitude to describe their responses using terms and language most familiar to each of them, and not bound to predetermined answers (Mikkelsen 1995). Key informants with knowledge related to land use and livelihoods in the indigenous territories were selected through snowball sampling (Berg 1995). Guiding questions for semi-structured interviews included past and current land use, factors influencing each land use, and household livelihood strategies. Information from key informant interviews was used to develop an interview guide of open-ended questions for semi-structured interviews with households as well as additional background to develop criteria for community selection (Whelan 2005).

Eight communities within the indigenous territories were selected considering a combination of the following criteria: an elevation gradient; access to infrastructure; access to services; and a total number of households. Four foothill and four valley communities were selected. Communities were classified into three zones designated as remote, intermediate, and accessible based on access to infrastructure and services (Table 1.1). The total number of households in the eight communities was estimated using health records and census data, supplemented by information corroborated with local informants. A random sample of at least 10% of households in each zone was selected, with a total of 82 households across the three zones (Table 1.1). Two key factors limited development of a larger sample: 1) the sizes of some communities limit the total number of potential respondents, making the local community members characteristic of rare populations for survey sampling; and 2) resource constraints only allowed for access to a limited percentage of the remote zone communities due to their locations. The mean household size and percent ethnic background are also listed in Table 1.1 to reflect a demographic profile of the respondents.

Five pre-test interviews were conducted using an interview guide prior to administering the full household survey. Survey interviews with households were combined with a participatory mapping exercise of farm land use and cropping history. Survey interviews also included an open-ended discussion of the future possibilities of organic production in Talamanca.

Data analysis

Interview data were coded and descriptive statistics were calculated. Responses to open-ended questions in semi-structured interviews can vary widely. When households gave multiple responses to a question, responses were aggregated by topic and the percentage of households mentioning each topic was calculated.

Land-use trajectory diagrams were constructed by compiling changes in land-use history from the mapping exercise. Since household interviews did not specify exact time periods for cropping history, land uses were designated sequentially as ‘Former use III’ (oldest land use) followed by ‘Former use II’, ‘Former use I,’ and ending with ‘Current use’. Thicker lines between land uses in the diagrams correspond to more prevalent land-use patterns. Although the process of land use change is not always linear and can include gradual shifts and rotations, the land-use trajectory diagrams display this change in linear form for ease of presentation.

Triangulation

Information gained through literature review and interviews was triangulated through participant observation and group discussions. Participant observation included living with households for a month and a half in each of the different zones, informal conversations with indigenous farmers and other household members, participating in activities of households, and observations from personal experience through working in the indigenous territories.

Several group discussions for feedback were held in each zone following completion of the semi-structured interviews.

Results

Abandonment and shifting of cacao agroforestry systems

Extension and research support promoting cacao agroforestry systems in the indigenous territories began in the mid-1980s (Table 1.2). These projects introduced improved production methods such as pruning, grafting of superior local germplasm, enrichment with fruit trees, and improvement of the shade canopy, and also provided workshops to train farmers and local extensionists in these practices. Projects also distributed cacao and shade tree seedlings for rehabilitation of abandoned cacao farms. Despite these efforts, land use has shifted away from cacao production in areas where other cash crops can be grown. Total cacao production in Costa Rica has declined from a peak of 32,500 ha harvested in 1968 to only 3,550 ha harvested in 2005 (Fig. 1.2a). Our household survey showed that of 42 plots that emphasized cacao when the household first began managing the land, only one (2%) remained in cacao at the time of the study. Cacao agroforestry systems were replaced by banana agroforestry (36%), mixed agroforestry (24%), and plantain (21%) (Fig. 1.3). Though mixed agroforestry systems often retained some cacao, they shifted to emphasize other crops, especially banana. While 30% of households surveyed had at least some cacao at the time of the study, only 36% of these sold their cacao for cash income. The remaining households either had abandoned their cacao or used it only for household consumption.

This trend of cacao agroforestry system abandonment or shifting to emphasize other crops can be understood in the framework of the vulnerability context in which households choose their livelihood strategies, and the structures and processes that influence livelihoods. Shocks and trends comprising the vulnerability context in Talamanca include crop disease, population growth, and concentration in population centers. Structures and processes include socioeconomic factors such as the shift from a subsistence to a cash-based economy, the relative prices of cacao and other cash crops, and institutional factors such as the availability of capital and government support for agriculture (Fig. 1.4).

Vulnerability context

Monilia

The fungal disease monilia (causal agent: *Moniliophthora roreri* Cif.) was a devastating shock to livelihoods throughout Talamanca when it arrived in the late 1970s, and continues to be one of the major factors limiting cacao yields (Villalobos and Borge 1998). Fungal spores of monilia infect young cacao pods, resulting in rotting and discoloration within the pod, partial or complete destruction of the beans (Ampuero 1967), and deformation or death in small pods (Campuzano 1980). The spores are dispersed from diseased pods, mainly through convection currents within the farm and wind (Evans 1981). Pod losses due to monilia range from 10% to 100% and have led to the abandonment of cacao cultivation in some parts of Latin America (Phillips-Mora 2003). The disease was first reported in Costa Rica in 1978 (Enriquez and Suarez 1978). Between 1978 and 1983, the area of land harvested declined from 30,000 ha to 9,100 ha (Fig. 1.2a), and total cacao production in Costa Rica declined by 79% (Fig. 1.2b). Cacao production in Costa Rica has never since recovered to pre-monilia levels. Our household survey showed that all households who had abandoned their cacao or shifted it to other crops mentioned monilia as the determining factor in their decision.

Control methods for monilia remain limited. Since cacao in Talamanca is grown for organic markets, control of monilia with synthetic fungicides is not an option for farmers (Krauss et al. 2003). Copper-based fungicides can be used in organic production, but are not economical when cacao yields are low or in areas with high rainfall (Hernández 1991, cited in Soberanis et al. 1999). No resistant cultivars are available, although work is ongoing to develop monilia-resistant germplasm (Phillips-Mora et al. 2005). The removal of diseased pods has been promoted in other regions as a cultural control practice (Soberanis et al. 1999; Leach et al. 2002), and biological control with fungal antagonists has also been investigated (Krauss and Soberanis 2002). Pod removal and biological control have both been tested in Talamanca, but results so far are inconclusive on the efficacy of these methods and their profitability (Krauss et al. 2003). Given the lack of profitable control methods and drastic yield losses, monilia continues to be a major barrier to reversing the production decline of cacao for many farmers in Talamanca.

Demographic trends

Demographic trends within the indigenous territories also form part of the vulnerability context affecting households and their livelihood strategies. Increased population pressure on cultivated land, for example, can be an important influence on transformations in agricultural production (Boserup 1981). The population of the indigenous territories has surged from 2,790 inhabitants in 1973 to 10,292 by 2000 (Yepez 1999; Municipality of Talamanca 2003). The population has also become more concentrated in the Talamanca Valley. Although the valley constitutes only 18% of the indigenous territories, over 80% of the population resides on these flat and fertile lands (Borge and Castillo 1997). These trends are due to both overall population growth and immigration of non-indigenous peoples. In the late 20th century, several groups of non-indigenous residents migrated to Talamanca due to drought in Guanacaste, Costa Rica, conflict in Nicaragua, and employment opportunities with the petroleum explorations of the Costa Rican Petroleum Refinery (RECOPE) (Villalobos and Borge 1998).

Pressure on land is likely to intensify as population growth continues. From 1976 to 1991, land under cultivation more than quintupled from 2,000 to 10,700 ha, largely due to an increase in plantain and organic banana production (Yepez 1999). More than half of households interviewed (59%) stated that they did not have enough land to meet their needs. When asked how much land they needed, the mean response was 7.8 ha. Our survey found that in the communities with better access to basic infrastructure and services, some households had no land at all (15.6%), while 22% of households had 1 ha or less. Present conditions leave many households with few options but to cultivate limited landholdings intensively while complementing on-farm activities with off-farm sources of income. In the communities of our study region that had less population pressure on land, group discussions with key informants indicated that cacao agroforestry systems were often abandoned and left to return to secondary forest. In areas with greater degrees of population pressure, cacao was predominantly replaced by banana agroforestry systems or plantain, or remained only partially in cacao production while shifting to emphasize other crops (see also Yepez 1999). These changes illustrate the role of demographic trends in household decisions to either intensify production of agroforestry systems or abandon cacao agroforestry systems to pursue other livelihood strategies.

Structures and Processes: Socioeconomic and institutional factors influencing livelihoods

Cacao production in Talamanca is also limited by structures and processes that favor the cultivation of alternative crops. These include the development of a cash-based economy, increased availability of domestic and international markets for plantain, higher and more regular income from plantain sales, wage labor opportunities in plantain, and a favorable policy context for plantain compared to organic crops. The economy within the indigenous territories has shifted from subsistence to a cash-based economy. This shift began with commercial production of cacao by the UFC in 1909 (Villalobos and Borge 1998). After the UFC withdrew from the Talamanca Valley in the 1940's, local residents continued to cultivate cacao as a cash crop (Villalobos and Borge 1998). The immigration of wage laborers and cash crop producers intensified the transition to reliance on cash income. When cacao production was no longer profitable following the onset of monilia in 1978, the demand for continued cash income led to the adoption of other cash crops such as plantain and organic banana. Plantain began to replace cacao as a cash crop in 1983-1984 (Fig. 1.5), when U.S. transnational companies and Nicaraguan importers began purchasing plantains in Talamanca (Somarriba 1993). By the late 1980s, the plantain market provided more financial security than cacao due to low and fluctuating cacao prices (Fig. 1.6). By contrast, markets for organic cacao and organic banana did not develop until the early 1990s (Hinojosa Sardan 2002).

Although an organic market for cacao in Talamanca exists, plantain provides higher and more regular income. Available estimates of average yearly gross income per hectare vary widely (Table 1.3), and systematic comparisons of cash crops in Talamanca do not exist beyond these sources. These estimates come from several previous studies conducted within the indigenous territories, some of which relied on interview data (Deugd 2001; Hinojosa Sardan 2002; Winowiecki unpublished data) and one on on-farm production data (APPTA production data 2004). An estimate of gross annual income for cacao was also calculated from yield and price data available from the FAO (FAOSTAT data 2006, http://faostat.fao.org). Some studies were conducted within only one production year (APPTA production data 2004; Deugd 2001; Hinojosa Sardan 2002; Winowiecki unpublished data). Some do not state their duration and methods with enough specificity for full comparison, but do provide additional context for understanding the patterns of factors affecting cacao production (Municipality 2003; Yepez 1999). Sample sizes from these studies vary from 6 farms (Deugd 2001) to 71 (Hinojosa 2002) to 325 farms (APPTA production data 2004). While these sources provide widely variable estimates of gross income from the three major cash crops in Talamanca, they illustrate a general pattern: plantain generates the highest gross income, followed by banana and finally cacao. Studies that calculated the benefit/cost ratios for these crops show the same pattern, with a benefit/cost ratio less than 1 for cacao compared to over 3 for plantain (Table 1.3). Costs of production in these studies included labor, services such as transportation, and purchased inputs (Deugd 2001; Hinojosa Sardan 2002). Some of the differences among studies may be due in part to different methods of calculating labor costs. In particular, including household labor as a cost may result in underestimating the benefit/cost ratio for cacao (Deugd 2001), since many households rely on the labor of family or traditional group work days for which they do not pay wages. However, each study alone presents the same pattern of a lower benefit/cost ratio for cacao compared to banana or plantain.

The results of our household interviews correspond to this pattern. Only 2% of households considered cacao an important source of income, compared to 23% for plantain (Fig. 1.7). Lower income from cacao results in part from low cacao prices, due to both international price trends (Fig. 1.6) and the lack of competition among cacao buyers in Talamanca (Andrade and Detlefsen 2003). Only two local associations in Talamanca currently buy cacao for one export market, whereas a variety of buyers exists for plantain for national and export markets. In open-ended discussions with respondents, 44% of households who commented on the future of organic agriculture in the indigenous territories mentioned low or unstable prices as obstacles. Regularity of income is also important because of the demand for a continuous supply of cash in an area with limited access to credit and savings mechanisms. While cacao has one major harvest per year, with one or two secondary harvests, plantain can be harvested and sold on a regular weekly or biweekly basis. Responses from households indicate that this cash structure affects livelihood strategies and decisions about land use.

Plantain farms also provide opportunities for wage labor due to their higher management intensity. Off-farm income has become an increasingly important livelihood strategy for households in the indigenous territories. When asked to list important sources of household income, 41% of households mentioned off-farm labor (Fig. 1.7). Labor invested in cacao production now carries the opportunity cost of wages that could be earned in plantain farms. This contributes both to low cacao yields and increased reliance on plantain for income. We found that of the 10 households that employed permanent labor, 80% used that labor in plantain. Of the 16 households that employed labor irregularly, 73% used that labor in plantain. In foothill communities which are unable to sell to plantain and organic banana markets, 80% of households had at least one member who worked as a wage laborer. This trend is also seen in valley communities, where households with limited landholdings often depend upon wage labor in plantain farms.

The lack of institutional support available for cacao compared to plantain has contributed to the decline of cacao agroforestry systems in areas where plantain can be grown. Institutional support for cacao existed in the form of research efforts and promotion of diverse farms by

NGOs during the 1980s (Table 1.2). However, that support was not enough to compete with support offered to plantain growers from the Costa Rican government and national and international plantain buyers. Plantain exporters have received economic incentives such as tariff exemptions or reductions and tax credits (Somarriba 1993; Mora 2005). In the indigenous territories, plantain buyers provide farmers with tools and agrochemical inputs and later deduct them from the sale of plantain, enabling households with little or no resources to begin plantain production (Whelan 2005). In our survey, 26% of total households reported receiving informal credit from plantain middlemen, who operate between producers and multinational corporations or national wholesale buyers. In the more accessible zone, 53% of households had access to informal credit, and all of this credit was from plantain middlemen. Also, the Costa Rican government provides extension services for plantain growers (Garcia 2003). Of the households in our survey, 9.8% mentioned receiving visits by government extensionists for plantain production, but none mentioned receiving a visit from a government extensionist for cacao production.

Organic certification requirements and legislation for timber sales from agroforestry systems are potential obstacles to cultivating cacao within the territories. Organic certification requires yearly inspections paid for by farmers. A three-year transition period with no chemical inputs is required to convert from plantain to organic systems (Soto 1998). Requirements also include an 8 m buffer zone separating organic farms from plantain farms with chemical use (Ecocert Canada 2006). Given the present conditions of land scarcity and poverty in Talamanca, farmers may be reluctant to take land out of production in order to meet these requirements. For example, 76% of households who responded on the subject of organic agriculture mentioned agrochemical use in nearby plantain as a barrier to the spread of organic systems. Only 4% of households surveyed considered cultivating cacao in the future. Similarly, current forest legislation acts as a disincentive to cultivate agroforestry systems. Timber harvests must be conducted with advance permission from the indigenous territories' development associations and payment of fees. According to Costa Rican and local indigenous law, farmers can only harvest trees from designated agricultural land with a maximum harvest of three trees of over 50-cm diameter at breast height per hectare and up to

9 trees per year, including fallen trees (Candela 2006). This strict legislation, combined with the excess fees and costs of tree harvesting, limits the potential of timber products to augment income from diversified farms.

Discussion

Efforts to promote cacao agroforestry systems as a conservation tool would benefit by addressing factors limiting cacao production. Our analysis indicates that producing cacao as a livelihood strategy remains bound to a variety of local, regional, and global factors. Low international market prices may inhibit farmer motivation to expand cacao production if they also have the choice to grow plantains for a higher and steadier income. Related to this, local buyers' organizations may help buffer global fluctuations in price, but can also set lower prices. Regional or local pricing may then relate to the presence or lack of a cooperative structural arrangement that would include or exclude indigenous farmers in economic decisions within the market. The prevalence of monilia in Talamanca drastically reduces cacao yields, and no control methods currently exist that would be feasible for farmers within the indigenous territories. This multiplicity of factors highlights the complexity that smallholders face in choosing livelihood strategies with tradeoffs beyond individual control. An important next step in addressing the factors limiting cacao production would be to conduct a sensitivity analysis to identify the response of profit gained from cacao production to each factor. A sensitivity analysis of organic cacao agroforestry systems in Belize identified labor-saving management practices and availability of credit as strongly influencing profit, while profit responded weakly to changes in cacao price policy and not at all to changes in timber sale prices (Rosenberg and Marcotte 2005). A similar analysis in Talamanca could help organizations promoting cacao to focus efforts on factors with a greater effect on profit for cacao farmers. While our analysis does not attempt to comment on the relative importance of each factor, in the following section we discuss potential avenues to address the limitations of cacao cultivation in Talamanca. Although many of these are specific to the Talamanca region, they illustrate the general importance of including an understanding of livelihoods in conservation efforts involving the promotion of diverse agricultural systems.

Addressing the vulnerability context

Continued research on feasible monilia control methods for farmers in Talamanca is needed in order to raise cacao yields and income generated from cacao agroforestry systems. A participatory evaluation of cultural and biological control for monilia in Talamanca found that both weekly pod removal and treatment with fungal antagonists reduced disease incidence (Krauss et al. 2003). However, neither practice was profitable during the two years of the study, and the authors recommended further research on combinations of the two strategies (Krauss et al. 2003). An evaluation of one project of the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Talamanca recommended the use of locally available fungicides such as compost tea, effective microorganisms (EM) products available from EARTH University, and supermagro, a biofertilizer with fungicidal properties (Altieri 2004). Increased extension efforts are also necessary to disseminate improved control methods. If monilia remains a major constraint to cacao production, it is extremely unlikely that farmers in Talamanca will consider cacao a profitable cash crop compared to banana or plantain.

Efforts to promote improved management practices such as shade canopy rehabilitation, pruning, and grafting of local superior varieties should be continued to help to raise cacao yields. In the Talamanca Valley, an increasing population on fixed land resources continues to reduce the available land per household. Consequently, cacao agroforestry systems will require more active management to compete with more intensified systems. While cacao cultivation is traditionally an extensive, low-management land use, improving management on a small area of land may be a viable strategy (Altieri 2004). Soil management techniques could also improve yields on low-fertility soils. These include practices which decrease nutrient leaching from the system, increase soil pH, minimize soil erosion, and increase soil fertility status through introduction of nitrogen-fixing shade trees.

Another strategy to improve cacao agroforestry systems is to manage several components more intensively, such as the timber and fruit species present in addition to cacao. Biweekly banana harvests from mixed systems can provide the regular income needed to sustain household livelihoods in between cacao harvests. Improved management and marketing of organic banana in mixed agroforestry systems with cacao could contribute to the viability of these systems. Plantain can also be grown in organic agroforestry systems, although cosmetic insect damage excludes it from export and results in a lower price for sale to the national market. A simulation model comparing mixed plantain, timber, and cacao agroforestry systems with monocultures of each crop in Panama found that the mixed agroforestry systems provided higher and more stable net incomes (Ramirez et al. 2001). While no one solution will alleviate all biophysical limitations for cacao production, a combination of management techniques may help to increase cacao yields and encourage farmers to plant and maintain cacao agroforestry systems.

Improving structures and processes

Increasing institutional support

Institutional support for cacao in the form of capital, extension efforts, and infrastructure is currently far below that available for plantain, which benefits from both public and private support at both the farm level and regional and international levels. Policies that provide incentives for organic production and cacao agroforestry systems are necessary if agroforestry systems with organic products are to expand beyond current levels. Technical support from government extension agencies and NGOs would provide incentives to keep cacao in production. Many local farmers have received training as extensionists in cacao management practices such as pruning and grafting. However, funding to employ them runs out when a project ends. Finding ways to keep local extensionists employed would help provide the institutional support needed to improve production in cacao agroforestry systems. Institutional support for cacao on the local level could also be improved by providing better access to tools and credit options for households interested in improving management practices. In addition, cacao farmers are currently not organized enough to collectively negotiate with buyers for better prices. Efforts to unite cacao farmers through community organizing and workshops on negotiation techniques could empower them to demand better prices for their product.

Modifications in current legal structures are necessary in order to remove disincentives for organic production in agroforestry systems. Although well intended, the certification process, buffer zone, and three-year transition period unfortunately act as regulatory barriers for households interested in changing to organic production. Changes in this process or financial support such as credit for households during the transition period would make this transition more feasible. Also, legal changes to allow for increased sale of timber products within sustainable limits would improve the profitability of diverse agroforestry systems. The current law regulating the sale of timber products is a national law administered by the indigenous governing bodies and could be modified to allow farmers to harvest timber sustainably in agroforestry systems while still protecting forested areas. An analysis of timber harvests in agroforestry systems in Talamanca concluded that timber could be extracted at double the current rate and still be sustainable (Suárez Islas 2001). Finally, efforts by the National Forestry Financing Fund (FONAFIFO) and CATIE to institute legal structures to allow for environmental service payments and the sale of carbon credits from land uses such as cacao agroforestry systems should be continued. The potential for including diverse organic banana agroforestry systems could also be explored.

<u>Generating additional income from cacao products</u>

Transformations toward a cash economy have created new pressures for households to generate cash income through both on-farm and off-farm activities. A livelihoods focus reveals the importance of the regularity and diversity of net income. Adding value to cacao through roasting, packaging, and marketing of chocolate products could diversify the Talamanca cacao market beyond its present reliance on only two buyers, offer households a more regular income, and generate off-farm employment opportunities. The Association of Indigenous Women of Talamanca (ACOMUITA) has sought to add value to cacao by acquiring equipment to process and package chocolate, with financial and technical support from the World Bank, USAID, and CATIE. While initial efforts are promising, there is room for improvement in quality control, packaging, marketing, and the involvement of more cacao-growing households within the territories. These efforts could benefit from increased support such as providing market liaisons outside the indigenous territories. There is presently an opportunity to reach local and national tourist markets by filling a niche for certified organic and indigenous-grown chocolate products. Diversification out of sole reliance on export markets would have the added benefit of buffering household livelihoods in times of commodity price fluctuations.

Agro-tourism also offers potential for generating higher incomes for cacao-producing households. Tourism in Talamanca has grown in the last several decades, including cultural and ecological tourism within the indigenous territories (The Nature Conservancy 2005). The Community Ecotourism Network of Talamanca was created in 1998, a product of the work of development organizations such as the Talamanca Ecotourism and Conservation Association (ATEC), the Association ANAI (formerly the Association of New Alchemists), and the Talamanca-Caribbean Biological Corridor Association. This network has trained local guides and offers tours of communities growing organic cacao, where tourists are presented with information about cacao agroforestry systems and served cacao as a beverage and in processed form. While these efforts to add value to cacao cultivation through agro-tourism are still in their initial stages, they offer potential for expansion to more communities within the indigenous territories.

Certified products such as organic cacao and banana can provide farmers with additional income through premium prices for organic products. Since the continued production of organic products depends on consumer demand, campaigns to generate awareness of ecological and social issues in agricultural production form a crucial part of any effort to promote cacao agroforestry systems as a conservation tool. One example is the certification of origins currently being developed for coffee, which allows consumers to purchase coffee based on the significance of a particular place and its people. Most of Talamanca's cacao is currently exported to only one company and processed with cacao from other places. Developing a certification of origins could differentiate Talamanca cacao products and potentially increase the price farmers receive for their cacao.

Conclusions

Incorporating a livelihoods framework into biodiversity conservation efforts that include agriculture can help identify the constraints households face for competing land uses and the socioeconomic and institutional structures and processes involved in land-use change. Equipping conservation efforts with this understanding could improve the promotion of diverse agroforestry systems as an alternative to monoculture. In places such as Talamanca where diverse agroforestry systems compete with a profitable and well-supported monoculture cash crop, conservation efforts to promote diverse agricultural systems must take into account the social and economic incentives for farmers to convert land to monoculture. Talamanca also demonstrates the importance of diversifying sources of income, recognizing both on-farm and off-farm opportunities, to compete with incentives for conversion to monoculture. In addition, our case study identifies intensified agroforestry systems that manage several cash crops as potential profitable alternatives to monoculture. These include regularly harvested crops such as banana or plantain that can provide continuous short-term income in addition to the seasonal income generated from cacao. Conservation efforts promoting more diverse land uses would benefit from greater inclusion of farmers and awareness of the social and economic realities that influence their livelihood strategies. While addressing factors that influence household livelihoods and land use may seem a difficult task or outside the expertise of conservationists, it is essential for the success of biodiversity conservation efforts that seek to include agricultural systems on private lands.

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Table 1.1. Characteristics of communities sampled.

	Remote zone				Intermediate zone		Accessible zone
Community	San José Cabécar	High Cohen	Orochico	High Mojoncito	Low Mojoncito	Sepecue	Shiroles
Distance from Bribri[1] (km)	40	36	25	22	19	17	13.5
Altitude (masl)	500	500	200	175	150	100	50
Total households	10	12	24	25	45	126	300
Households interviewed	2	3	3	7	11	24	32
Percent interviewed	20%	25%	13%	28%	24%	19%	11%
Mean household size (st. dev.)	6.3 (± 2.8)				4.6 (± 2.1)		4.9 (± 2.2)
Mean age of head of household (female)	38.0 (± 11.7)				34.3 (±10.5)		38.5 (±12.3)
Mean age of head of household (male)	41.4 (± 9.0)				38.1 (±8.9)		42.6 (±13.1)
Mean household landholdings (ha) (st. dev)	57.0 (± 65.3)				42.1 (± 55.1)		6.8 (± 11.0)
Mean plot size (ha) (st. dev)	7.2 (± 20.1)				6.5 (± 18.9)		7.6 (± 21.6
Percent Bribri	69%				80%		68%
Percent Cabecar	31%				13%		17%
Percent other	0%				7%		15%

[1]Bribri is the nearest urban center with access to infrastructure outside the indigenous territories.

Table 1.2. Conservation and development efforts promoting cacao in Talamanca.

Organization	Project	Date
Coopetalamanca[a]	Rehabilitation of abandoned cacao farms	1984
ANAI[a]	Diversification of agroforestry systems Promotion of new cacao genotypes	1984-1991
Asociación de Pequeños Productores de Talamanca (APPTA)[a,c]	Reforestation in cacao farms, thinning and pruning	1987-1990 1991-1995 1995-2000
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)[b,d]	Planting of timber and leguminous shade species with cacao	1989-1999
The Nature Conservancy[f]	EcoEnterprise fund for chocolate	2000
CATIE and World Bank Global Environmental Fund[e]	Biodiversity in cacao agroforestry systems	2001-2004
CATIE	Environmental service payments for aboveground carbon storage	2004-2006

a= Acuña 2002, b= Beer 1991, c= Hinojosa Sardan 2002, d= Somarriba et al. 2001, e= Somarriba et al. 2003, f= Niler 2002.

Table 1.3. Available estimates of yearly income and benefit/cost ratios for primary cash crops in Talamanca.

Crop	Frequency of harvest	Average yearly gross income/ha	Benefit/cost ratios
Cacao	1-2 times per year	$19 ± 16[e] $80-120[a] $111 ± 73[b] $270 ± 88[c]	0.14[e] 0.78 ± 0.80[c] 1.54[f]
Banana	Every 2 weeks	$160-240[d] $200 ± 143[e] 1100 ± 339[c]	0.97[e] 1.81 ± 0.66[c]
Plantain	Every 1-2 weeks	$600 ± 397[e] $700-$3,500[f,g]	3.42[e] 3.68[f]

Modified from a=Winowiecki unpublished data; b=Yield and price data 1991-2002, FAOSTAT data 2006, http://faostat.fao.org, c=Deugd 2001; d=APPTA production data 2004, e=Hinojosa Sardan 2002; f=Yepez 1999; g= Municipality of Talamanca 2003.

Figure 1.1. Dominant land uses in Talamanca, Costa Rica.

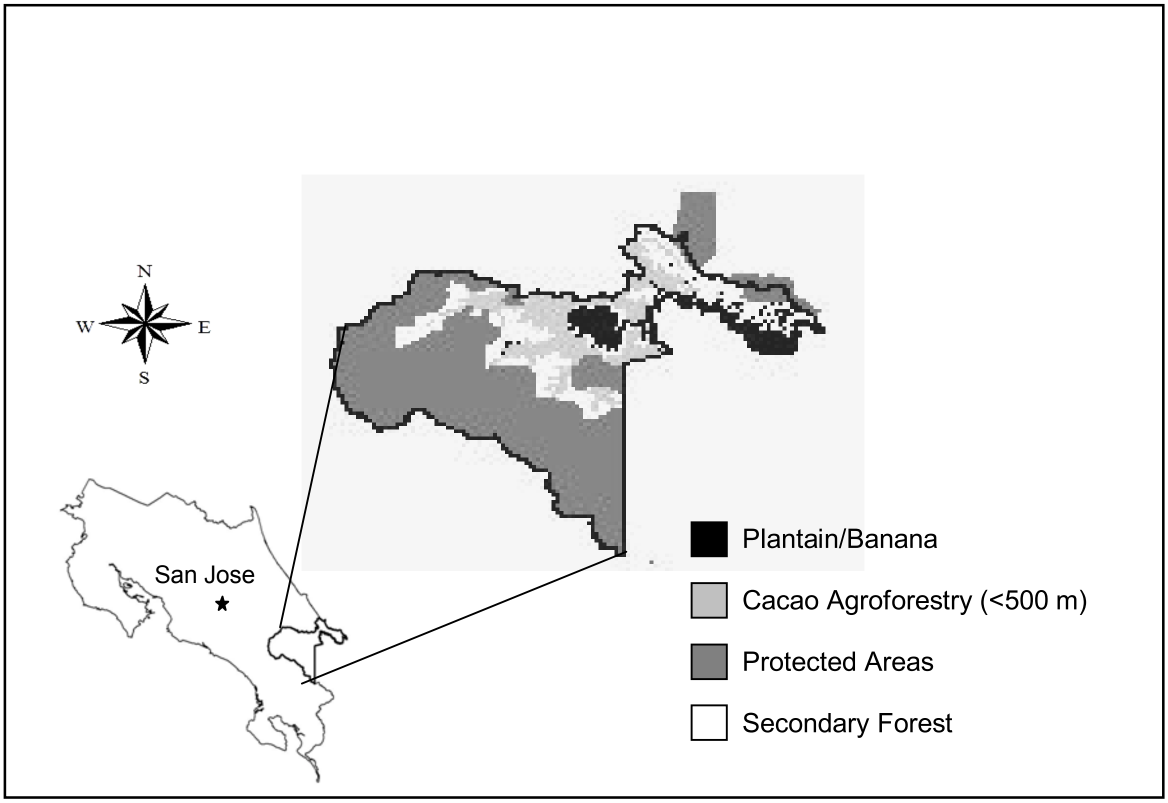
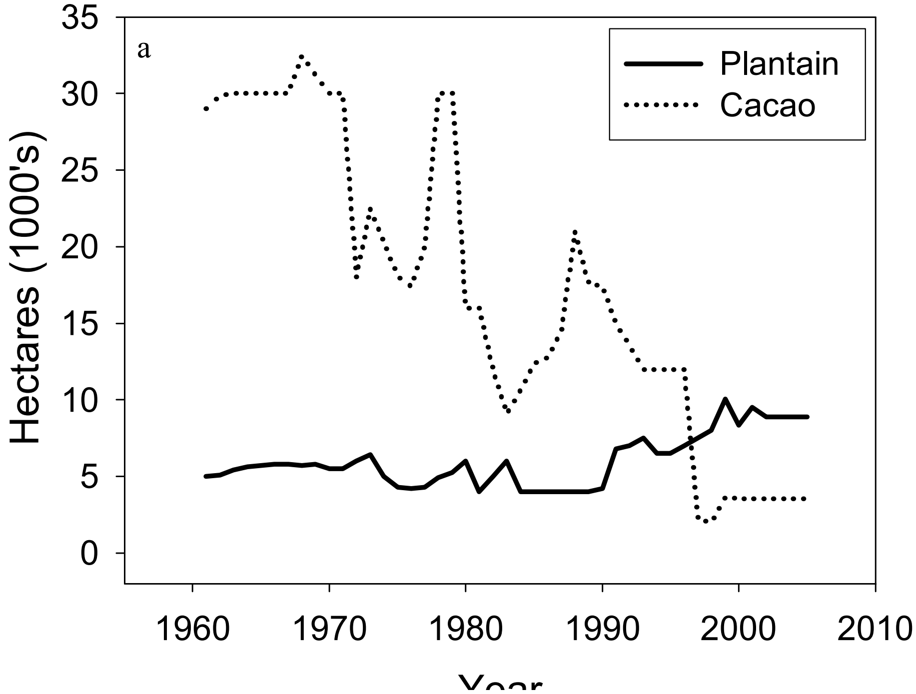


Figure 1.2. a) Area in Costa Rica harvested for plantain and cacao. b) Costa Rican production volume of plantain and cacao.

(Source: FAO databases, http://faostat.fao.org)



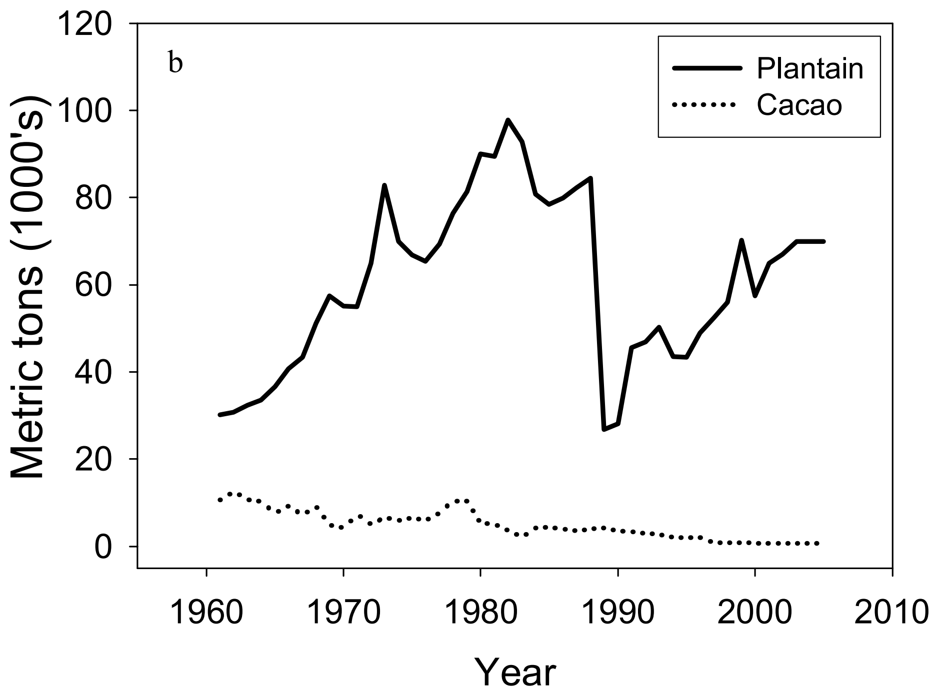


Figure 1.3. Shifts out of cacao agroforestry systems for household parcels whose management began with cacao agroforestry systems in 8 communities in Talamanca.

Thicker lines reflect more common land use pathways. Numbers of plots are in parentheses. AFS = agroforestry systems. 'Other' includes tubers, fruit trees, and home gardens. Source: Whelan 2005.

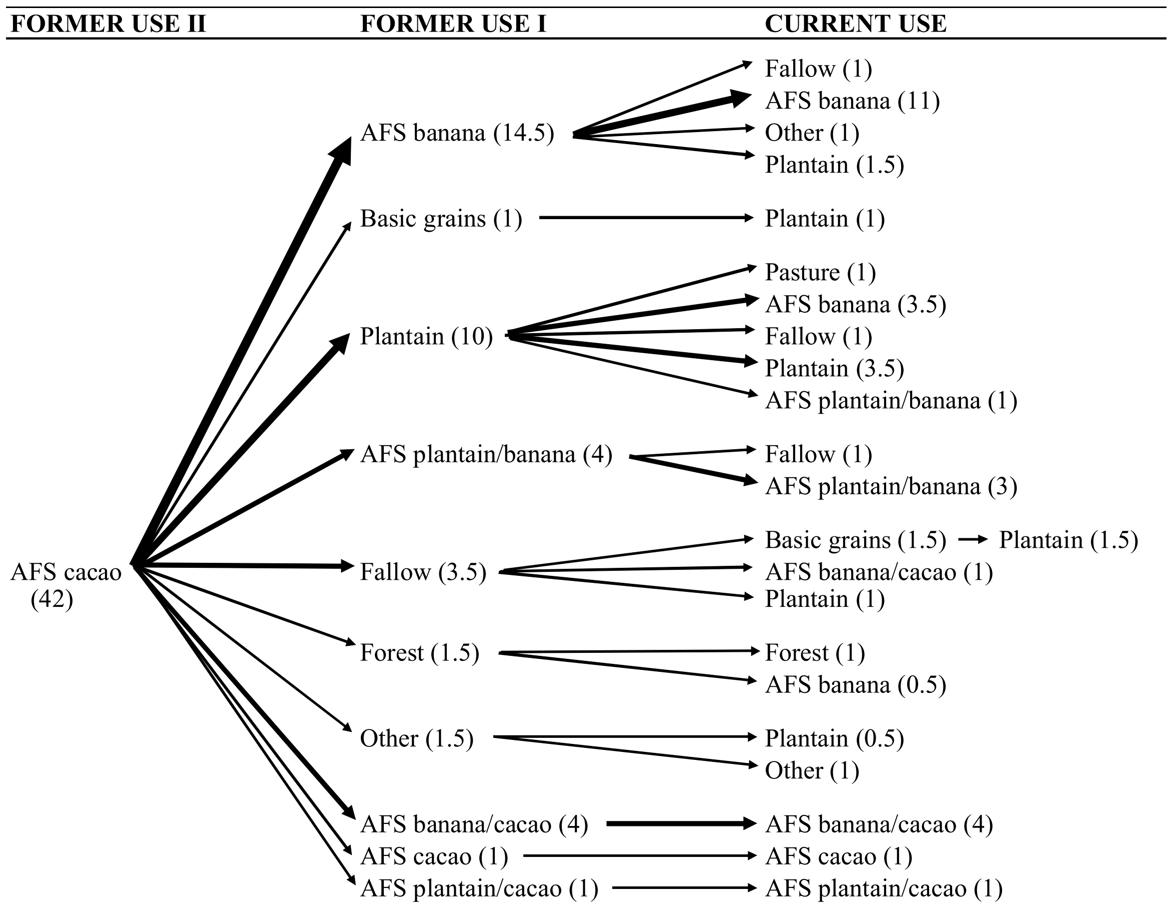


Figure 1.4. Factors influencing abandonment and conversion of cacao agroforestry systems in Talamanca.

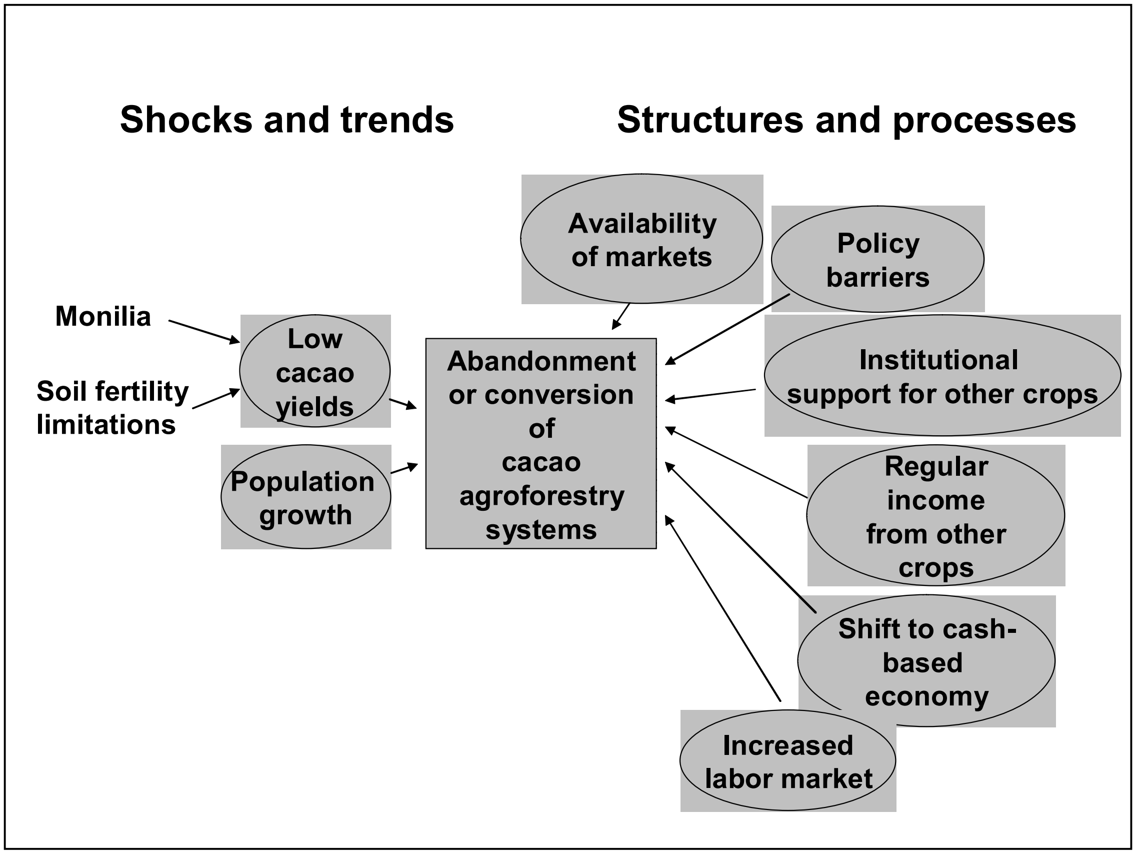
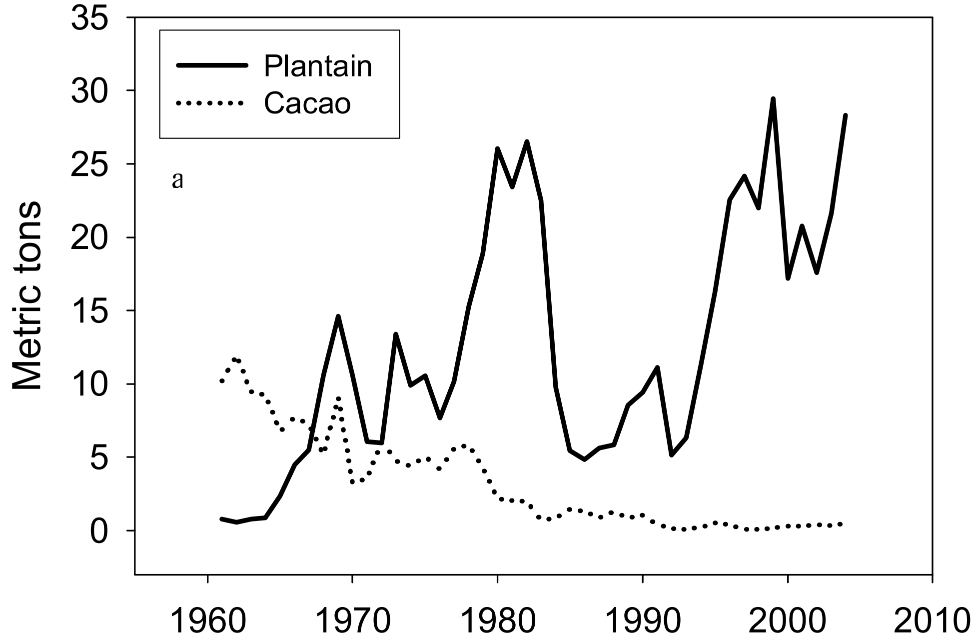


Figure 1.5. a) Volume of annual Costa Rican exports of plantain and cocoa beans. b) Value of annual Costa Rican exports of plantain and cocoa beans.

(Source: FAO databases, http://faostat.fao.org)



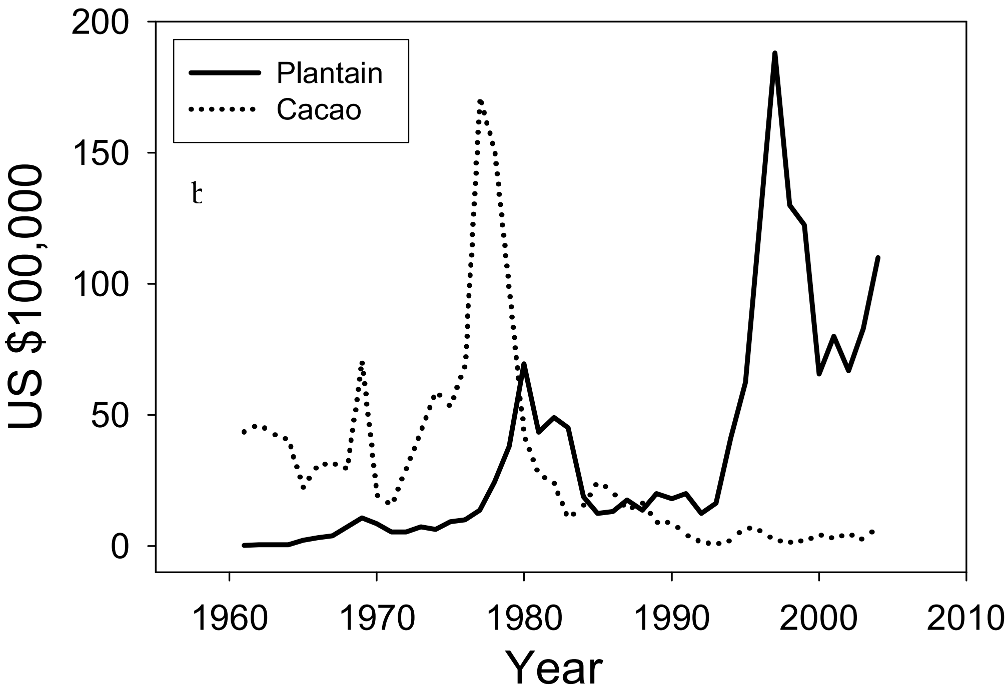


Figure 1.6. International cocoa bean prices.

(Source: International Cacao Organization, http://www.icco.org/menustats.htm).

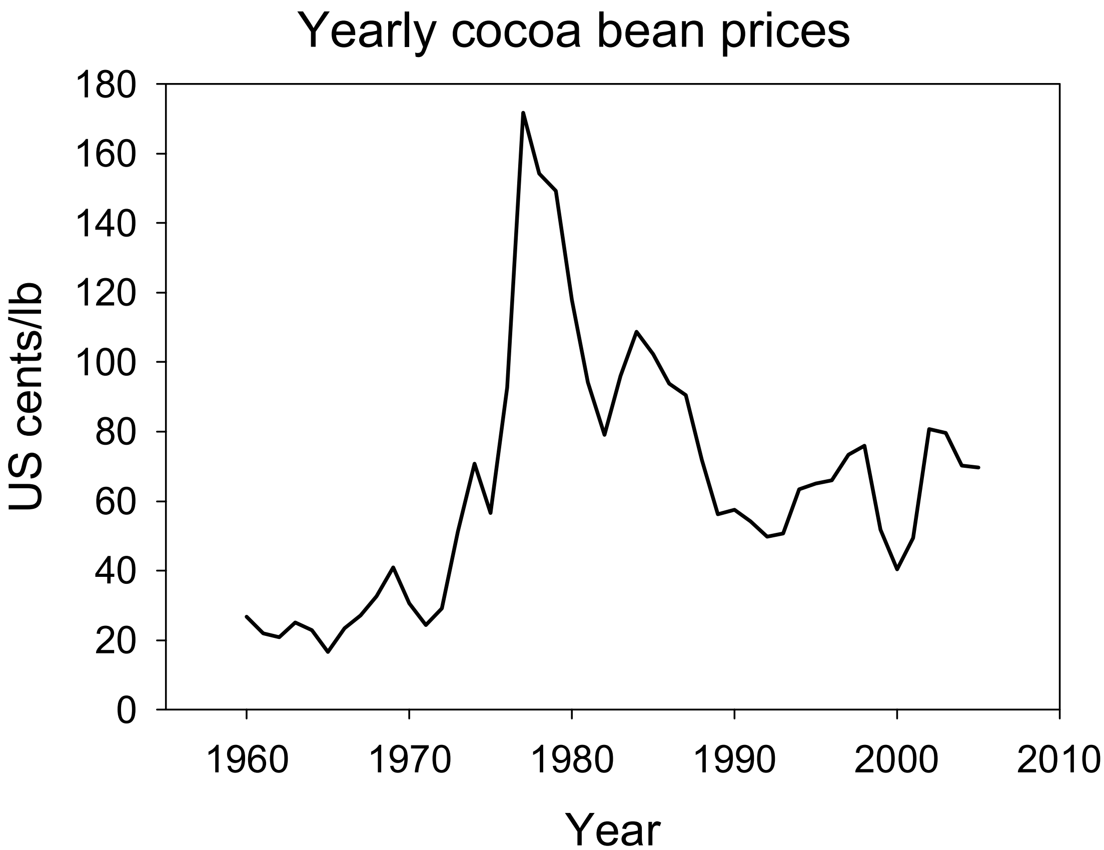
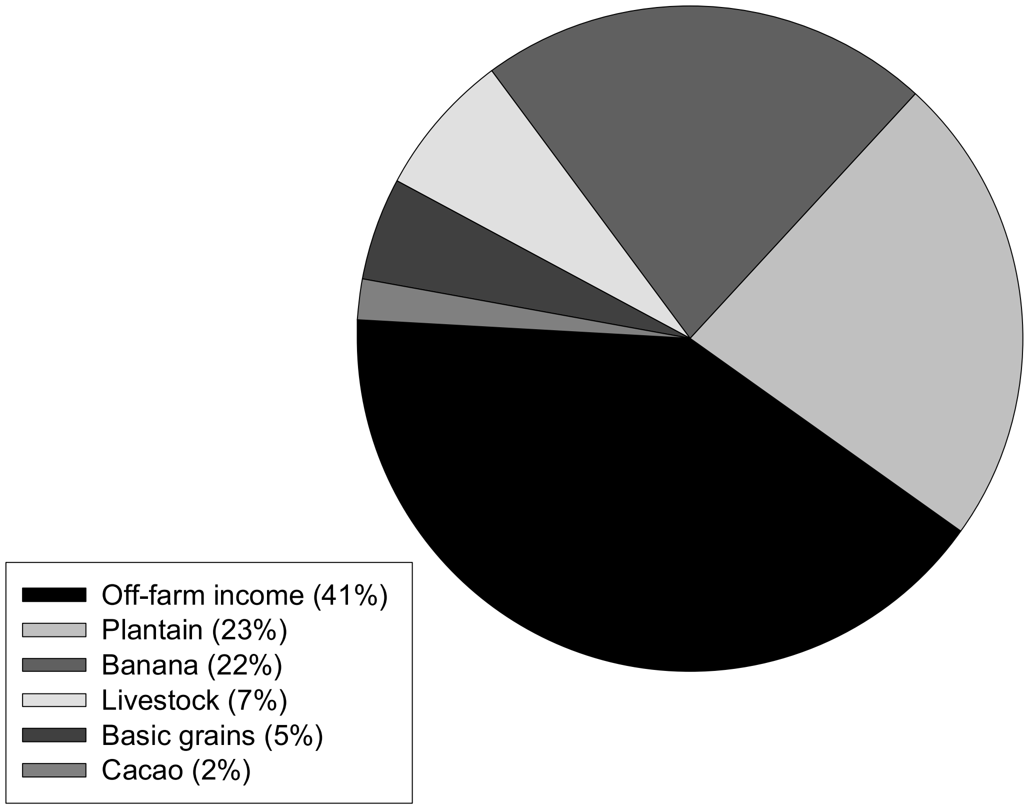


Figure 1.7. Household responses to the question: What are important income sources for your household?



Chapter 2: A rapid rural appraisal of pest management practices in plantain and organic banana production and cost-benefits of plantain production in the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica

Abstract

The use of pesticides in the cultivation of cash crops such as banana and plantain is increasing, in Costa Rica and worldwide. Agrochemical use and occupational and environmental exposures in export banana production have been documented in some parts of Central America. However, the extent of agrochemical use, agricultural pest knowledge, and economic components in plantain production are largely unknown in Costa Rica, especially in remote, high-poverty areas such as the Bribri-Cabécar Indigenous Territories. Our objective was to integrate a rapid rural appraisal of indigenous farmer pesticide application practices and pest knowledge with a cost-benefit analysis of plantain production in the Bribri-Cabécar Indigenous Territories, for the development of better agricultural management practices and improved regulatory infrastructure. Interviews conducted with 75 households in 5 indigenous communities showed that over 60% of participants grew plantain with agrochemicals. Of these plantain farmers, over 97% used the insecticide chlorpyrifos, and 84% applied nematicides, 64% herbicides, and 22% fungicides, with only 31% of participants reporting the use of some type of protective clothing during application. The banana weevil (*Cosmopolites sordidus* Germar) was ranked as the most important agricultural pest by 85% of participants, yet only 28% could associate the adult and larval form. A cost-benefit analysis conducted with a separate group of 26 plantain farmers identified several national markets and one export market for plantain production in the Indigenous Territories. Yearly income averaged $6,200/ha and yearly expenses averaged $1,872/ha, with an average cost-benefit ratio of 3.67 for plantain farmers. Farmers applied an average of 9.7 kg a.i./ha/yr of pesticide products and 375 kg/ha/yr of fertilizer, but those who sold their fruit to the national markets applied more nematicides, herbicides, and fertilizers than those who sold primarily to export markets, suggesting a lack of appropriate application knowledge. Results indicate that the quantity of agrochemicals applied in plantain cultivation is less than that applied in export banana, but the absence of appropriate agrochemical

application practices in plantain cultivation may pose serious risks to human and environmental health. Culturally appropriate farmer education and certification programs are needed as well as the development of safe-handling practices, regulatory infrastructure, and adequate agrochemical storage, transport, and waste disposal facilities. Long-term solutions however, are dependent on the development of policies and infrastructure that support non-chemical pest management, alternatives to pesticides, and the identification of organic plantain markets.

Introduction

Agricultural production worldwide has been accompanied by continuous growth in the number and quantity of agrochemicals applied to crops (Carvalho 2006). This trend is increasingly evident in Central America, where pesticide use has essentially doubled during the past 20 years from an estimated 30,000 tons of active ingredients applied annually in the 1980s to over 57,000 tons by 1999 (Wesseling et al. 2001a, Wesseling et al. 2005). In 2000, Costa Rica ranked second in the world in pesticide use, applying an average of 52 kg a.i./ha, and fourth in the world in fertilizer use with 385 kg/ha (World Resources Institute 2007). In 1998, over 18,000 metric tons of formulated agrochemicals were imported into Costa Rica, representing an estimated 280 different pesticides and sold under approximately 2,000 different brand names (de la Cruz and Castillo 2003). More than one-third of these agrochemicals in Costa Rica are used on banana and plantain production (Castillo et al. 2000). Banana and plantain (*Musa* spp.) comprise over 25% of Costa Rica's foreign exchange (Hernandez et al. 2000), contributing to substantial income generation and employment opportunities in both local and national economic sectors. Costa Rica is currently the second largest exporter of bananas in the world, exporting 95% of over 2.2 million metric tons of bananas produced annually, and the fourth largest exporter of plantains in the world, exporting over 40% of 70,000 metric tons of plantain produced annually (FAO 2007).

Pesticide use is associated with environmental contamination and human health problems worldwide (Lacher and Goldstein 1997; Dinham and Malik, 2003, Maroni et al. 2006). A number of human and environmental poisonings have been documented in commercial banana plantations in Costa Rica and Central America (Castillo et al. 1997, Castillo et al. 2000, Sass 2000, Wesseling et al. 2001b, Wesseling et al. 2005). Although increased documentation and research on agrochemical use in banana plantations are still badly needed, the need is even greater for such information relevant to plantain cultivation. No studies are known regarding pesticide use on plantain farms in Costa Rica, despite the fact that export quality plantain production in Costa Rica roughly follows the same agrochemical regime as commercial banana.

Agricultural lands in the Sixaola River Valley, located in the Talamanca region of southeastern Costa Rica, provide 52% of the plantain, 90% of the organic banana, and 6% percent of the commercial banana production in Costa Rica (Municipality of Talamanca 2003). Both plantain and banana have had a profound impact on the economy and environment of this poorest region of Costa Rica, and currently constitute the primary source of income for area residents either as revenue directly generated from household farms or as wage labor on commercial plantations (Borge and Castillo 1997, Dahlquist et al. 2007). Commercial banana production is limited to approximately 3,000 ha along the lower portions of the Sixaola River, where bananas for export are grown on large-scale plantations with intensive, prescribed agrochemical applications of up to 45 kg a.i./ha/yr (Hernandez et al. 2000, IRET 2000, de la Cruz and Castillo 2003). Unlike banana, where the majority of fruit is exported, plantain is grown for both national and international markets (FAO 2007), with varying intensities of agrochemical applications based on technology and knowledge adopted from commercial banana production. Commercial banana and plantain production relies on fungicides for control of black sigatoka (*Mycosphaerella fijiensis* Morelet), as well as herbicides for weed control, combination insecticide-nematicides for control of the banana weevil (*Cosmopolites sordidus* Germar) and nematodes (*Radopholus similis* (Cobb) Thorne, *Heliotylenchus multicinctus* (Cobb) Golden, *Meloidogyne* spp., and *Pratylenchus* spp.), and insecticide-impregnated bags covering the fruit for control of thrips (*Chaetanaphothrips orchidii* Moulton, *C. signipennis* Bagnall) that cause cosmetic damage on the fruit peel.

Within the Bribri-Cabécar Indigenous Territories, banana and plantain are grown primarily on the extensive, agriculturally-rich floodplain of the upper Sixaola River Valley, in small-scale household farms that range from organic banana and plantain in mixed agroforestry systems, to monocultures with moderate agrochemical use (Dahlquist et al. 2007). Plantain has historically been part of subsistence production in the Bribri-Cabécar Indigenous Territories, and was not grown for export until the late 1980s (Villalobos and Borge 1998). With the highest concentration of poverty in Talamanca occurring within the Indigenous Territories (Municipality of Talamanca 2003), plantain has quickly become an important cash crop and much needed source of income for indigenous farmers. In the Indigenous Territories, historical cropping systems such as the cultivation of basic grains, cacao agroforestry systems, and traditional fallows are rapidly being abandoned in favor of monoculture plantain cultivation for national and export markets (Dahlquist et al. 2007). During the past 20 years, plantain cultivation in Talamanca has increased from 1,270 ha of plantain in production in 1981 (Somarriba 1993) to over 6,600 ha in 2001 (Municipality of Talamanca 2003), representing a significant land-use change in the region.

Little is known about agricultural pest management and agrochemical use within the Bribri-Cabécar Indigenous Territories. No information exists on the intensity and frequency of pesticide applications, pesticide costs, market options, or farmer knowledge of agrochemical alternatives and pest biology. Farmers within the Indigenous Territories have few economic resources and poor access to health and educational facilities, including agricultural extension services. Legislation regulating pesticide use is absent within the Indigenous Territories. These factors have been associated with a high incidence of environmental and human poisonings in other areas (Aragon et al. 2001, Hurtig et al. 2003, Konradsen et al. 2003, Karlsson 2004). Our objectives were to determine the extent of agrochemical use and agricultural pest knowledge in banana and plantain cultivation as well as the costs and benefits of plantain production for Bribri-Cabécar Indigenous farmers. This information is essential for any further research, conservation programs, or rural development efforts in the Indigenous Territories as well as for the development of national and regional public health and agricultural management initiatives.

Methods

Our work integrates two different studies conducted within the Bribri-Cabécar Indigenous Territories from 2004 to 2006: a rapid rural appraisal of plantain and organic banana production and integrated pest management practices, and a cost-benefit analysis of plantain production. Both studies were based on participatory methods (Mikkelsen 1995) for integration into larger biophysical research projects on integrated pest management and ecological risk assessments for pesticide use.

2004 Rapid Rural Appraisal

A rapid rural appraisal (RRA) of 75 households was conducted from June-August 2004 in five banana- and plantain-growing communities (Shiroles, Amubri/Tsuidi, Sepeque, Gavilán Canta, and Boca Urén) located on the extensive floodplain within the Bribri-Cabécar Indigenous Territories. Methods included semi-structured interviews, participant observation, transect walks, and informal discussions with key informants and farmers (Mikkelsen 1995). Organic banana farmers were included since organic banana is often grown in agroforestry systems that include plantain. In each of the five communities, 15 families that cultivated plantain, organic banana, or both were randomly selected and interviewed with the assistance of two local indigenous assistants. Interview questions covered subjects such as plantain and banana management and pest control techniques, farmers' knowledge and attitudes regarding the pest status of the banana weevil and the effectiveness of control methods, the amount, type, and frequency of pesticides used for plantain production, methods of pesticide handling and storage, protection used during application, health effects experienced, and why farmers chose to use or not use pesticides.

2006 Plantain Cost-Benefit Analysis

Twenty-six monoculture plantain farmers from the primary plantain-producing communities of Shiroles and Sepeque participated in a study of the costs and benefits of plantain production within the Indigenous Territories. With the aid of local agricultural extensionists, farmers were asked to report all sources of income from their plantain production, including the different national and export markets that they sell their fruit to each week. Farmers were then asked to list all costs associated with their plantain farms including the type and quantity of agrochemicals used, equipment rented, workers paid, and transportation costs. Comparisons of total income generated and total costs expended per hectare per year were then calculated with farmers to help them determine the financial status of their plantain production.

Data Analysis and Triangulation

For both datasets, interview data were coded and summary statistics were calculated. Where open-ended questions were used, responses were aggregated by topic and the percentage of participants mentioning each topic was calculated. A Kruskal-Wallis test of variance and simple linear regression were conducted to determine significant relationships and correlations among farmer demographics and pesticide use. One-way analyses of variance (ANOVA) at the 95% confidence level were used to test for significant differences among different farmer groups in the cost-benefit analysis. Amount of fertilizer was calculated based on the combined elemental composition of the two most widely used products, urea (46% N) and a complete N-P-K formula (10-30-10% respectively). Active ingredients for pesticides were calculated based on those product formulations available in the Bribri-Cabécar Indigenous Territories. The active ingredient value for insecticide-impregnated plastic bags was obtained from IRET (2000), and represents the amount of chlorpyrifos per hectare calculated by weight from the number of impregnated plastic bags on banana plants spaced at 2 m x 2 m per hectare.

All data gained through literature review and interviews were triangulated through both participant observation and group discussions (Mikkelsen 1995). Participant observation included living with community members, informal conversations with indigenous farmers and other household members, participating in household and farming activities, and observations from personal experience through working in the Indigenous Territories (Dahlquist et al. 2007). Several group discussions for feedback were held after each study for reiteration and confirmation of gathered datasets.

Results

Rapid Rural Appraisal (RRA)

The average RRA participant was 40 years old and possessed a US-equivalent education of 4^{th} grade. Participants represent approximately 20% of households in the floodplain of the Bribri- Cabécar Indigenous Territories (Yepez 1999, InBio 2007). Sixty percent of participants interviewed grew plantain in monoculture, with an average holding of 2.75 ha. The remaining 40% did not grow plantain or grew it in combination with certified organic banana in mixed agroforestry systems (averaging 1.5 ha), in which agrochemical use is not allowed. Plantain in these organic agroforestry systems is generally grown for household use as no market currently exists for organic plantain in Costa Rica. Twenty-four percent of respondents had both monoculture plantain farms as well as separate organic agroforestry banana or plantain farms. All participants combined represented a total of 123 ha in monoculture plantain and 70 ha in organic banana or mixed organic banana and plantain agroforestry systems, with overall farmer holdings in banana or plantain averaging 2.5 ha. Thirty-nine percent of participants were female land-owners who cultivated an average of 2.10 ha of plantain or banana, compared to an average of 2.95 ha cultivated by male land-owners. Land holdings were not found to be significantly different between male and female landowners. In Bribri-Cabécar society, women are often the head of household, and land ownership has traditionally been matrilineal with land passing from mother to daughter (Villalobos and Borge 1998). However, we observed a difference in farm management between older and younger women. While older women work on their own farms and answered our interview questions about management practices themselves, younger women tended to refer these questions to their husbands. Even though the younger women were still the official owners of the land, the men were the ones working on the farm. This pattern was strongest in plantain-growing households, where the men were generally responsible for applying pesticides.

When asked to name the most important agricultural pest on their farm, over 85% of RRA participants placed the banana weevil as the first or second most important pest, and 57% of respondents ranked black sigatoka as the first or second most important agricultural pest (Table 2.1). Other pests of banana and plantain were described less frequently by participants, including Panama disease (causal agent *Fusarium oxysporum* Schlecht *f. sp. cubense*), nematodes, palm weevils (*Rhynchophorus palmarum* L.), parrots, and thrips. The banana weevil was mentioned most frequently as the most important pest, and mentioned at least once by 94.7% of participants. However, only 28% of respondents recognized the relationship between the adult and larval stages of the banana weevil life cycle, and over 20% of respondents indicated the banana weevil was the same as nematodes or other non-pest beetles or weevils present in their farms (*Alegoria dilatata* LaPorte, *Polytus mellerborgii* Boheman).

The most commonly used control method for banana weevil mentioned by participants was application of nematicides with insecticidal activity, used by 46.6% of participants. Cultural control methods were used by 16% of participants. Cultural control methods include the removal of debris and weeds from the base of the mat, desuckering, removal or destruction of rotted stems, and weeding by machete. Pseudostem traps were used by 9.3% of participants. These traps are constructed of two pieces of fresh banana or plantain stem cut lengthwise and then placed on top of each other in the field to attract weevils away from nearby plants (Gold et al. 2002). The jabillo or sandbox tree (*Hura crepitans* L.) was used by 5.3 % of participants. Jabillo latex has been used historically by the Bribri and Cabécar as a fish poison. It contains the piscicidal compound huratoxin (Sakata et al. 1971) and several other toxic compounds which could have insecticidal activity (Barbieri et al. 1983, Stirpe et al. 1983). The latex is extracted from the bark and mixed with water to make a botanical insecticide, which is applied to the base of the banana mat as a drench. Pheromone traps were not used, but mentioned as a previously available control by 12% of participants. These traps contain a lure with the aggregation pheromone of the banana weevil, which is produced in Costa Rica (Ndiege et al. 1996). The remaining 32% of respondents did not use any control method for the banana weevil.

A summary of the range of range of pesticide use regimes used on plantain farms in Talamanca compared to that of commercial banana is shown in Table 2.2. In Talamanca, the majority of intensive plantain, where pesticide applications are estimated to reach 15 kg a.i./ha/yr (IRET 2000), occurs outside the Indigenous Territories just upstream from commercial banana plantations in plantain cooperatives that sell export-quality fruit to multinational corporations. Within the Bribri-Cabécar Indigenous Territories, the majority of plantain production can be considered to be moderate to low-intensity, with most farmers applying only a few types of pesticides, less frequently, and primarily only when they can afford to do so. Almost all participating farmers (97.8%) with monoculture plantain holdings reported using insecticide-impregnated plastic bags to cover their fruit during maturation (Table 2.3). These bags are used in banana- and plantain-producing regions throughout Costa Rica, and are impregnated with 1% chlorpyrifos by weight to protect the fruit from cosmetic damage to the peel caused by thrips. As there are no facilities or infrastructure in place in the Bribri-Cabécar Indigenous Territories to accommodate the disposal of agrochemical waste such as used insecticide-impregnated bags and empty pesticide containers, participants were asked what they did with the used plastic bags. Over 52% of respondents reported burying them, 30.5% reported burning them, and 5.5% reported either burning or burying the used bags after use. However, approximately 11% of respondents reported recycling the bags, which after triangulation with community groups proved to be an option that was only available for a few years in the late 1990s when for a short period of time bags were recycled by a now defunct plantain farmer cooperative.

After the insecticide-impregnated bags, nematicides are the most commonly used pesticide in indigenous plantain production, applied by about 85% of participants with monoculture plantain holdings (Table 2.3). Nematicides with insecticidal activity are applied primarily during planting by over 80% of respondents, and by over 50% of respondents when the plants are maturing to control the banana weevil. Thirty-one percent of participants reported applying nematicides, both during planting and afterwards around the base of the plant. The most commonly used nematicide is terbufos (Counter®), followed by oxamyl (Vydate®), and then ethoprofos (Mocap®). Herbicides, most commonly glyphosate (Round-up®) and more recently paraquat and diuron (combined in the product Biomorun®), are used by approximately 64% of participants with monoculture plantain. Many indigenous farmers also mentioned manually weeding their fields with machetes, and only applying herbicides once or twice a year when they could afford it. Fungicides to control black sigatoka were reported to be used by only 22% of participants, as they are relatively expensive for most small-scale farmers. Although a great number of fungicides exist in Costa Rica for use in commercial banana, the only fungicides found to be available in the Indigenous Territories are propiconazole (Tilt®), and more recently difenoconazole, which is also commonly referred to as Tilt. Finally, only one-third of participants reported using some type of protective clothing during pesticide application. Protective clothing during application is defined as the use of full-length clothing that covers arms and legs and is changed immediately after application, the use of gloves, and covering the face with clothing or a mask during fumigation applications. After triangulation with community members, this percentage may be inflated, as many indigenous plantain farmers, including those who reported wearing protective clothing, in practice prefer not to apply their own pesticides. If farmers can afford it, they prefer to hire unskilled laborers for this service, who are usually young men in the community who do not own land.

When asked the open-ended question about what they thought about pesticides, over one-third of all participants responded that they damage the land. In other responses, 9% said that pesticides were too expensive to use, 13.3% reported that they give a better product, and 17.3% responded that they cannot use pesticides because of proximity to their own or their neighbor's certified organic banana holdings. Interestingly, the remaining one-quarter of respondents chose not to answer this question. This may be due to the fact that pesticide use in the Bribri-Cabécar Indigenous Territories is still considered "taboo" or a forbidden subject, as indigenous leaders often assert that there is no pesticide use in the Indigenous Territories in order to maintain a public image based on exclusively organic production. In a Kruskal-Wallis or Chi-Squared test of variance at the 95% confidence level, age and amount of land were significantly related ($p < 0.05$) to higher pesticide use, with younger participants and larger landowners using more agrochemicals than older or smaller landowner participants. However, no significant relationships were found among pesticide use and participants' educational level, control methods used, gender, or banana weevil knowledge.

Plantain Cost-Benefit Study

In a follow-up cost-benefit study of Bribri-Cabécar farmers with monoculture plantain holdings, farm holdings were similar to those observed in the RRA conducted two-years earlier, with participants reporting monoculture plantain farms ranging from 1 to 5 ha in size with an average farm size of 2.8 ha. In this subset of only monoculture plantain farmers from two of the five communities surveyed in the previous RRA, one-fourth of participants were female land-owners who cultivated an average of 2.57 ha of plantain, compared to an average of 2.83 ha cultivated by male land-owners. In terms of pesticide use, approximately 98% of plantain farmers in the cost-benefit study reported using chlorpyrifos-impregnated bags and 80% reported applying nematicides, fungicides, and herbicides. In addition, 100% of cost-benefit participants reported applying fertilizer. Compared to the 2004 RRA study shown in Table 2.3, the 2006 cost-benefit study participants reported higher fertilizer use, as well as increased fungicide and herbicide use. This is likely due to the fact that the 2006 cost-benefit study was conducted in two of the largest towns within the Indigenous Territories, which have a wealthier population, increased access to agrochemicals, and more available plantain markets compared to other three more remote and relatively poorer areas of the Territories that were included in the broader 2004 study. In this study of plantain market values and associated agrochemical use, all participating farmers reported selling their plantains to at least two different markets, with some farmers selling their fruit to as many as four different markets. Currently, there are five different options for selling plantain in the Bribri-Cabécar Indigenous Territories: one option to sell to the export market and four different options for selling to national markets. In general, farmers aspire to sell their best fruit (based on maximum finger length, bunch weight, and cosmetic appeal) to the export market because it commands the highest and most consistent price per plantain plant or fruit bunch. In each farm, however, bunches that do not meet length and weight requirements for the export market are sold to the next best national market buyer. The different national markets roughly correspond to four different classes of medium to low fruit quality, the lowest of which must be peeled and bagged by the farmer before purchase. Overall, 60% of participating farmers, hereafter referred to as "export producers," primarily sell their plantains to the export market, boxing their own fruit for buyers to collect. These export producers then sell their "leftovers" or lower quality fruit to one or more of the national markets depending on the fruit size and quality. The other 40% of participating farmers, referred to as "national producers," sell their fruit exclusively to the one or more national markets.

A breakdown of farm age, gross income, expenses, and agrochemical use in monoculture plantain cultivation is shown in Table 2.4. Participating farmers reported a wide-range of different farm ages, which refers to the age of planting material or plantain root stock. However, export producers as a group tended to have slightly younger-aged farms compared to national producers. Yearly gross income from all markets averaged $6,307/ha for all producers, with no significant differences between national producers ($6,505/ha) and export producers ($6,183/ha). Total average yearly expenses were also similar between export ($1,840/ha) and national ($1,925/ha) producers. From these, the average benefit-cost ratio for all participating farmers was calculated to be 3.67, although the range was from 1.45 to 7.8. Average yearly expenses include costs of agrochemical inputs, hired labor, transportation, rental equipment, and fuel. For all producers, yearly agrochemical inputs alone averaged $380/ha for fertilizers and $368/ha for pesticide products. Export producers sold an average of 482 kg/ha/week of fruit, with approximately 59% of their production going to the export market. Similarly, national producers sold an average of 461 kg/ha/week to one or more of the available national market buyers. Agrochemical use varied widely among participating farmers, with fertilizer use averaging 375 kg a.i./ha/yr and total pesticide use averaging 9.7 kg a.i./ha/yr. As a group, national producers reported using more fertilizer and more pesticides per hectare per year than export producers.

Discussion

Results from both studies highlight the need for improved agricultural pest knowledge, agrochemical management, and infrastructure as well as the identification of low-cost alternatives to pesticide use and the development of profitable organic plantain markets. With the exception of those farmers who have worked on commercial banana plantations or in plantain cooperatives outside the Indigenous Territories, many indigenous farmers apply agrochemicals based on knowledge gained from their neighbors or from the middlemen who buy their fruit (Polidoro and Dahlquist, unpublished observation). Gaps in knowledge obtained through these avenues may decrease the efficiency and safe-handling of pesticide applications. For example, nematicides with insecticidal activity are used in commercial plantations for both nematode and banana weevil control. However, indigenous farmers apply them primarily for banana weevil control as most do not have any knowledge of nematodes and cannot identify the signs of nematode damage. Only 10 % of RRA participants even mentioned nematodes, although high levels of *R. similis* infestations, up to 15,789 nematodes/100 g of root tissue, have been reported in plantain farms in the Indigenous Territories (Meneses Hernández 2003).

In other studies on agricultural pest knowledge in maize-bean-squash polycultures (Morales and Perfecto 2000) and rice (Joshi et al. 2000), farmers mentioned larger, more visible pests more frequently and gave them a higher ranking compared to agricultural pests that are less visible. This was also the case in a participatory rural appraisal of constraints to plantain production in Ghana, in which farmers perceived the banana weevil to be more important than less visible pests (Schill et al. 2000). Since nematodes are microscopic and observation of damage may require dissection of roots, it is not surprising that many farmers in our study were unaware of nematodes in their farms. Also, some farmers indicated that they applied nematicides when they saw other, non-pest insects such as earwigs, centipedes, or beetles similar in size and color to the banana weevil. Other studies (Dinham 2003) have also found that farmers who could not identify agricultural pests sprayed more often when they saw other insects. Thus, many farmers in the Indigenous Territories may be over-applying nematicides for banana weevil control or under-applying them for nematode control.

Nematicide use, however, in the Indigenous Territories is generally high, with some national producers applying nematicides up to six times a year, or twice that of commercial banana production. The purchase of fruit for both national and export plantain markets occurs through middlemen operating in the Indigenous Territories. These middlemen also provide farmers with tools and agrochemicals and later deduct their cost from the farmer's plantain sale (Whelan 2005). Export producers in the Bribri-Cabécar Indigenous Territories are linked with middlemen connected to the export plantain cooperatives. By contrast, national producers sell their fruit for the best price to whichever middleman is available in their area, who often have a higher turnover in staff, routes, and pricing schemes, and are less consistent than the export middlemen in their ability to provide agrochemicals, knowledge, or resources (Madrigal-Aguilar and Morales-Carbonell 1995). The cost-benefit study found that national producers as a group are applying fertilizers, nematicides, and herbicides more frequently and in higher quantities than export producers without any significant production or financial benefits. This higher application of agrochemicals is likely a consequence of a lack of appropriate pest or agrochemical use knowledge.

Pesticide handling practices in the Indigenous Territories are another area of concern. The majority of indigenous farmers do not use any protective clothing during pesticide application, and many application practices observed in the Indigenous Territories pose serious health risks to the applicators. Of most concern are nematicides and insecticides, as they include extremely toxic organophosphates and carbamates known for both chronic and acute poisonings in a variety of agricultural settings (Wesseling et al. 2002, de Silva et al.

2006). Over 97% of indigenous plantain farmers place chlorpyrifos-impregnated bags over large portions of their farm every week by hand, receiving prolonged organophosphate dermal and inhalation exposure. The nematicides terbufos and ethoprofos used by approximately 80% of plantain farmers are granulated organophosphates applied to the soil with bare hands or from an empty tuna can without any form of protection or gloves (Polidoro and Dahlquist unpublished observation). The less-frequently applied nematicide oxamyl is a liquid-formulated carbamate that is mixed with water, usually in a 55 gallon drum, after which plantain seedlings are dipped by hand into the mixture before planting, or it is sprayed with a manual sprayer onto the stems of maturing plants to protect against the banana weevil. Although not quantified, many RRA participants reported symptoms of pesticide exposure including nausea, headache, and rash (Wesseling et al. 2002) when applying agrochemicals, particularly the chlorpyrifos-impregnated bags.

In Talamanca and around the world, damaged or leaky backpack sprayers constitute a major source of pesticide exposure to rural farmers (Mekonnen and Agonafir 2002, Matthews et al. 2003). As opposed to the application of fungicides by airplane in commercial banana plantations, which is host to other drift and runoff problems (Hernandez and Witter 1996), fungicides in the Indigenous Territories are applied by motorized backpack sprayer. With this technique, the applicator sprays the fungicides directly overhead from side to side, inevitably receiving some portion of the falling spray. In addition, farmers are generally unaware of re-entry times after spraying. Other hazardous practices include unsafe transport of agrochemicals and improper storage in households or in the field. Children may be most at risk (Cantor and Goldman 2002), as they often work with or around pesticides on farms with relatives even though the minimum legal age to work with or apply pesticides is 18 years in Costa Rica (de la Cruz and Castillo 2003).

In the Indigenous Territories there are no known mechanisms in place to regulate the application, formulation, sale, transport, or storage of agrochemicals. The lack of infrastructure for dealing with agricultural waste is cause for additional concern. The amount of waste generated in commercial banana production including used plastic fruit bags, rejected fruit, and discarded cut stems, crown and flowers is estimated to be 52 tons per 100 tons of exported fruit (Hernandez et al. 2000), with some of the organic waste deposited in compost fields and most of the plastics recycled. In the Indigenous Territories, however, there are no available composting or recycling facilities to absorb agricultural waste. Used pesticide containers are often rinsed out in the river and left in the field or reused in the household. Used plastic fruit bags are generally either burned or buried, but are often thrown out or washed in rivers (Polidoro and Dahlquist unpublished observation). The solid waste generated by the amount of plastic bags used in banana and plantain production is estimated to be a staggering 67 kg ha/yr (Russo and Hernandez 1995). Recycling options exist in Costa Rica, but lack of transport and means for organized collection within the Indigenous Territories has prevented the used bags from getting to recycling plants.

There is a pressing need for alternatives to pesticide use in the Indigenous Territories. As no market currently exists for organic plantain either in Costa Rica or internationally, alternatives to pesticides must provide similar or better fruit yield and quality standards, as well as equal or increased financial benefits, as currently obtained from fruit grown with pesticides. Alternatives exist, but further efforts are needed to evaluate their efficacy for pest control and to develop the infrastructure to make them available to farmers. For example, white bags made of either plastic or cloth and containing no insecticide are currently in use to reduce cosmetic damage on organic banana sold as fresh fruit to national grocery chains (Asociación de Pequeños Productores de Talamanca (APPTA) personal communication). A potential alternative to fungicide application for black sigatoka control is an effective microorganism (EM) product developed by EARTH University in Guápiles (Tabora et al. 2006). Pesticide alternatives for nematode control within the Indigenous Territories are more limited (Stoorvogel and Vargas 1998). Sterilization of planting material with hot water is a cultural control that has been used in Latin America, but the danger of over-cooking the sucker exists (Sarah 1998). Preliminary ressearch has been conducted to isolate endophytic fungi for biological control of nematodes (Meneses Hernández 2003), but much further work is necessary before this will be a viable control method. Effective microorganism products such as “Nemout” and fermented organic matter (Bokashi) are also being developed at

EARTH University for nematode control (Tabora et al. 2006). RRA participants mentioned several alternatives for banana weevil control: pseudostem traps, cultural control, jabillo latex used as a drench, and pheromone traps. Pseudostem trapping is extremely labor-intensive, as it requires setting traps at the base of each mat and maintaining them every 3 to 5 days (Gold et al. 2001). The effect of cultural control or general farm sanitation on banana weevil populations in Costa Rica is unknown, although a study conducted in Uganda found that destruction of crop residues every 1-2 weeks decreased weevil populations and damage levels (Masanza et al. 2005). The application of jabillo latex is a convenient local resource. However, participants commented that working with the latex is unattractive because of its skin and eye irritant properties. Pheromone traps used at commercial rates were found to reduce banana weevil damage in plantain farms by one-third after one year of trapping (Dahlquist et al. unpublished). Studies conducted in commercial banana and plantain in Costa Rica also found reductions in banana weevil damage over 10-17 months (Alpizar et al. 2000). These traps are locally available within Costa Rica, but an evaluation of costs and benefits is needed to determine their economic viability for small farmers.

While many of these alternatives to pesticides are promising, they are outside the market relationships involved in plantain production and there is currently no distributor selling them to farmers. Technology transfer in the Indigenous Territories comes primarily from commercial banana and plantain exporters, and alternatives to pesticides or fertilizers are not part of this process. Adoption of alternatives to agrochemicals in the commercial plantations would likely result in adoption of the same technologies by farmers in the Indigenous Territories. If this does not occur, a separate infrastructure would be necessary to make any viable alternatives available to indigenous plantain farmers.

Conclusion

The range of pesticide application regimes in banana and plantain production in Talamanca reflects the variability in access to available plantain markets, agrochemicals, and resources. In the Indigenous Territories, plantain production clearly provides a much needed source of income; however, increased agrochemical use in plantain was not significantly related to increased production or income. The expansion of pesticide use in plantain production is cause for human and environmental concern. The lack of appropriate agrochemical knowledge and application practices, including the absence of protective clothing, poorly maintained equipment, and the potentially unnecessary over-application of agrochemicals, such as nematicides, may pose serious threats to human and environmental health. Although the overall environmental impact of pesticide applications in moderate to low intensity plantain production is probably less than that documented in commercial banana plantations (Hernandez and Witter 1996, Henriques et al. 1997, Hernandez et al. 2000), it is likely exacerbated by accidental over-applications and unregulated agrochemical use.

Additional research on pesticide routes of exposure, fate, transport, and toxicology is required in Talamanca as many area residents work directly with pesticides to maintain agricultural production on household or commercial farms, as well as rely on river and groundwater resources for consumption, fishing activities, and household use. The Talamanca region of Costa Rica is renowned for its high biodiversity as evidenced by the number of nationally and internationally protected terrestrial, marine, and freshwater areas. Development and enforcement of agrochemical laws to protect human health and reduce environmental contamination is necessary. In the case of Talamanca, efforts should be increased to provide all plantain farmers with culturally appropriate agrochemical and agricultural pest information, including certification programs for pesticide applicators and farmer field schools that emphasize agricultural pest identification and signs of damage. Regional efforts should aim to extend infrastructure for safe agrochemical transport, storage, and appropriate waste disposal into all plantain-producing areas including the Bribri-Cabécar Indigenous Territories. In the long-term however, there is a need to provide effective and low-cost alternatives to chemical pest control, and to develop both national and international organic plantain markets.

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Other Authors

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Table 2.1. Ranking of agricultural pests by rapid rural appraisal participants (N=75)

Pest	Spanish name	Latin name	Individuals mentioning the pest (%)	Individuals ranking pest as most important (%)	Individuals ranking pest as second most important (%)
Banana weevil	Picudo negro	*Cosmopolites sordidus* Germar	94.7	68	18.6
Black sigatoka	Sigatoka negra	*Mycosphaerella fijiensis* Morelet	78.6	28	29.3
Panama disease	Mal de Panamá	*Fusarium oxysporum* Schlecht f. sp. *cubense*	22.7	2.7	6.7
Palm weevil	Picudo del coco; picudo del palmito; picudo grande	*Rhynchophorus palmarum* L.	21.3	5.3	2.7
Nematodes	Nemátodos	*Radopholus similis* (Cobb) Thorne, *Heliotylenchus multicinctus* (Cobb) Golden, *Pratylenchus* spp., *Meloidogyne* spp.	10.7	4	2.7
Leaf cutter ants	Hormigas, zompopos	*Atta cephalotes* L., others	6.9	0	2.7
Parrots	Loros	*Aratinga finschi, Amazona farinosa,* others	6.7	0	1.4
Thrips	Trips	*Chaetanaphothrips orchidii* Moulton, *C. signipennis* Bagnall	4	0	1.4
Moko	Moko	*Pseudomonas solanacearum* EF Smith	2.7	1.4	0
Sugarcane weevil	Picudo amarillo, picudo rayado	*Metamasius hemipterus* L.	10.7	0	0
Small banana weevil	Picudo pequeño, picudo chiquito	*Polytus mellerborgii* Boheman	6.7	0	0
Others*			8.1	0	0

*Each mentioned by 5% or less of participants and not ranked: Erwinia (*Erwinia chrysanthemi*), Lepidopteran defoliators (*Caligo memmon*, *Caligo teucer,* etc.), and bees (*Trigona corvina*, etc).

Table 2.2. Summary of the range of pesticide-use regimes in banana and plantain production in Talamanca, Costa Rica

	Intensive Banana	Intensive Plantain	Moderate Intensity Plantain	Low-Intensity Plantain	Agroforestry Banana and Plantain
Fungicides	**Rotation of Mancozeb, Tridemorph, Bitertanol, and Difenoconazole**	**Rotation of Mancozeb, Tridemorph, Bitertanol, and Difenoconazole**	**Propiconazole OR Difenoconazole**	**None**	**None**
How Applied	Airplane	Motorized hand sprayer	Motorized hand sprayer		
Frequency	Every 8-15 days	3 to 6 times per year	1 to 3 times per year		
Nematicides	**Terbufos and Carbofuran**	**Terbufos or Ethoprofos and Oxamyl**	**Terbufos or Ethoprofos and Oxamyl**	**Terbufos or Ethoprofos**	**None**
How Applied	Manual hand pump	Manual hand pump	Manual hand pump or by hand	By hand	
Frequency	3 times a year (and during seeding)	3 times a year (and during seeding)	1 to 2 times a year (and during seeding)	Only during seeding	
Herbicides	**Glyphosate, Paraquat, Diuron**	**Glyphosate, Paraquat, Diuron**	**Glyphosate, Paraquat, Diuron**	**None**	**None**
How Applied	Manual hand pump	Manual hand pump	Manual hand pump		
Frequency	3 to 6 times per year	3 to 6 times per year	1 to 3 times per year		
Post-Harvest Fungicides	**Imazalil and Thiabendazole**	**Imazalil and Thiabendazole**	**None**	**None**	**None**
How Applied	In packing plant	In packing plant			
Frequency	3 to 7 times/week	3 to 7 times/week			
Insecticides	**Chlorpyrifos**	**Chlorpyrifos**	**Chlorpyrifos**	**Chlorpyrifos**	**None**

How Applied	Bagged fruit	Bagged fruit	Bagged fruit	Bagged fruit	
Frequency	3 to 7 times/week	1-3 times/week	1 time/week	1 time/2 weeks	
Total Active Ingredients	35-45 kg/ha/yr*	10-15 kg/ha/yr*	3-9 kg/ha/yr	<3 kg/ha/yr	None

* Source: IRET 2000

Table 2.3. Characteristics of agrochemical use by rapid rural appraisal participants in monoculture plantain farms

Agrochemical Use (N=45)	Individuals (%)
Insecticide use (plastic fruit bags)	97.8
Nematicide use	84.4
Herbicide use	64.4
Fungicide use	22.2
Fertilizer use	66.7
Nematicide Use (N=38)	
Use during planting	81.5
Apply to plant during maturation	52.6
Use during and after planting	31.5
Use terbufos (Counter®)	42.1
Use oxamyl (Vydate®)	15.7
Use ethoprofos (Mocap®)	7.8
Use a combination of nematicides	34.2

Table 2.4. Summary of benefits, costs and agrochemical use in plantain production

All Producers (N=26)	Min	Max	Average	S.D.
Farm age (years)	2	18	5.0	3.24
Yearly gross income ($US/ha)	1,848	12,646	6,307	2,360
Yearly expenses ($US/ha)	810	3,214	1,872	675
Fertilizer product costs ($US/ha)	126	976	380	220
Pesticide product costs ($US/ha)	0	815	368	218
Fertilizer use (kg/ha/yr)	120	968	375	218
Fungicide use (kg a.i./ha/yr)	0.0	2.6	1.1	0.8
Nematicide use (kg a.i./ha/yr)	0.0	16.3	5.0	4.2
Herbicide use (kg a.i./ha/yr)	0.0	5.4	2.5	1.7
Insecticide use (kg a.i./ha/yr)	0.7	0.7	0.7	n/a
Total pesticide use (kg a.i./ha/yr)	0.7	24.4	9.7	5.4
Export Market Producers (N=16)				
Farm age in years	2	7	4.0	1.6
Yearly gross income ($US/ha)	3,530	12,646	6,183	2,371
Yearly expenses ($US/ha)	810	2,827	1,840	651
Export market supply (kg/ha/week)	153	490	284	97
National market supply (kg/ha/week)	35	470	198	153
Income from export market (%)	31	96	65	19
Fertilizer use (kg/ha/yr)	120	770	353	201
Pesticide use (kg a.i./ha/yr)	0.7	16.7	8.3	4.8
National Market Producers (N=10)				
Farm age (years)	2	18	6.6	4.5
Yearly gross income ($US/ha)	1,848	9,876	6,505	2,455
Yearly expenses ($US/ha)	1,266	3,214	1,925	746
National market supply (kg/ha/week)	103	721	461	201

Fertilizer use (kg/ha/yr)	120	968	410	251
Pesticide use (kg a.i./ha/yr)	2.7	24.4	11.9	5.9

Chapter 3: An assessment of banana weevil (*Cosmopolites sordidus* Germar) populations and damage in smallholder organic banana farms in Talamanca, Costa Rica

Abstract

The banana weevil (*Cosmopolites sordidus* Germar) is a pest in smallholder banana production systems throughout the tropics. Damage levels and effects on yield vary depending on local conditions and varieties, and have not been quantified in organic banana agroforestry systems within the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica. We sampled twenty-one farms in indigenous communities for banana weevil damage levels and yield in "Congo" banana. Percent damage in the central cylinder and cortex was estimated from two cross-sections through the corm, 10 and 15 cm below the collar. Banana bunches were weighed at harvest, and damage was estimated the following day in harvested plants. Farmers were interviewed to collect information on farm history, age, and management practices. Spearman correlation coefficients were used to identify pairwise relationships between all variables measured. Yield was correlated with damage in the cortex of the banana corm, but not in the central cylinder. Almost all (94.7%) of the damage was in the cortex. We conclude that the banana weevil does have an effect on yield in Congo banana, and that improved banana weevil management could benefit farmers by increasing the productivity of organic banana in the agroforestry systems of Talamanca.

Key words: agroforestry, cacao, *Musa*, Bribri, Cabécar

Introduction

Organic agroforestry systems including banana (*Musa* sp.), cacao (*Theobroma cacao*), and fruit and timber species are an important source of income in the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica (Dahlquist et al. 2007). These diversified systems provide farmers with year-round income from banana and seasonal income from cacao harvests, without relying on agrochemicals. However, these systems are not as profitable as intensified plantain production, the other major source of income in the indigenous territories, and much land has been converted to plantain production in the recent past (Dahlquist et al. 2007). Concerns about application of pesticides in plantain production have been noted, including effects on public health and wildlife (Polidoro et al. 2008). Efforts are needed to improve the productivity of organic agroforestry systems if the continued conversion of land to plantain production is to be avoided. Improving cacao production has been the focus of many efforts toward this goal (Dahlquist et al. 2007). Since organic banana provides more income than cacao, efforts to improve banana yield could also contribute to the profitability and stability of these systems.

Improved pest management could contribute to higher yields in organic banana agroforestry systems. The banana weevil (*Cosmopolites sordidus* Germar) is a pest in smallholder banana production systems throughout the tropics. Farmers interviewed in a rapid rural appraisal conducted within the indigenous territories identified the banana weevil as an important pest in their farms (Polidoro et al. 2008). However, banana weevil damage levels and effects on yield have not been quantified in organic banana agroforestry systems within the indigenous territories. The pest status of the banana weevil is controversial, and can vary depending on local conditions and *Musa* cultivars (Gold et al. 2001). Baseline information on banana weevil damage levels in organic banana agroforestry systems in the indigenous territories is needed before an improved pest management strategy can be developed.

Organic banana grown in the indigenous territories is sold for processing as puree in baby food. Recently, the Asociación de Pequeños Productores de Talamanca (APPTA) has begun a project to produce bananas for sale as organic fresh fruit in supermarkets (Juan Carlos Barrantes, personal communication). Banana sold as fresh fruit provides farmers with a much higher price than banana sold for puree. This project has expressed interest in improved pest management in banana in order to raise yields. In addition, the project has been promoting intensified management practices such as regular desuckering and control of fungal diseases to improve yield and to prepare banana bunches for fresh fruit sale. The effects of intensified management on banana weevil damage are not known for these systems. Management of diseases, reducing competition from weeds, and controlling plant spacing can increase plant vigor, which can contribute to increased tolerance of banana weevil damage (Gold et al. 2001). Factors that affect humidity, such as the amount of weed cover and shade and the level of farm sanitation can affect weevil movement and oviposition (Gold et al. 2001).

Our objectives were to: 1) determine current levels of banana weevil damage in organic banana agroforestry systems in Talamanca, Costa Rica, 2) determine the relationship, if any, between yield and banana weevil damage in these systems, and 3) identify potential relationships between damage levels and on-farm variables including management practices, farm age and history, and density of banana mats.

Materials and methods

The study was conducted from July to October 2005 in the localities of Amubri 1, Amubri 2, Cachabri, and Tsuidi since the fresh fruit export project focused on those communities. The fresh fruit project had been promoting more intensive management of banana with the goal of producing an export-quality organic banana bunch for sale in supermarkets. These practices had been implemented for approximately three months before the study began. Management practices promoted included regular desuckering, deleafing, and manual weeding, control of black Sigatoka (*Mycosphaerella fijiensis* Morelet) with microbial antagonists (EM, EARTH University, Guápiles, Costa Rica), use of untreated cloth or plastic bags on developing banana bunches to prevent cosmetic damage from thrips (*Chaetanaphothrips orchidii* Moulton and *C. signipennis* Bagnall), replanting with controlled spacing, and post-harvest practices for fresh fruit preparation. Traditional management in indigenous agroforestry systems is low-intensity, with infrequent desuckering and weeding, little or no deleafing, irregular spacing, and no inputs.

A total of 21 organic banana agroforestry system farms was sampled, with 16 farms involved in the fresh fruit export project and five not involved. The banana cultivar “Congo” was selected for sampling since it is the cultivar used in the fresh fruit export project. Farms were selected based on the following criteria: 1-2 ha in size and containing enough Congo banana mats to sample at least five harvested plants. The number of sampled farms not involved in the fresh fruit export project was small because it was difficult to find farms not in the project that had enough Congo plants.

In each farm, 5-10 Congo plants were sampled for bunch weight and banana weevil damage. Bunch weight was recorded at the time of harvest. Percent damage was measured by destructive sampling of harvested plants on the day of harvest or up to 3 days following harvest. Although only already harvested plants were sampled, farmers were reimbursed for any potential damage to the remaining banana suckers. The entire corm was unearthed, and two cross-sections were cut through the corm at 10 and 15 cm below the collar (modified from Gold et al. 1994, Gold et al. 2005 following consultation with D. Alpizar). A transparent grid was used to count the number of 1 cm^2 sections with damage from larval tunnels in the central cylinder and cortex. The diameters of the entire cross-section and the central cylinder were recorded and used to calculate the area for each cross-section, both the total area and the area of the central cylinder. The area of the cortex was calculated by subtracting the area of the central cylinder from the total area. The number of 1 cm^2 sections with damage was then divided by the area to calculate the percent damaged area for each cross-section. The percentages from the two cross-sections were averaged for each plant to obtain the percent of the total corm area damaged, the percent of the central cylinder area damaged, and the percent of the cortex area damaged. The number of banana pseudostems in each harvested mat was also recorded.

A 20-30 minute interview was conducted with the owner of each farm sampled to determine the following farm variables: area, history of land use, approximate number of banana mats of “Congo” (*Musa* AAA), “Lacatan” (*Musa* AAA), “Gros Michel” (*Musa* AAA), and finger banana (Datil or *primitivo*) (*Musa* AA), and the frequency of manual weeding, deleafing, and desuckering practices.

Data analysis

Since data were not normally distributed and sample sizes were small when comparing categories, nonparametric tests were used. Relationships between bunch weight, total damage, central cylinder damage, cortex damage, density of banana mats, farm age, and frequencies of management practices were determined using Spearman correlation coefficients (SAS Institute 2001). Differences in bunch weight, total damage, central cylinder damage, cortex damage, density of banana mats, farm age, and frequencies of management between farms in the fresh fruit export project and farms not in the project were analyzed with a Wilcoxon rank-sum test (SAS Institute 2001). Differences among communities and farm history categories were analyzed with a Kruskal-Wallis test (SAS Institute 2001), and differences between farms with a history of plantain cultivation and farms with no prior plantain cultivation were analyzed with a Wilcoxon rank-sum test (SAS Institute 2001).

Results

Damage and yield

The mean total damage from all farms was 2.85% (±0.31%), with a range of 0.26% to 5.32% (per farm). Mean central cylinder damage was 0.49% (±0.11%), and mean cortex damage was 4.40% (±0.45%). The mean bunch weight was 14.0 (±0.8) kg, and the mean number of pseudostems per mat was 3.0 (±0.2). For all damaged plants in all farms, 94.7% of the damage was in the cortex. We observed that often larval galleries appeared to stop at the boundary of the cortex and central cylinder, creating the effect of a ring of damaged tissue around a relatively untouched circle. Yield was negatively correlated with damage in the cortex (R^2=0.28, P=0.029) (Fig. 3.1), but not with damage in the central cylinder (R^2=0.082, P=0.27). Farms in the community of Amubri 2 had significantly lower total damage (P= 0.032), central cylinder damage (P= 0.0030), and cortex damage (P= 0.029) than in Amubri 1 and Cachabri (Fig. 3.2). There was no effect of community on yield (P=0.22) or number of pseudostems per mat (P=0.73).

Effect of management

Yield was significantly higher in farms involved in the fresh fruit export project (14.7 kg) than in farms not involved (11.7 kg) (*P*=0.032). There was no effect of management on number of pseudostems per mat (*P*=0.15), total damage (*P*=0.39), central cylinder damage (*P*= 0.93), or cortex damage (*P*=0.48). There were no significant differences between farms involved in the project and farms not involved in the project in the frequency of manual weeding (*P*=0.2314) or the frequency of desuckering (*P*= 0.1033). The frequency of deleafing was significantly higher in farms involved in the fresh fruit export project (0.95 deleafing events per week) than in farms not involved in the project (0.61 deleafing events per week) (*P*=0.0072). The frequency of deleafing and frequency of desuckering were positively correlated (R^2=0.62, *P*=0.0008).

Farm variables

Farm history was described as one of four cropping systems utilized before the banana mats were planted: 1) cacao only, 2) cacao mixed with plantain, 3) plantain only, and 4) pasture or fallow. There was no effect of farm history on yield (*P*=0.68), number of pseudostems per mat (*P*=0.35), total damage (*P*=0.46), central cylinder damage (*P*=0.66), or cortex damage (*P*=0.40). Similarly, there was no effect of history of plantain cultivation on yield (*P*=0.29), total damage (*P*=0.31), central cylinder damage (*P*=0.23), or cortex damage (*P*=0.41).

The mean age of farms (corresponding to how long the farm had included organic banana) was 8.5 (±1.2) years, ranging from 1 to 20 years. Farm age was not correlated with yield (*P*=0.74), number of pseudostems per mat (*P*=0.55), total damage (*P*=0.74), central cylinder damage (*P*=0.56), or cortex damage (*P*=0.73). Density of banana mats was not correlated with yield (*P*=0.50), number of pseudostems per mat (*P*=0.47), total damage (*P*=0.81), central cylinder damage (*P*=0.85), or cortex damage (*P*=0.58).

Discussion

This study presents the first assessment of banana weevil damage in organic banana agroforestry systems within the Bribri-Cabécar Indigenous Territories in Talamanca, Costa Rica. Since the relationship between yield and damage was significant, we conclude that the banana weevil is a pest on Congo banana in these systems. We observed variation in damage levels among different communities, with one community having lower damage levels. Possible reasons for this include local variation in soil fertility and similar management practices or sources of planting material among members of the same community.

Almost all of the damage we observed was in the cortex of the banana corm, outside the central cylinder. We observed a clear difference between the central cylinder and cortex, with damage in the cortex often stopping just at the boundary of the central cylinder and cortex. Damage in the central cylinder has been demonstrated to have a greater effect on yield than damage in the cortex in highland cooking banana in Uganda (Gold et al. 2005). By contrast, in our study yield was correlated with cortex damage, but not with central cylinder damage; however this may be due to the extremely low levels of central cylinder damage we observed. Damage in the central cylinder is considered to have a stronger effect on yield because it interferes with the vascular system of the banana plant, disrupting transport of nutrients (Gold et al. 2001, Gold et al. 2005). However, damage to the cortex can also reduce yield by adversely affecting root development, which can lead to snapping and toppling (Gold et al. 2005).

The degree of penetration into the central cylinder, measured by the ratio of central cylinder to cortex damage, has been suggested as a way to compare *Musa* cultivars for resistance to the banana weevil (Gold et al. 1994). We observed a low ratio (0.11) of inner to outer damage. Antibiosis causing larval mortality is considered to be the primary modality of host plant resistance to the banana weevil (Gold et al. 2001, Kiggundu et al. 2007). Mechanisms of antibiosis proposed by Gold et al. (2001) include toxic or antifeedant secondary plant compounds and physical properties such as sticky latex and corm hardness. The pattern we observed in Congo plants indicates that some mechanism inhibits larval tunneling into the central cylinder. Indigenous farmers describe their banana cultivars as “hard” compared to plantain, which is easier to cut with a machete. Our experience in the field confirms this observation, as it was sometimes difficult for experienced indigenous field assistants to cut through the banana corms. In some studies, corm hardness was higher in banana weevil resistant *Musa* cultivars (Pavis and Minost 1993, Ortiz et al. 1995). However, Ortiz et al. (1995) found that corm hardness and weevil damage were not correlated in segregating progenies, and Kiggundu (2000) found no relationship between corm hardness and weevil damage. Mechanisms of antibiosis may vary among cultivars. Comparisons with other cultivars would be required to evaluate the level of antibiosis in Congo, if any, and to determine the mechanisms involved.

Banana bunch weight was significantly higher in farms in the fresh fruit project. The higher yield in these farms could be a result of the improved management practices promoted by the project. Control of black sigatoka by deleafing and application of microbial antagonists would be expected to increase yield by increasing the number of healthy leaves providing photosynthate to the developing banana bunch. Weeding, desuckering, and regular spacing would also increase yield by reducing competition for nutrients. It is also possible that farmers who joined the project had higher yields to begin with, if more motivated farmers who already invested more time in farm management were more likely to join the project. Even so, these results indicate that improved management increases yield. Although yield was significantly correlated with banana weevil damage in the banana cortex, there was no difference in banana weevil damage levels between farms in the project and farms not in the project. While yield was significantly correlated with banana weevil damage in the banana cortex, the relationship was not strong, and it is not possible to determine the amount of yield increase that might result from improved banana weevil management. Since management appears to have a noticeable effect on yield, focusing on the improved farm management practices promoted so far could be a good strategy for the fresh fruit project.

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Figure 3.1. Relationship of yield and banana weevil damage in the banana cortex.
$y = -0.83d + 17.6$, where y = bunch weight and d = cortex damage. Spearman R^2=0.28, P=0.029.

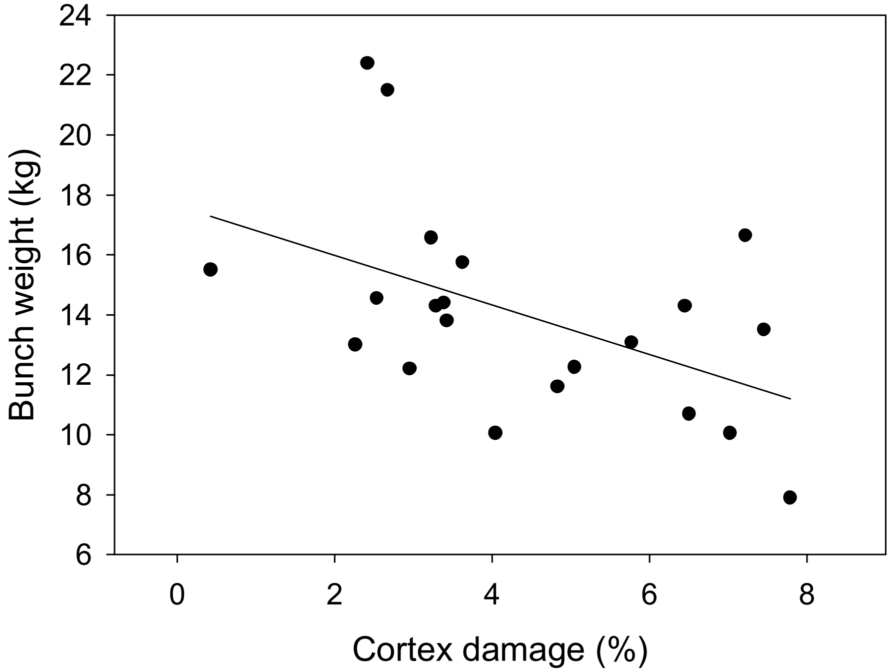
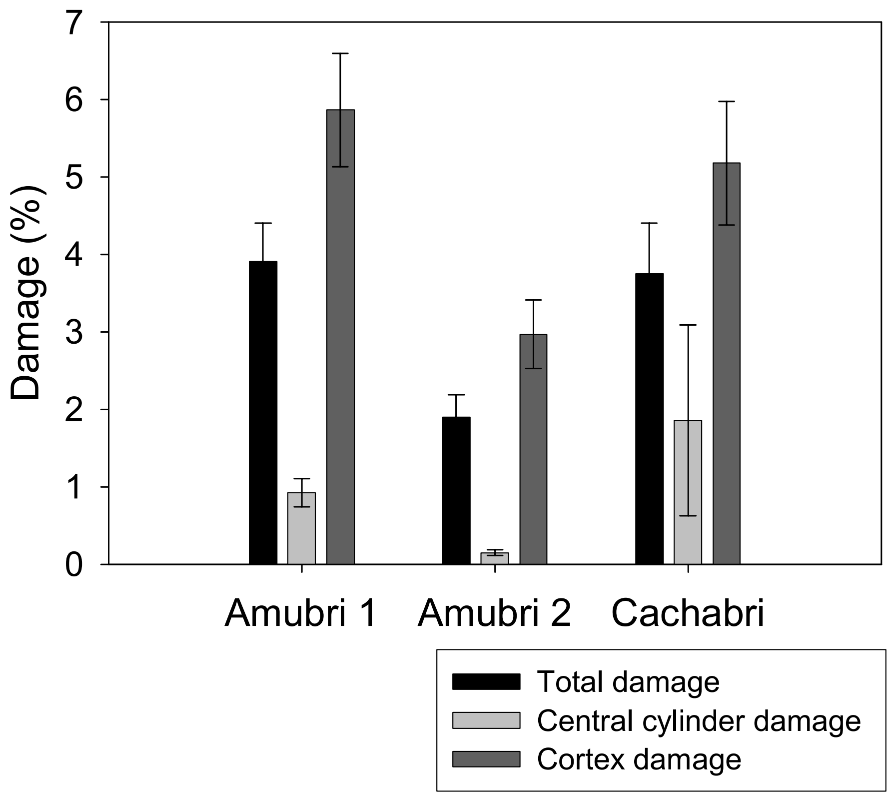


Figure 3.2. Banana weevil damage in Amubri 1, Amubri 2, and Cachabri.

The community of Tsuidi is not included since only one farm in the sample was located there.



Chapter 4: An evaluation of pheromone trapping for banana weevil (*Cosmopolites sordidus* Germar) management in Costa Rican smallholder plantain farms

Abstract

The banana weevil (*Cosmopolites sordidus* Germar) is an important arthropod pest of banana and plantain (*Musa* spp.) in Costa Rica. Pitfall traps using lures containing the aggregation pheromone of the banana weevil have reduced weevil damage in large banana and plantain plantations (>200 ha), but have not been tested in small (0.25-3 ha) farms. Pheromone traps could provide an alternative to insecticides currently in use by small-scale farmers. Our objective was to evaluate the effects of pheromone traps on banana weevil damage and plantain yield in smallholder plantain farms within the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica. Mass trapping with pheromone lures was conducted in six farms, and five farms served as controls with no traps. Four pheromone traps per hectare were placed in a line at 20 m spacing, and the line was moved monthly to rotate traps within the farm. Number of weevils per trap was recorded weekly. The mating status of a sub-sample of female weevils collected from traps was determined by examining the spermatheca for presence of sperm. Each farm was sampled for weevil damage and plantain bunch weight before and after 58 weeks of trapping. Bunch weight was assessed at harvest, and percent damage was estimated in harvested plants from two cross-sections through the corm. Damage was not significantly different after one year in the control farms (P=0.37), but dropped from 5.1% to 3.4% in the farms with pheromone traps (P=0.017). Damage was correlated with initial trap catches. Bunch weight increased in the farms with traps and decreased in control farms, but these differences were not significant. Almost all (99%) of dissected females had mated before being captured in the traps. The reduction in damage in farms with pheromone traps indicates that traps are effective in smallholder plantain farms.

Introduction

Plantains (*Musa* sp.) are a major cash crop for farmers in the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica, and one of the most important economic activities in the area. In 2006, Costa Rica had 11,000 ha in plantain production, yielding 76,635 metric tons of plantain (FAO, http://fao.faostat.org). The Talamanca region, located on the Atlantic coast in southeastern Costa Rica, provides 52% of this production (Municipality of Talamanca, 2003). Plantain production systems in Talamanca range from large exporter plantations in the coastal Sixaola Valley that rely on agrochemical application regimes similar to those used in commercial banana production, to household farms as small as 0.25 ha in the indigenous territories with little to no agrochemical application that sell plantains to the national market (Polidoro et al. 2008). The highest concentration of poverty in Talamanca occurs within the indigenous territories (Municipality of Talamanca, 2003), and many farmers there depend on plantain as a source of income (Dahlquist et al. 2007).

The banana weevil (*Cosmopolites sordidus* Germar) weevil is a pest on banana and plantain throughout the tropics. Farmers participating in a rapid rural appraisal of pest management practices in plantain and organic banana in the indigenous territories ranked the banana weevil as the worst pest in their farms (Polidoro et al. 2008). While the banana weevil is not considered an important pest in commercial banana plantations (Ostmark 1974), it has eluded control in smallholder production systems (Karamura and Gold 2000). Damage caused by the larvae, which tunnel into the banana or plantain corm, can reduce yield and plantation life, and heavy infestation can lead to crop failure in newly planted fields (Gold et al. 2001). Yield loss can also occur through toppling of damaged plants (Gold et al. 2001). Control methods vary in efficacy, and currently include synthetic pesticides (Sponagel et al. 1995), cultural controls such as farm sanitation (Masanza et al. 2005) and pseudostem traps (Gold et al. 2002), biological control with entomopathogens (Treverrow et al. 1991, Nankinga and Moore 2000) or myrmicine ants (Castineiras and Ponce 1991), host plant resistance (Kiggundu et al. 2003), botanical pesticides such as neem (Musabyimana et al. 2001), and mass trapping with pheromone lures (Alpízar et al. 1999, Tinzaara et al. 2005b). However, plantain and banana production systems vary widely throughout the tropics, and each control method must be evaluated under local agroecological conditions to determine its efficacy for smallholder production (Gold et al. 2001). No previous studies exist on banana weevil damage levels in the indigenous territories of Talamanca, and the few previous studies on banana weevil control methods are unpublished and cannot be located.

Few alternatives to pesticide use exist for banana weevil management in smallholder plantain farms within the indigenous territories. Current management relies mainly on general farm sanitation and the use of combination nematicide-insecticides. These chemicals are toxic organophosphates or carbamates, and farmers rarely use appropriate safety practices during application (Polidoro et al. 2008). The most commonly used nematicide-insecticide is terbufos (Polidoro et al. 2008), an organophosphate, which is applied to the soil to kill adult weevils (Sponagel et al. 1995). The efficacy of pesticides used to control the banana weevil has been questioned. Pesticides that are not systemic will not kill the larvae unless they remain effective until the adults emerge and contact the soil (Sponagel et al. 1995). Banana weevil populations resistant to certain insecticides have developed in some areas (Collins et al. 1991, Gold et al. 1999). Effects of pesticides on wildlife are also a concern, as birds have been observed to ingest granules of terbufos (Ostmark pers. comm). Terbufos has been found in low concentrations in rivers adjacent to banana and plantain farms in the indigenous territories, and the compound as well as its metabolites are toxic to fish (Polidoro 2007).

Given the public health and environmental concerns associated with pesticide use in Talamanca, there is a need for alternative pest management practices for the banana weevil. The male-produced aggregation pheromone of the banana weevil, sordidin, has been identified (Beauhaire et al. 1995), and a lure containing the four diastereomers of sordidin and a host plant kairomone is commercially available within Costa Rica as “Cosmolure+” (Ndiege et al. 1996). Pheromone traps using Cosmolure+ have been shown to reduce banana weevil damage in commercial plantain plantations (>200 ha) on the Atlantic coast of Costa Rica over a trapping period of 10-17 months (Alpízar et al. 1999, 2000). However, these traps have not been evaluated in smallholder plantain farms (0.25 – 3 ha) within the indigenous territories. The efficacy of pheromone traps must be evaluated under local agroecological conditions (Tinzaara et al. 2002); for example, a recent evaluation of the pheromone trapping system in Uganda found no reduction in banana weevil populations or damage over 21 months of trapping (Tinzaara et al. 2005b). Smallholder plantain farms within the indigenous territories are much smaller than commercial plantations (0.25 – 3 ha) with a lower intensity of both cultural management and agrochemical applications (Polidoro et al. 2008), resulting in a lower density of plantain mats per hectare, a more open canopy, higher weed levels, and sometimes the presence of other crops within the plantain farm. Given the differences from commercial plantations in management practices and farm size, an evaluation of the pheromone trapping technique is necessary in order to determine its efficacy in these smallholder plantain farms.

In addition, the mating status of female banana weevils arriving at pheromone traps has not been evaluated in any agroecological system (Tinzaara et al. 2002). The physiological status of an insect can influence its behavioral responses to volatiles (Anton et al. 2007); for example, in the Mediterranean fruit fly (*Ceratitis capitata*), mating causes females to stop responding to the male-produced pheromone and start responding to plant volatiles (Jang 1995). If mating alters the response of female banana weevils to the aggregation pheromone with the result that mated females are not removed with the same efficiency as unmated females, the pheromone traps may have limited efficacy in reducing banana weevil populations (Tinzaara et al. 2002).

The objectives of this study were to 1) determine the levels of banana weevil damage present in smallholder plantain farms and 2) evaluate the efficacy of pheromone trapping as a management practice in these farms. This research was part of a larger, interdisciplinary effort to address issues of biodiversity conservation and sustainable production in the Bribri-Cabécar Indigenous Territories.

Materials and methods

Farm selection

The Bribri-Cabécar Indigenous Territories are located in southeastern Costa Rica between 9°21’38” and 9°39’30” N and 82°50’40” and 83°18’37” W (Fig. 4.1). The study was conducted in the Valle de Talamanca floodplain in three communities along the Telire River (Bambú, Suretka, and Isla Lari). This area has an altitude of approximately 50-70 masl, annual rainfall of 2800 mm with no marked dry season, mean annual relative humidity of 88%, and a mean annual temperature of 25.6 °C, with a maximum of 30.5 °C and minimum of 20.4°C (Kapp 1989, Borge and Castillo 1997). Twelve plantain farms were selected based on the following criteria: size (2.5 ha or smaller), farmer interest in the project (Beer 1991), and medium intensity of management. Medium intensity of management was defined based on the description of low to moderate intensity management in Polidoro et al. (2008) as no fungicide use, manual weed control with occasional herbicide use, use of insecticide-impregnated plastic bags on maturing bunches, and nematicide-insecticide use at replanting. Six farms were assigned to the pheromone trap evaluation based on farmer interest, and six remained with no traps as controls. One farmer in the control group decided not to continue participating at the end of the study, leaving five farms as controls.

Trapping with pheromone lures

Mass trapping was conducted at commercially recommended rates developed in large plantations (Alpízar et al. 1999). Four pheromone traps per hectare were placed in a line at 20 m spacing. This line of four traps was moved forward 20 m every 4-5 weeks to rotate traps in a 4 x 4 grid of trap locations within the hectare, returning to the initial location after three forward movements (Fig. 4.2). Lures were replaced at the time the traps were moved. Farm areas were measured by delineating their perimeters with a GPS unit (Trimble Navigation, Sunnyvale, CA). Since farm sizes varied, the number of traps placed in each farm was determined based on the area of the farm (Table 4.1). Traps consisted of a pitfall trap made out of a 600 ml plastic soda bottle. Square openings (4 x 8 cm) were cut on two opposing sides for weevil entry approximately 8 cm from the base, and the packet of lure (Cosmolure+, ChemTica, San José, Costa Rica) was suspended inside the trap from the lid of the bottle. Traps were buried in the soil up to the bottom edge of the openings and filled with water laced with an odor-free liquid soap (Bacterol-100, CEQSA, San José, Costa Rica). Traps were serviced each week to replace the soapy water. The trapping period was 58-59 weeks for each farm. Given the remoteness of the region and the difficulty of obtaining transportation to farms and coordinating with farmers for damage and yield sampling during harvests, the beginning and ending dates of trapping periods were not the same among farms (Table 4.1). The number of weevils in each trap was recorded weekly in each farm. Daily rainfall (mm) was recorded with a rain gauge at two locations within the indigenous territories (Shiroles and Bambú). Rainfall was recorded in Shiroles from May 13, 2006 to September 29, 2007. Rainfall in Bambú was recorded from February 6, 2007 to September 29, 2007.

Mating status

The mating status of a sub-sample (n=96) of female weevils collected from traps was determined by examining the spermatheca for presence of sperm. Sub-samples of weevils were collected from a total of twelve traps taken from two farms (Farm 1 and 2) on June 26, 2007 and two farms (Farm 5 and 6) on August 1, 2007. Weevils were collected from traps in the middle of the trapping week, 3 days after servicing the traps, in order to collect a fresher sample. The body was snapped between the thorax and abdomen and preserved in 70% ethanol. Weevils were sexed according to the patterns of pits on the rostrum (Longoria 1968) and the number of males and females was recorded. Females were dissected in a saline solution (Ephrussi and Beadle 1936). The spermatheca was removed and examined under 40X magnification to determine presence or absence of sperm. One live female weevil was dissected to confirm visual identification of sperm in the spermatheca.

Yield and damage measurements

In both trapping and control farms, 10-16 harvested plantain plants per farm were sampled for weevil damage and yield parameters before trapping (2006) and after 58 weeks of trapping (2007). Bunch weight, number of hands and fingers per bunch, and the terms of sale of the bunch were recorded at the time of harvest. Farmers are paid by the bunch rather than by weight, with smaller bunches (usually, less than 28 fingers) combined into a two-for-one payment. Consequently, each bunch was classified as either large enough for payment as one bunch, or a two-for-one smaller bunch. Percent damage was measured by destructive sampling of harvested plants on either the day of harvest or the following day. Although only already harvested stems were sampled, farmers were reimbursed for any potential damage to the remaining plantain suckers. The entire corm was unearthed, and two cross-sections were cut through the corm at 10 and 15 cm below the collar (modified from Gold et al. 1994, Gold et al. 2005 following consultation with D. Alpízar). A transparent grid was used to count the number of 1 cm^2 sections with damage from larval tunnels in the central cylinder and cortex. The diameters of the entire cross-section and the central cylinder were recorded and used to calculate the area for each cross-section, both the total area and the area of the central cylinder. The area of the cortex was calculated by subtracting the area of the central cylinder from the total area. The number of 1 cm^2 sections with damage was then divided by the area to calculate the percent damaged area for each cross-section, and the percentages from the two cross-sections were averaged for each plant to obtain the percent of the total corm area damaged, the percent of the central cylinder area damaged, and the percent of the cortex area damaged. In 2006, the number of plantain stems in each harvested mat was also recorded.

Farmer interviews

At the time of the 2006 sampling, farmers were interviewed to gather information about their farms. Information collected included farm age, history of land use, extent of damage from the 2005 flooding event, replanting practices after the flood, frequency of nematicide and fertilizer use, and soil type (sand, clay, or mixed clay and sand).

Data analysis

Pearson correlation coefficients were determined for yield and damage variables from the 2006 sampling of all 12 farms, before trapping began. Farmer responses to interview questions were classified into two or three categories per question and analyzed with an ANOVA (SAS Institute 2001) to test for differences among categories in damage and yield from the 2006 sampling. Differences between categories of fertilizer use were analyzed with a Savage test (SAS Institute 2001). A linear regression was conducted on age of farm and damage and yield measurements.

Differences in yield and damage measurements between 2006 and 2007 were analyzed with a t-test (SAS Institute 2001) conducted separately on control farms and trapping farms. The relationship between damage and trap catch means was analyzed with a linear regression. For each farm, linear regressions were conducted on the means of trap rotation periods over time. Since data for trap catches and weekly rainfall means were not normally distributed, Spearman correlation coefficients were determined for weekly trap catches and weekly rainfall for the week before traps were collected and with a time lag of one week.

Traps were moved forward in a grid within 1 ha sections of farm every 4-5 weeks, with approximately 13 rotation periods over the 58 weeks of trapping. To determine if weekly trap catches changed over time within the 4-5 week trap rotation periods, ranks of trap catch means for weeks 1-4 within each trapping period were compared for each farm separately with an ANOVA (SAS Institute 2001).

Results

Banana weevil damage levels in smallholder plantain farms

In the first measurement of damage and yield parameters (2006), the mean total corm damage for all 12 farms was 3.9% (± 0.6%). Of the total corm area damaged, 17.7% (± 2.5%) was in the central cylinder, and the ratio of central cylinder to cortex damage was 0.47 (± 0.07). The mean central cylinder damage was 2.5% (± 0.5%), and the mean cortex damage was 4.8% (± 0.6). The mean bunch weight per farm was 12.1 kg (± 0.5), mean number of hands per farm was 5.4 (± 0.2), and mean number of fingers per farm was 27.8 (± 0.9). Of the plantain bunches sampled, a mean of 44.3% (± 6.6%) per farm were sold as one unit instead of two-for-one.

In 2006, bunch weight was significantly correlated with number of hands (R^2=0.72, P=0.0005) and number of fingers (R^2=0.68, P=0.001). There was no relationship between bunch weight and total damage (P=0.97), central cylinder damage (P=0.54), or cortex damage (P=0.81). Similarly, there was no relationship between number of hands and total damage (P=0.64), central cylinder damage (P=0.26), or cortex damage (P=0.81), or between number of fingers and total damage (P=0.48), central cylinder damage (P=0.67), or cortex damage (P=0.48). The mean number of stems per mat was 3.6 (± 0.2). The number of stems per mat was correlated with the number of hands per bunch (R^2=0.37, P=0.048), but not with bunch weight (P=0.14) or number of fingers (P=0.31).

Interview results are presented according to categories in Table 4.2. Farms with high fertilizer use had a higher bunch weight (13.4 kg) than those applying less frequently (11.4 kg) (P=0.0499). No relationship was found between bunch weight and extent of flooding (P=0.72), planting before or after flood (P=0.89), extent of replanting (P=0.57), farm age (P=0.44), nematicide use (P=0.81), and soil type (P=0.19). Similarly, no relationship was found between total damage and extent of flooding (P=0.51), planting before or after flood (P=0.43), extent of replanting (P=0.51), farm age (P=0.23), nematicide use (P=0.96), fertilizer use (*P*=0.93), and soil type (*P*=0.74). History of land use was not analyzed as 7 of the 12 farms had been planted out of a shrubby fallow or *tacotal*, and the other 5 each had a different previous land use (cacao, plantain, pasture, forest, or caña blanca (*Gynerium sagittatum*) fallow.

Damage levels and yield before and after trapping

In the control farms, there was no significant difference between 2006 and 2007 in total damage, (*P*=0.37), central cylinder damage (*P*=0.32), or cortex damage (*P*=0.42) (Table 4.3). In trapping farms, total damage decreased significantly from 5.1% in 2006 to 3.4% in 2007 (*P*=0.017) (Fig. 4.3). Central cylinder damage in the trapping farms decreased from 3.4% to 2.4%, but this difference was not significant (*P*=0.23), and cortex damage decreased significantly from 6.1% to 4.0% (*P*=0.0063) (Table 4.3). Of the six farms with pheromone traps, four (Farms 1, 4, 5, and 6) showed a large decrease in total damage, and two (Farms 2 and 3) showed a slight increase from 2006 to 2007 (Table 4.4).

Bunch weight was not significantly different between 2006 and 2007 in control farms (*P*=0.38) or trapping farms (*P*=0.20) (Fig. 4.4). Similarly, there were no significant differences between 2006 and 2007 for number of hands (*P*=0.74) or number of fingers (*P*=0.67) in control farms, or for number of hands (*P*=0.13) or number of fingers (*P*=0.38) in trapping farms (Table 4.3). However, in trapping farms the percentage of bunches sold as 1 unit increased significantly from 52.6% in 2006 to 75.2% in 2007 (*P*=0.044). This percentage also increased in control farms from 34.4% in 2006 to 52.3% in 2007, but the difference was not significant (*P*=0.23) (Table 4.3). Data from individual farms are presented in Table 4.5.

Trap catch numbers

Two farms (Farm 5 and 6) had a slight, but significant negative correlation between weekly trap catches and average weekly rainfall in Shiroles with a time lag of one week (Table 4.6). Daily rainfall was weakly correlated between the two rainfall measurement sites in Shiroles and Bambú (R^2 = 0.02, P=0.04), but weekly rainfall was not correlated between the two sites (R^2 = 0.094, P=0.084). Trap catches were not correlated with rainfall from either site in the week immediately before trap collection. There was no significant trend in the mean number of weevils per trap over time for farm 1, 2, 3, or 4 (Fig. 4.5 A-D), but mean number of weevils per trap declined over time in farms 5 and 6 (Fig. 4.5 E-F). The mean number of weevils per trap did not decline over time within the 4-5 week trapping periods (P=0.33, 0.79, 0.98, 0.84, 0.24, and 0.07 for farms 1-6, respectively). Total damage in 2006 in the six trapping farms was significantly correlated with mean trap catch numbers from the first three months of trapping (Fig. 4.6). The two farms with pheromone traps in which damage did not decrease from 2006 to 2007 had the lowest trap catches in the first three months, and also the lowest damage levels (Table 4.7).

Sex ratio and mating status

A total of 129 weevils (32 males and 97 females) were collected in the sub-sample of twelve traps for evaluation of female mating status. The mean ratio of females to males per trap was 3.75 (± 0.66). Out of 96 spermathecae dissected, 95 had visible sperm (99.0%) and were assumed to have mated prior to arriving at the pheromone traps.

Discussion

Pheromone traps employed according to commercial recommendations were effective in reducing banana weevil damage in the smallholder plantain farms participating in our study. Total corm damage in farms with trap decreased by 33%, while control farms with no traps showed a 42% increase in total corm damage. Further research is necessary to determine the effects of this reduction in damage on plantain yield. While bunch weight did increase in trapping farms and decrease in control farms, differences were not significant. However, there was a significant increase in the percentage of bunches sold as one unit in farms with pheromone traps, while the increase in control farms was not significant. Since bunches are sold as either one unit or two-for-one rather than by weight, the percentage sold as one unit is the most relevant to farmers in the indigenous territories.

Banana weevil damage indirectly affects the harvested bunch through interfering with nutrient transport and allocation to aboveground plant tissues, so a strong relationship between damage and yield is not often found (Gold et al. 2001). In a small on-farm study such as ours that does not control for other factors affecting yield such as nematodes, black Sigatoka, and soil fertility, and given the variability among smallholder farms in the tropics, it is not surprising that relationships between banana weevil damage and yield parameters were not observed. Consequently, it is difficult to predict the increase in yield that might result from a 33% reduction in damage. Also, yield increase is not the only factor to consider, as loss of plants through toppling may also be reduced by reducing damage. A study with a larger sample size in smallholder plantain farms would be useful in determining the relative contributions of banana weevil, nematodes, fungal diseases, and nutrient deficiencies to yield loss, and in predicting the resulting gains from management of each limiting factor. More information on the effects of nematode populations on yield in smallholder plantain farms would be particularly relevant, since the combination nematicide-insecticides are currently applied for both nematode and banana weevil control.

Although it is not clear whether weevil populations decreased over time, we assume that enough weevils were removed to either reduce corm damage or prevent it from increasing. The correlation between initial damage and initial trap catches supports this assumption: since farms with higher initial trap catches also had higher damage, it is reasonable to assume that removing weevils from the farm would have an effect on new damage. The pheromone traps removed approximately 380 weevils/ha per month, for totals of 2,800-8,200 weevils/ha removed over the 58 weeks of trapping. The two farms in which damage did not decrease exhibited the lowest trap catches and the lowest initial damage. It is possible that trapping does not have a large effect in reducing damage below a certain threshold of weevil population density. However, the increase in damage in the other two farms was low (5-12%) compared to the increase in control farms (42%). This indicates that even in farms in which trapping does not reduce weevil damage, it may prevent it from increasing as it normally would from year to year in the absence of management (Gold et al. 2005).

Trap catches decreased significantly over time in two of the six treatment farms. In the other four, trap catches did not show any pattern over time. Trap catches did not decrease from week to week within the 4-5 week trap rotation periods in any of the farms, indicating that 4-5 weeks is not long enough to decrease the number of weevils in a sub-section of the farm when traps are left in the same place for that interval. Since we did not measure population density before and after trapping, it is difficult to assess whether banana weevil populations were lower as a result of trapping or not. If trap catches did reflect population density in the farms, the lack of a decrease in population density could mean that traps do not remove enough weevils to reduce recruitment. Also, banana weevils may be sedentary for long periods of time (Gold and Kagezi unpublished data, cited in Gold et al. 2001), and it is possible that some percentage of the population is not active or does not respond to the pheromone due to physiological state. Immigration from neighboring farms may also be a factor. The two farms in which trap catches decreased were isolated from other farms that could have acted as weevil sources; however, two of the farms in which trap catches did not decrease were also isolated.

We detected a large amount of variation in trap catches within each farm. This variation may be related to farm management practices such as manual weeding, herbicide application, nematicide/insecticide application, or clearing the mat and surrounding area of weeds and debris (*rodaja*). Records of herbicide and nematicide/insecticide applications were made during the trapping period; however, there was no noticeable change in trap catches following these applications. An aggregated distribution of banana weevils within a farm or small variations in trap placement such as distance from a plantain mat (Tinzaara et al. 2002) could also contribute to variation in trap catches. Trap catches were correlated with weekly rainfall means with a time lag of one week in only two of the six trapping farms, and not correlated with weekly rainfall means the week immediately before trapping in any farm. This is consistent with other field trials of pheromone traps, which found no correlation between weekly trap catches of banana weevils and weekly rainfall in South Africa (DeGraaf et al. 2005) or between monthly trap catches and monthly rainfall in Uganda (Tinzaara et al. 2005b). A mark-recapture experiment in Uganda found a significant, though small, correlation between trap catches and humidity, but no relationship between trap catches and rainfall, wind speed, or temperature (Tinzaara et al. 2005a). In Talamanca, rainfall is patchy and very local, and it is possible that farms with pheromone traps did not receive the same weekly rainfall as at the rainfall measurement locations. In the relatively constant climate of the lowland tropics, it is difficult to relate trap catches to variables such as temperature and humidity, which change little from week to week.

Mean weekly trap catches in the smallholder plantain farms of Talamanca were 22.3 weevils/trap/week for all farms over 14.5 months. These numbers contrast with studies in subsistence highland banana farms in Uganda, where trap catches were only 2.4 weevils/trap/week over 21 months (Tinzaara et al. 2005b). A multitude of differences between these cropping systems could affect trap catches, including *Musa* genome group and variety, the presence of other crops in the subsistence farms, different species and infestation levels of weeds, climate and seasonality, management intensity, field sanitation, and plant spacing. In Talamanca, the cropping systems most similar to the Ugandan subsistence banana farms occur on indigenous organic banana agroforestry farms, which have a diversity of crops, irregular plant spacing, and low management intensity (Somarriba and Harvey 2003). However, a preliminary trial of pheromone traps in organic banana agroforestry farms in the indigenous territories gave a mean of 16.5 weevils/trap/week (Dahlquist unpublished data), which is not low compared to large banana plantations in Costa Rica (6 weevils/trap/week) (Alpízar et al. 2000). While further research would be necessary to evaluate the effects of high weed infestations, irregular spacing, intercropping, and low field sanitation on pheromone trap catches, the trial in the agroforestry systems in Talamanca does not indicate that these factors decrease trap catches.

Similarly, trap catches in the smallholder plantain farms in our study were not low compared to those observed in large plantain plantations on the Atlantic coast of Costa Rica (about 17 weevils/trap/week over 17 months, estimated from graph) (Alpízar et al. 1999). The smallholder plantain farms in Talamanca had much higher weed levels and lower field sanitation than commercial plantations, and represent an intermediate level of management intensity and field sanitation. We recorded the number of stems per mat as a reflection of the intensity of farm management; commercial plantations would have only two (the harvested stem and one sucker), while subsistence farms without desuckering management can have as many as 10. The plantain farms in our study had a mean of 3.6 stems per harvested mat, representing an intermediate management intensity. This lends support to the idea that the differences in trap catch numbers between Ugandan and Costa Rican studies are not due to differences among cropping systems. However, trap catches in a South African evaluation of pheromone traps in commercial Cavendish banana plantations were approximately 11.6 weevils/trap/week over five weeks (estimated from graphs) (DeGraaf et al. 2005). If Ugandan and South African banana weevil populations are similar in their behavioral responses, this could indicate that differences in management intensity do affect trap catches. However, other differences such as *Musa* variety exist between the Ugandan and South African systems, and controlled studies would be necessary to determine the effects of each factor on pheromone trap catches.

Another possible explanation for the lower trap catches in Uganda compared to our findings in Costa Rica is differences in banana weevil responses to volatiles among geographically distinct populations. It is difficult to determine how long banana weevil populations on different continents have been isolated from each other, as reintroductions may have occurred with the introduction of new *Musa* germplasm. However, a RAPD marker comparison of banana weevils from the Canary Islands, Costa Rica, Colombia, Uganda, and Madeira indicated that biotypes may exist in different geographical areas as a result of limited gene flow among populations and genetic drift (Magaña et al. 2007). Male banana weevils produce six antennally-active volatile compounds, four of which have been identified as diastereomers of sordidin, the major pheromone (Beauhaire et al. 1995). Genetic differences in pheromone blend composition, behavioral responses to the pheromone blend, or behavioral responses to host plant volatiles could be responsible for the low trap catches observed in Uganda. Differences in pheromone blends among populations in different geographical areas have been found in lepidopteran sex pheromones (Klun et al. 1975, McElfresh and Millar 2001) and scolytine aggregation pheromones (Domingue et al. 2006), and have explained differences in trap catches between North American and South American biotypes of the fall armyworm *Spodoptera frugiperda* Smith (Batista-Pereira et al. 2006). In pheromone trap trials in South Africa, trap catches were higher for traps with lures containing only the four diastereomers of sordidin (Cosmolure) than lures containing the four diastereomers plus a plant kairomone (Cosmolure+) (DeGraaf et al. 2005). While host plant volatiles increased weevil response to the pheromone in bioassays (Tinzaara et al. 2003), it is not known how different populations respond to specific compounds. Geographically separate populations may also respond differently to on-farm conditions such as weed infestation level or the presence of other crops.

The mean ratio of females to males in the sub-sample of twelve traps was 3.75. Sex ratios that are skewed towards females have been observed in pheromone trap catches for other coleopteran species with aggregation pheromones, such as the sugarcane weevil borer *Rhabdoscelus obscurus* Boisduval (Curculionidae) (Sallam et al. 2007) and the lesser grain borer *Rhyzopertha dominica* L. (Bostrichidae) (Edde and Phillips 2006), although other species such as the pales weevil *Hylobius pales* Herbst (Curculionidae) have similar numbers of males and females in traps (Fettig et al. 1998). The higher number of females in our study contrasts with others that have trapped approximately equal numbers of female and male banana weevils in Costa Rica (Ndiege et al. 1996, Jayaraman et al. 1997), although these studies did not report actual numbers of males and females. Similarly, a trial of pheromone traps in Uganda found ratios of 0.93-0.96 females to 1 male (Tinzaara 2000). Nonetheless, a mark-recapture study in Uganda recovered an approximate ratio of 2.5 females to 1 male in pheromone-baited pitfall traps (Tinzaara et al. 2005a), and field trials of Cosmolure+ in South Africa found female to male ratios ranging from 3.3 to approximately 4.25 (DeGraaf et al. 2005). Further study would be necessary to determine the conditions under which more females than males arrive at pheromone traps, such as seasonal differences between males and females in activity or responsiveness to the pheromone.

The female-biased ratios of weevils caught in pheromone traps could represent the actual numbers of females and males in the population; however, most studies using methods other than pheromone trapping have found sex ratios close to 1:1 (Gold et al. 2001). Alternatively, female-biased ratios may indicate that females respond more strongly to the pheromone than males. Female banana weevils made significantly more visits than males to male-produced volatiles in olfactometer bioassays, and EAG responses to male-produced volatiles were larger for females than for males (Budenberg et al. 1993). Differences between numbers of females and males captured may also reflect differences in activity of the sexes. Female banana weevils have been observed to move greater distances than males in a mark-recapture experiment (Gold and Kagezi unpublished data, cited in Gold 2001), and it is not known how environmental differences among geographical locations and agroecosystems might affect female and male activity. Weevil response to the pheromone involves a synergistic interaction with host plant volatiles (Tinzaara et al. 2003), and this interaction could differ between males and females in agroecosystems with different varieties of banana or plantain.

Tinzaara et al. (2002) hypothesized that if mated weevils did not respond to pheromone lures, use of the traps would be unlikely to suppress weevil populations. Dissections of females from trap catches in this study show that mated females in Costa Rican plantain farms do respond to the pheromone lures. Only one virgin female was found among the 96 females dissected; all others (99%) had mated. Females become sexually mature at 5 to 20 days after emergence (Uzakah 1995, cited in Gold et al. 2001), and following mating can oviposit for up to 11 months without additional mating (Cuille 1950, cited in Gold et al. 2001). Since banana weevil populations have overlapping generations in which adult weevils can live for 2-4 years (Gold et al. 2001), and females mate within a few days following emergence and likely retain sperm for several months, the high proportion of mated females in trap catches may simply reflect the proportion of mated females in the population. Studies in Tonga found that 4% of female weevils were infertile (Litsinger 1974, cited in Gold et al. 2001), indicating a low percentage of unmated females in the population although the methods used to determine this are not known. Dissections of banana weevils coming to Cosmolure+ traps in

South Africa found that approximately 10% of females had no eggs (DeGraaf et al. 2005); this may overestimate the percentage of unmated females, since it may include mated weevils that have not yet developed eggs. Alternatively, the virtual absence of unmated females in pheromone trap catches in this study could indicate that virgin females are less responsive to the aggregation pheromone; however, this would contradict patterns found in other species in which unmated females are more responsive (Anton et al. 2007).

Our results indicate that pheromone traps effectively reduce banana weevil damage in the smallholder plantain farms of Talamanca, Costa Rica. Further efforts to promote the traps and make them available are necessary if traps are to be adopted by plantain farmers in the indigenous territories. Although the lures are produced within Costa Rica, the sale of agricultural inputs is currently through the middlemen who buy plantains from indigenous farmers for either export or sale to the national market (Polidoro et al. 2008). A few agricultural supply stores exist within the territories, and these may provide a means of distribution of the traps. This situation highlights the need not only for alternative pest management technologies, but for access to them within the indigenous territories. Further research on alternatives to pesticides, as well as improved infrastructure to promote and distribute them, could greatly benefit Bribri and Cabécar communities by increasing the quality of both their public health and their natural resources.

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Table 4.1. Characteristics of farms with pheromone traps.

Farm	Community	Size (ha)	No. traps	Dates of trapping	Landscape context
T1	Bambú	0.58	2	5/12/06 – 6/22/07	Adjacent to plantain and organic banana on all sides
T2	Bambú	1.62	8	5/19/06 – 6/29/07	Adjacent to river on one side and surrounded by secondary forest
T3	Isla Lari	2.42	10	7/21/09 – 8/31/07	Adjacent to plantain on all sides
T4	Suretka	0.93	4	7/21/06 –9/28/07	Adjacent to river on one side, roads on two sides, and backyard gardens on one side
T5	Bambú	1.44	6	8/11/06 – 9/28/07	Adjacent to river on one side and surrounded by secondary forest
T6	Bambú	0.4	2	8/11/06 – 9/28/07	Adjacent to river on one side and surrounded by secondary forest

Table 4.2. Results of interview data in 2006, prior to placement of pheromone traps in trapping farms.

Farm	Age (yrs)	History	Extent of flooding	Extent of replanting	Planting before or after flood	Nematicides used	Frequency of fertilizer use	Soil type
C1	2	Shrub fallow	N	E	A	No	Low	S/C
C2	9	Shrub fallow	N	N	B	Yes	Low	S/C
C3	3	Pasture	P	P	B	Yes	Low	S/C
C4	4	Forest	N	N	B	Yes	Low	C
C5	1	Shrub fallow	E	E	A	Yes	High	S
C6	2	Plantain	E	E	A	No	Low	S
T1	2	Shrub fallow	E	E	A	No	Low	S
T2	4	Shrub fallow	P	P	B	Yes	High	C
T3	8	Cane fallow	N	N	B	Yes	Low	S
T4	2.5	Shrub fallow	E	P	A	No	Low	S
T5	5	Cacao	P	P	B	Yes	High	S
T6	4	Shrub fallow	P	E	B	Yes	High	C

Farms C1-C6 are control farms with no pheromone traps; farms T1-T6 are farms with pheromone traps.
Extent of flooding: E = entire farm flooded, P = part of farm flooded, N = no flooding.
Replanting after flood: E = entire farm replanted, P = part of farm replanted, N = not replanted.
Planting before or after flood: A = after, B = before.
Fertilizer use: High = more frequently than every 6 months, Low = every six months or less.
Soil type: S = sandy, C= clay, S/C= mixed sand and clay.

Table 4.3. Means of damage and yield measurements.

	Control farms		Trapping farms	
	2006	2007	2006	2007
Bunch weight (kg)	11.5 (±0.8)	10.6 (±0.3)	12.7 (±0.7)	14.1 (±0.7)
Number of hands	5.2 (±0.3)	5.3 (±0.2)	5.6 (±0.2)	6.0 (±0.1)
Number of fingers	27.4 (±1.7)	26.5 (±0.6)	28.8 (±0.8)	30.0 (±1.0)
Bunches sold as 1 unit instead of 2 for 1 (%)	34.4 (±11.4)	52.3 (±7.9)	52.6 (±7.5)	75.2 (±6.3)
Total damage (%)	2.6 (±0.9)	3.7 (±0.8)	5.1 (±0.5)	3.4 (±0.4)
Damage in central cylinder (%)	1.2 (±0.5)	2.1 (±0.7)	3.6 (±0.7)	2.4 (±0.6)
Damage in cortex (%)	3.5 (±1.0)	4.7 (±1.0)	6.1 (±0.5)	4.0 (±0.4)
Total square centimeters	25.5 (±8.7)	31.6 (±6.6)	48.3 (±2.9)	33.4 (±4.5)
% of total damage in central cylinder	13.5 (± 2.6)	21.3 (±4.1)	13.7 (±3.0)	18.7 (± 4.3)
Ratio central/cortex	0.28 (±0.06)	0.44 (±0.09)	0.59 (±0.11)	0.61 (±0.14)

Means of control farms in 2006 exclude Farm C6, which was withdrawn from the study in 2007.

Table 4.4. Damage measurements in 2006 and 2007.

Farm	Total damage (%)		Central cylinder damage (%)		Cortex (outside) damage (%)		Total damage (cm^2)	
	2006	2007	2006	2007	2006	2007	2006	2007
C1	1.5	1.3	0.68	0.62	2.3	1.8	10.2	13.0
C2	5.2	3.9	3.0	0.92	6.4	5.5	50.9	40.3
C3	4.2	3.3	2.0	1.8	5.6	4.1	40.0	23.2
C4	1.3	6.2	0.31	4.0	1.8	7.8	20.3	50.7
C5	1.0	4.0	0.21	3.3	1.5	4.5	6.0	31.0
C6	2.5	-	1.8	-	2.9	-	24.9	-
T1	6.5	3.5	5.9	1.4	7.3	4.7	47.0	23.6
T2	3.6	3.8	1.9	1.8	4.7	5.0	44.4	52.5
T3	4.3	4.8	1.7	5.5	5.6	4.4	41.1	40.3
T4	5.0	2.2	2.7	1.2	6.5	2.8	48.0	26.0
T5	6.4	3.1	4.7	2.4	7.7	3.5	62.0	27.4
T6	4.8	3.0	4.9	2.3	4.9	3.5	47.2	30.9

Farms C1-C6 are control farms with no pheromone traps; farms T1-T6 are farms with pheromone traps. The owner of Farm C6 withdrew from the study in 2007.

Table 4.5. Yield measurements in 2006 and 2007.

Farm	Bunch weight (kg)		Number of hands		Number of fingers		Sold as a unit (%)	
	2006	2007	2006	2007	2006	2007	2006	2007
C1	13.4	11.7	6.0	5.3	32.0	25.8	66.7	41.7
C2	10.6	10.2	5.4	5.2	25.5	24.7	20.0	30.0
C3	8.9	10.8	4.3	4.9	21.8	26.8	0.0	70.0
C4	12.65	9.9	5.0	5.4	28.6	27.1	40.0	50.0
C5	11.8	10.6	5.4	5.8	28.7	28.2	45.5	70.0
C6	11.3	-	5.1	-	24.3	-		-
T1	12.9	14.1	6.0	5.7	28.0	27.3	56.3	55.6
T2	15.1	16.8	6.1	6.5	33.0	32.3	69.2	85.7
T3	10.0	12.0	5.1	5.8	27.9	27.9	46.7	70.0
T4	11.4	14.2	5.1	5.9	27.6	32.9	20.0	100.0
T5	13.9	15.3	5.7	5.9	28.4	31.7	53.3	70.0
T6	12.9	12.4	5.7	5.9	27.8	28.0	70.0	70.0

Farms C1-C6 are control farms with no pheromone traps; farms T1-T6 are farms with pheromone traps. The owner of Farm C6 withdrew from the study in 2007.

Table 4.6. Correlation of weekly trap catches and weekly rainfall.

Farm	T1	T2	T3	T4	T5	T6
Rainfall recorded in Shiroles	R^2 = 0.00063 P = 0.86	R^2 = 0.00013 P = 0.93	R^2 = 0.018 P = 0.32	R^2 = 0.000088 P = 0.94	R^2 = 0.075 P = 0.038	R^2 = 0.10 P = 0.013
Rainfall recorded in Bambú	R^2 = 0.0098 P = 0.72	R^2 = 0.11 P = 0.16	R^2 = 0.028 P = 0.40	R^2 = 0.012 P = 0.57	R^2 = 0.0070 P = 0.65	R^2 = 0.024 P = 0.40

Table 4.7. Mean trap catches and total damage before and after trapping.

	Mean trap catches in first and last three months		Total damage	
Farm	2006	2007	2006	2007
T1	32.6	28.111	6.5%	3.5%
T2	15.4	15.114	3.6%	3.8%
T3	14.4	11.133	4.3%	4.8%
T4	20.2	12.417	5.0%	2.2%
T5	42.4	13.764	6.4%	3.1%
T6	32.5	11.917	4.8%	3.0%

Trap catch means are taken from the first and last three months of 58 weeks of trapping.

Figure 4.1. Map of the Valle de Talamanca with location of plantain farms.

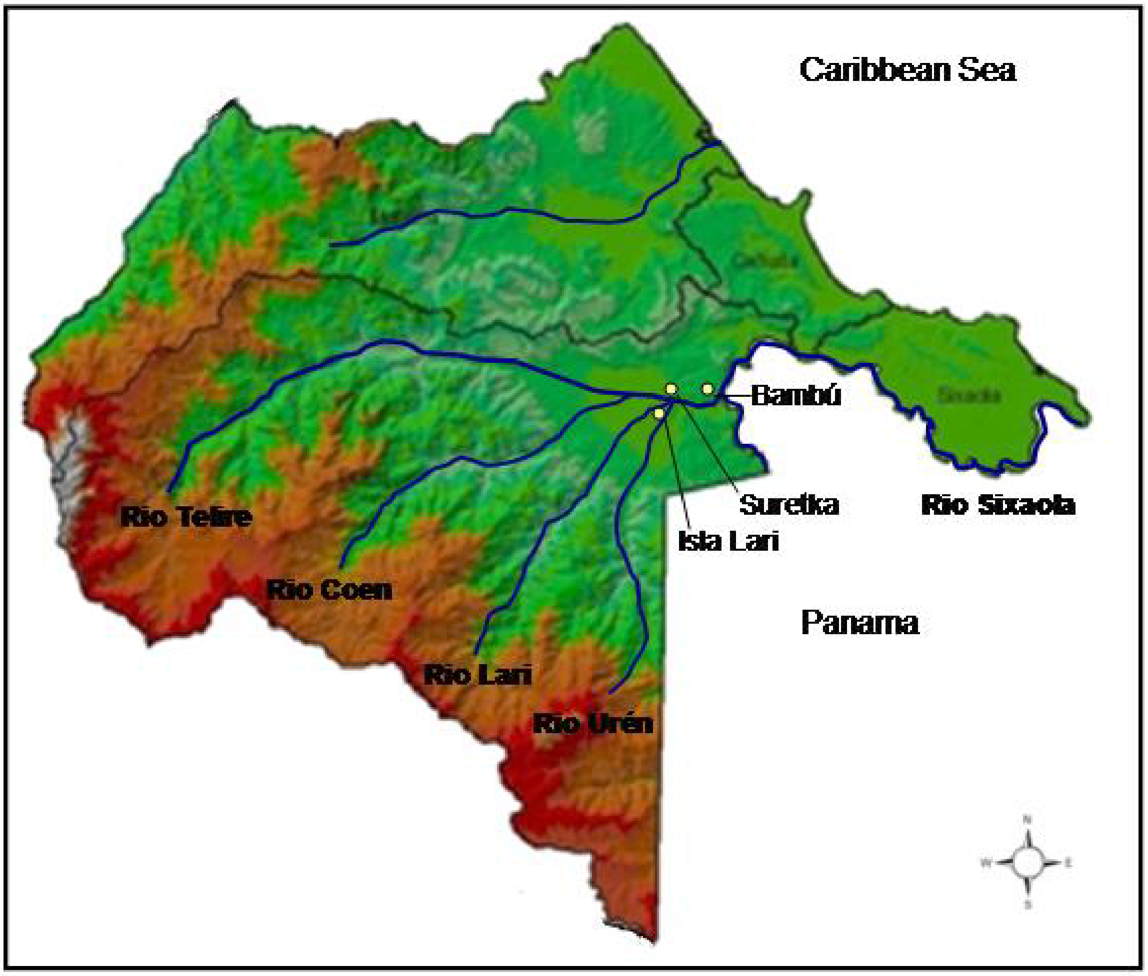


Figure 4.2. Movement of pheromone traps in a grid of 20 m spacing within a 1 ha section of farm.

The line of four traps was moved 20 m forward every 4-5 weeks, and was returned to its original location after three forward movements to begin the cycle again.

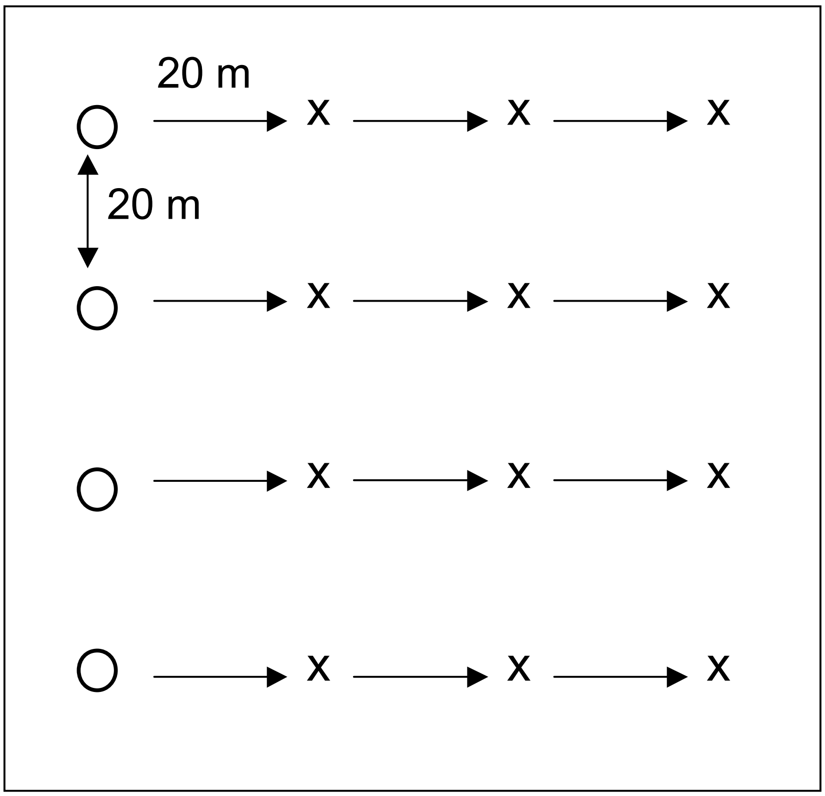


Figure 4.3. Total corm damage in 2006 and 2007 in trapping and control farms.

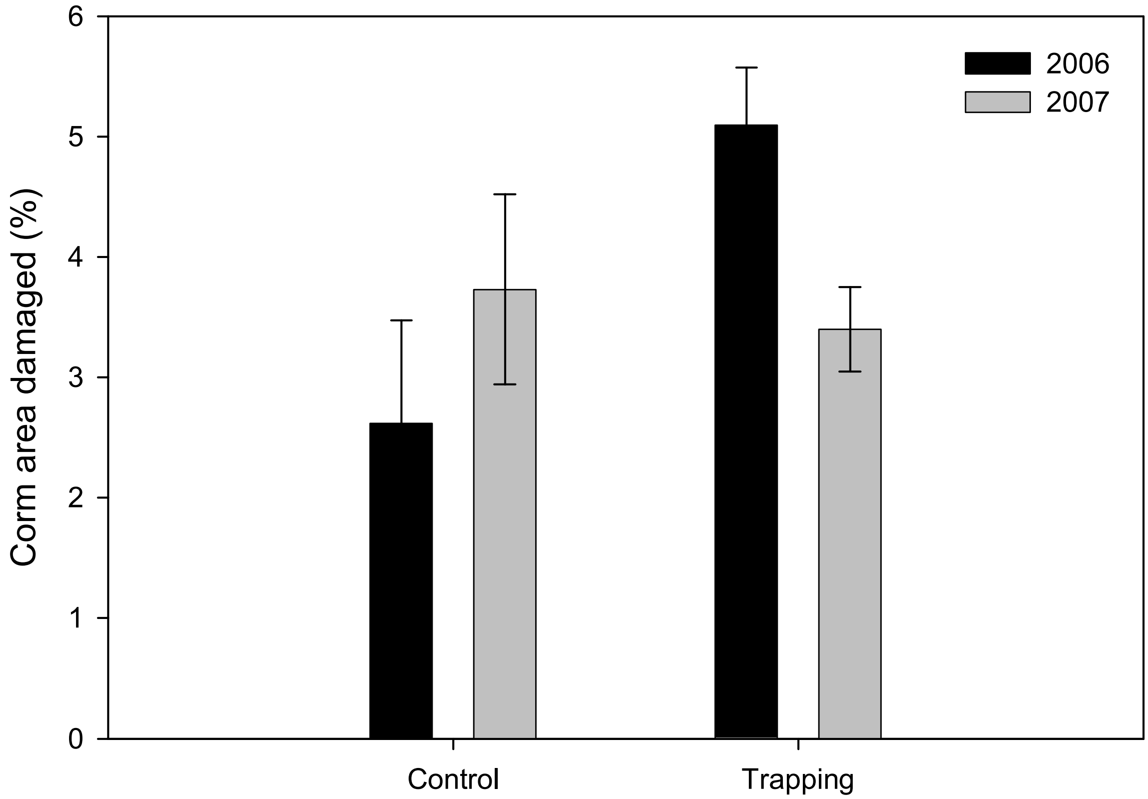


Figure 4.4. Plantain bunch weight in 2006 and 2007 in trapping and control farms.

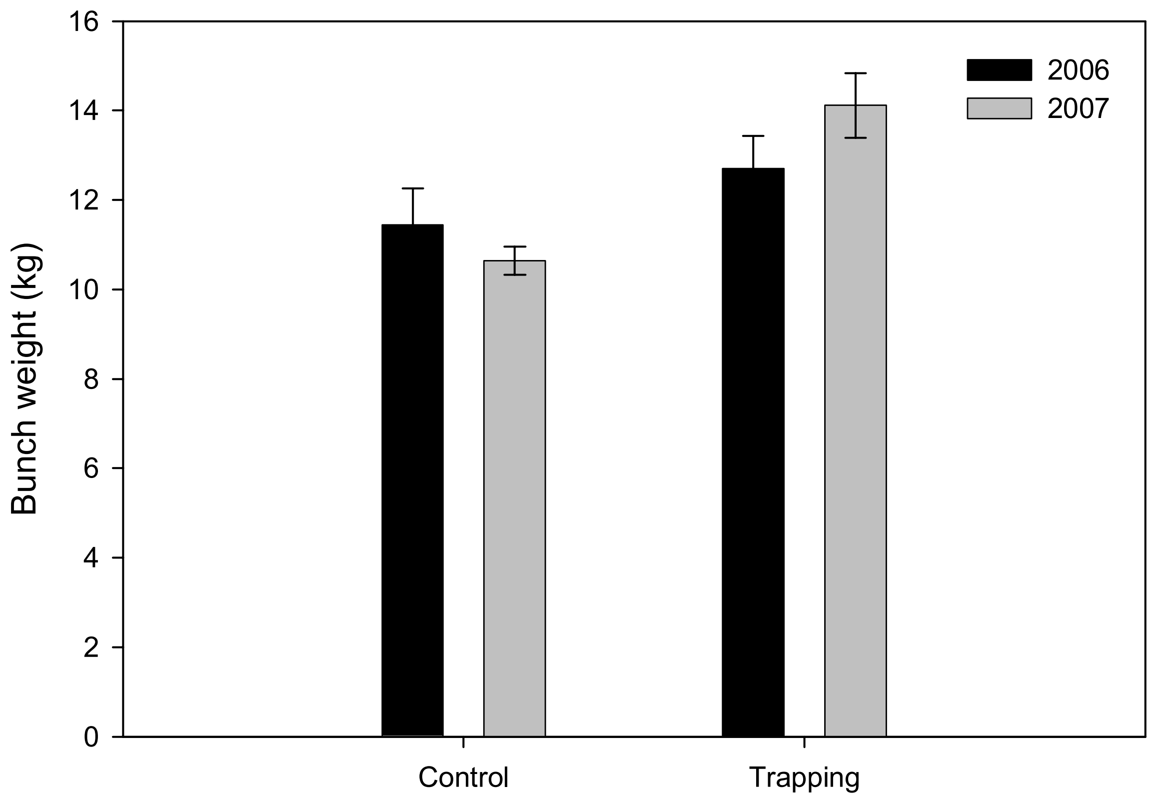


Figure 4.5. Means of trap catches for trap rotation periods (each period is 4-5 weeks).

A) Farm 1 ($R^2 = 0.08$, P=0.31), B) Farm 2 ($R^2 = 0.03$, P=0.56), C) Farm 3 ($R^2 = 0.02$, P=0.69), D) Farm 4 ($R^2 = 0.20$, P=0.11) E) Farm 5 ($R^2 = 0.65$, P=0.0005), and E) Farm 6 ($R^2 = 0.30$, P=0.04).

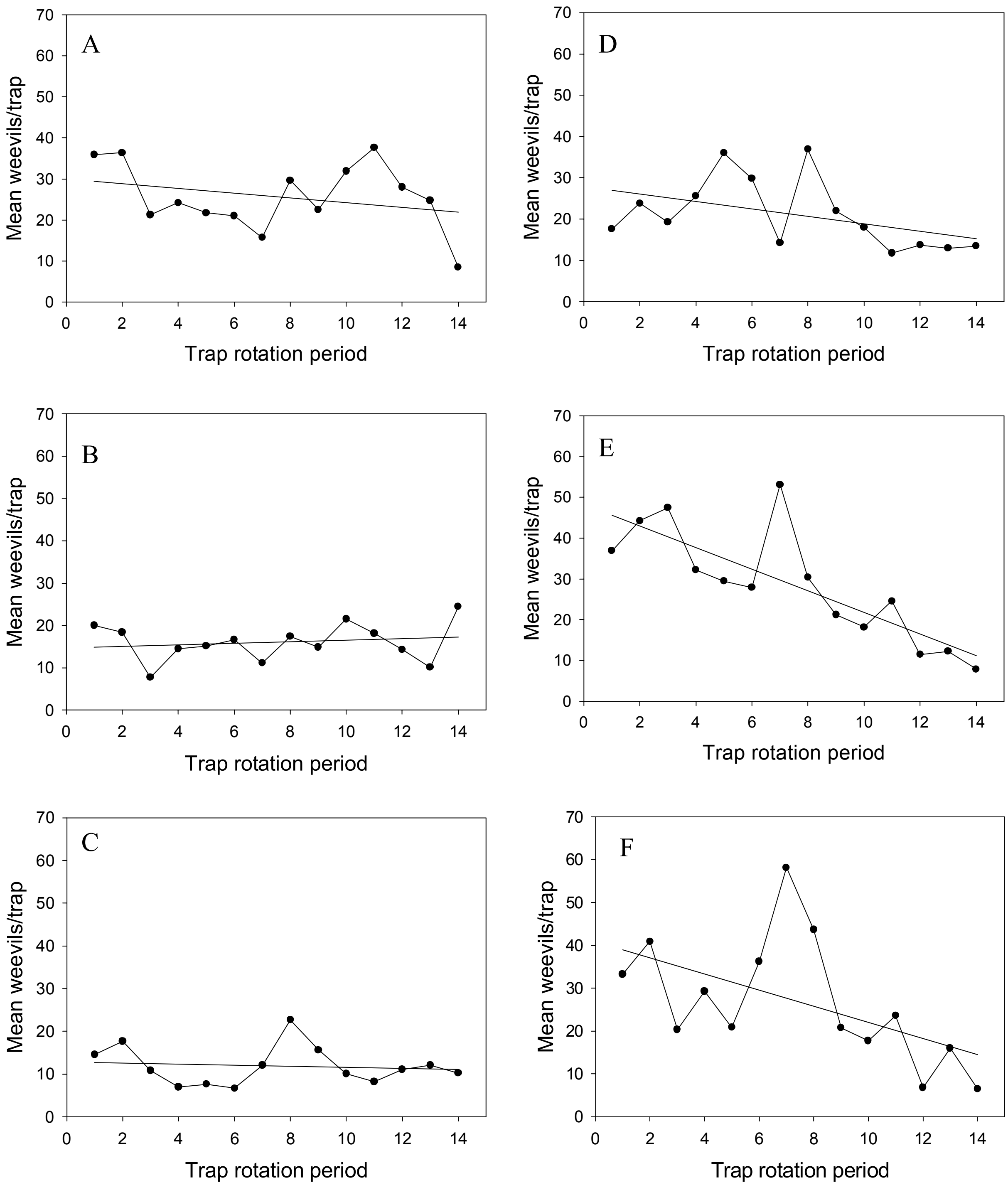
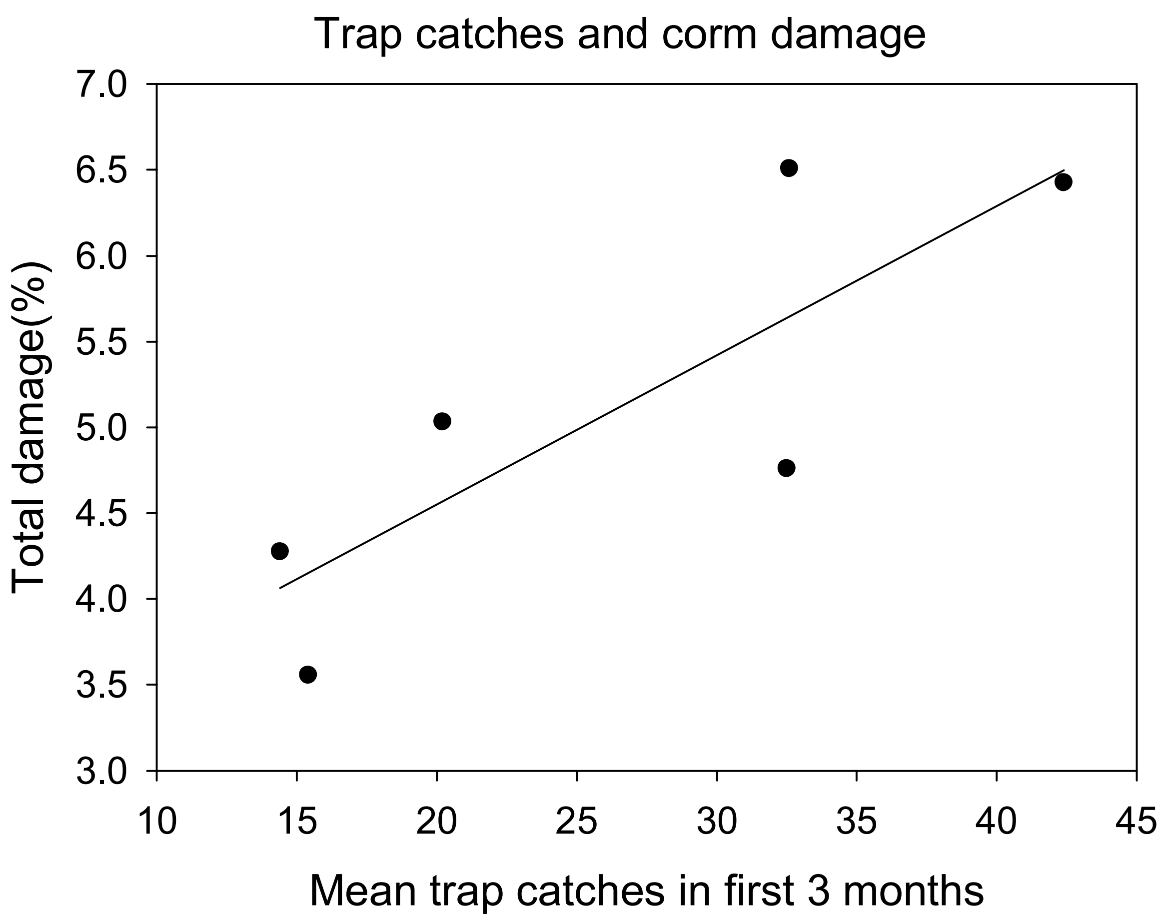


Figure 4.6. Total corm damage vs. mean of trap catches in the first three months of trapping.

$d = 0.087*n + 2.812$, where d = total damage and n = mean number of weevils per trap in the first three months. $R^2 = 0.69$, P=0.04.



Chapter 5: Movement patterns of the banana weevil *Cosmopolites sordidus* (Germar) in relation to its host plant in Costa Rica

Abstract

The banana weevil (*Cosmopolites sordidus* Germar) is a pest of bananas and plantains (*Musa* spp.) throughout the tropics, and has been shown to be attracted to volatiles of its host plant. Previous studies on banana weevil orientation to volatiles demonstrated that weevils oriented upwind to host plant volatiles under controlled conditions of constant airflow. In order to test banana weevil orientation to host plant volatiles under field conditions in Costa Rica, we used harmonic radar to track nightly movement of individual females. Harmonic radar tags consisting of a diode and wire antenna were glued to the elytra. Tagged weevils were released in hexagonal arrays of six weevils. Each replication consisted of four arrays: 1 m from banana pseudostem tissue, 2 m from a banana pseudostem tissue, and control arrays 1 or 2 m from a center point that did not contain banana pseudostem tissue. After each night, individual weevils were located with harmonic radar and their distance, bearing, and depth in soil recorded. Weevils released in the presence of banana pseudostem tissue moved significantly farther and burrowed less deeply in a 24-hour period than weevils in control arrays. The angle with respect to the center of the array was smaller in the presence of banana pseudostem tissue, and movement was oriented at a release distance of 1 m from the banana pseudostem tissue. The distance of release did not affect the number of weevils arriving at the banana pseudostem tissue. A separate double-marking experiment showed that tag attachment did not affect ability to reach banana pseudostem tissue. We conclude that harmonic radar is an appropriate method for the study of short-range insect movements in the tropics, and that the banana weevil responds to host plant volatiles under field conditions at 1 and 2 m distances.

Introduction

The banana weevil (*Cosmopolites sordidus* Germar) is a pest of banana and plantain (*Musa* spp.) throughout the tropics, where it is narrowly oligophagous on two genera, *Musa* and *Ensete* (Gold et al. 2001). Attraction to host plant volatiles from corm, pseudostem, and senescing leaf tissues has been demonstrated, suggesting that the banana weevil uses host plant volatiles in host location. Previous studies of banana weevil response to host plant volatiles have shown attraction in olfactometer bioassays at distances of approximately 5 cm to corm and pseudostem material (Budenberg et al. 1993), 10 cm to pseudostem, corm, and senescing leaf material (Braimah and van Emden 1999), and 50 cm to corm and pseudostem material (Cerda et al. 1996). Weevils were also shown to orient upwind (anemotaxis) to pseudostem material on a locomotion compensator under controlled conditions of constant airflow at 2 m (Tinzaara et al. 2003). However, orientation to volatiles has not been evaluated under field conditions of plant spacing and airflow. Plant spacing in banana or plantain farms ranges from 2-4 m in commercial plantations (Stover and Simmonds 1987) and can be much greater in subsistence polycultures. Wind speed and direction at ground level in farms are likely to be low and variable.

The banana weevil is a pest in smallholder plantain and organic banana farms in the Bribri-Cabécar Indigenous Territories of Talamanca, Costa Rica. Farmers interviewed in a rapid rural appraisal conducted in the indigenous territories in 2004 (Polidoro et al. 2008) mentioned reinvasion of banana weevils from neighboring farms as a possible disincentive to managing for the banana weevil. Smallholder banana and plantain farms within the indigenous territories are small (0.25-3 ha), and many are adjacent to other farms. Adjacent farms may be contiguous, with land of different owners marked by shrubs between rows of plantain or banana mats, which are generally spaced at 3 m. In other cases, adjacent farms are separated by a few meters of vegetation, a road, or similar feature. Banana weevil responses to host plant volatiles have not been evaluated at distances above 50 cm. An improved understanding of the distance from which the banana weevil can locate its host plant would be useful in this landscape, in which banana and plantain plants belonging to different farms are separated by distances of a few meters.

Although the banana weevil apparently has functional wings, it has never been directly observed to fly (Gold et al. 2001) and is assumed to move only by crawling. Banana weevil movement is nocturnal, and nightly movement rates calculated from previous studies range from 0.03 m per night (Gold and Kagezi unpublished data, cited in Gold et al. 2001) to 15 m per night (Cendana 1922, cited in Gold et al. 2001). Harmonic radar has been used successfully to track movements of carabid beetles on the ground (Mascanzoni and Wallin 1986, Wallin and Ekbom 1994, O'Neal et al. 2004). Insects are tagged with a small, light diode that reflects a radar signal at a harmonic frequency of the transmitted signal. The diode can be attached to a light, short wire to increase the range of detection. Tagged weevils can be released and relocated with a portable radar transmitter and detector unit.

We employed the harmonic radar technique to answer the following questions: 1) Do banana weevils orient toward host plant tissue under field conditions at 1 and 2 m? 2) How does the presence of host plant tissue affect weevil movement? and, 3) Does the distance of release affect the ability of weevils to find their host plant?

Materials and methods

The study was conducted on the commercial farm of the Tropical Agricultural Research and Higher Education Center (CATIE) in Turrialba, Costa Rica. At 700 masl, this area has an average yearly temperature of 21 °C and annual rainfall of 2600 mm. Banana weevils were collected from banana fields on the CATIE grounds using pheromone traps (Ndiege et al. 1996). Traps consisted of a pitfall trap made out of a 600 ml plastic soda bottle. Square openings (4 x 8 cm) were cut on two opposing sides for weevil entry approximately 8 cm from the base, and the packet of lure (Cosmolure+, ChemTica, Heredia, Costa Rica) was suspended inside the trap from the lid of the bottle. Traps were buried in the soil up to the bottom edge of the openings, with small holes cut in the base of the bottle to prevent filling with water. Weevils were collected every three days and maintained on pieces of banana pseudostem (cv. Gros Michel) in a plastic bucket.

A field (0.12 ha, 60 x 20 m) on the CATIE grounds that previously had only weeds was cleared. Four circular plots within the field were manually hoed weekly to keep soil loose and free of weeds, and the rest of the field was allowed to grow back. Within each plot, points for weevil release were marked in a hexagonal array. Each array had six release points at equal distances from each other and from the center, at a distance of 1 m in two of the plots and 2 m in the other two plots. The top side of the hexagon was oriented along an east to west line using a compass (Fig. 5.1). A 4-m buffer was kept clear of vegetation around the edge of the hexagonal arrays, so that the plots with 1-m arrays had a diameter of 10 m and the plots with 2-m arrays had a diameter of 12 m. Release points at the corners of the hexagons were marked with wooden stakes, as metal flags interfered with harmonic radar location. The base of the stake was set 10 cm west of the release point to avoid interference with weevil movement.

Banana weevil males produce an aggregation pheromone to which both males and females are attracted (Ndiege et al. 1996). To avoid effects of attraction of weevils to each other, only female banana weevils were used. Weevils were sexed according to the pattern of punctuations on the rostrum (Longoria 1968) and the angle of inclination of the ninth abdominal segment (Roth and Willis 1963). Females were starved for 30 hours before release, provided water and kept in a plastic container. Tags were attached the day before weevil release. Tags consisted of a 4.3 mg Schottky barrier diode (SD101BWS from General Semiconductor, now Vishay, http://www.vishay.com/) soldered to an 8 cm antenna of fine gauge (0.07 mm) Teflon coated iron wire (product # TFIR-003-50, Omega Engineering Inc., www.omega.com) (O'Neal et al. 2004). Each tag weighed approximately 22 mg, while an individual female weevil weighed approximately 112 mg. The antenna wire was painted with nail polish to identify individual weevils, and each weevil was marked with a distinctive pattern of scratches on the elytra corresponding to its position of release. Weevils were removed from the plastic container, allowed to dry, and cleaned gently with a paper towel.

The surface of the elytra was scratched with a pin to roughen it before gluing. Weevils were kept immobile on the tip of a pipette attached to a vacuum pump. Tags were attached to the elytra with superglue gel, and weevils were kept on the vacuum pump until the glue had dried. Individual females were kept in separate plastic containers until the time of release.

Weevils were released in the four cleared plots in a randomized complete block design with a 2x2 factorial treatment structure. The two factors were distance of release (1 or 2 m from center of array) and presence or absence of banana pseudostem tissue. Each separate release of weevils was considered a block, with five releases conducted one at a time on February 19, March 7, March 14, April 13, and April 28, 2007. Each of the four plots was assigned to one of the following four treatments: 1) weevils released at corners of 1 m hexagonal array with banana pseudostem tissue in the center, 2) weevils released at corners of 1 m hexagonal array with nothing in the center, 3) weevils released at corners of 2 m hexagonal array with banana pseudostem tissue in the center, and 4) weevils released at corners of 2 m hexagonal array with nothing in the center. Banana pseudostem tissue was from cultivar Gros Michel (*Musa* AAA) collected from CATIE fields approximately 1 h before weevil release. Six tagged female weevils were released in each plot at dusk (5:30-6:00 p.m.) to avoid predation by birds. The cardinal direction each weevil was facing at release was randomly selected.

Weevils were located the following morning and an additional 1-4 days following release, depending on the length of time they survived in the plots, using a handheld RECCO harmonic radar transmitter/receiver unit (RECCO Rescue Systems, Lidingo, Sweden, www.recco.com). When a weevil was located, its position was marked with a wooden stake 10 cm to the west. The distance traveled the night before and the bearing of movement from the previous position was determined using a measuring tape and compass (Wallin and Ekbom 1988). The depth of weevils buried in the soil was measured in centimeters using the end of a marked pencil, taking care not to completely unearth the weevil. Banana pseudostem tissue was examined each morning for presence of weevils.

The average wind speed and direction, temperature, and humidity were measured each night at 5 min intervals with a Vantage Pro 2 weather station with an anemometer and datalogger (Davis Instruments, Hayward, CA). The anemometer was placed 10 cm above soil level to record wind speed and direction near the surface of the ground.

A separate double-marking experiment was conducted to evaluate the effects of tagging on weevil movement (Turchin 1998) on May 7-9, 2007 in the same four cleared plots described above. In each plot, a hexagonal array with 1 m spacing was marked for weevil release, and six additional release points were marked at 1 m from the center between the corners of the array, for a total of 12 release points. A piece of banana pseudostem tissue was placed at the center of each array. Six tagged and six untagged weevils were released at dusk on May 7. The number of tagged and untagged weevils reaching pseudostem pieces was recorded for three days.

Data analysis

Orientation towards banana pseudostem tissue

The angle of movement with respect to the center of the hexagonal array (angle to center) was calculated as an absolute value between 0 and 180° (Fig. 5.1). Data for angle to center were not normally distributed. The effects of experimental block and the two treatment factors (distance of release and presence/absence of banana pseudostem tissue) on the angle to center were analyzed with a three-way rank-based ANOVA (available at http://www.stat.wmich.edu/slab/RGLM/). The effect of presence of banana pseudostem tissue on the angle to center was analyzed without consideration to distance of release with a one-way circular ANOVA using the high concentration multisample F-test, assuming a von Mises distribution (Mardia and Jupp 2000, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS). The effect of distance of release (corners of 1-m vs 2-m arrays) on the absolute value of the angle to center was analyzed without respect to presence/absence of banana pseudostem tissue with a separate one-way circular ANOVA. The angle to center was analyzed with a one-sample Wilcoxon signed-rank test to determine significant difference from 90° and distribution-free 95% confidence intervals for each combination of treatment factors (available at http://www.stat.wmich.edu/slab/RGLM/).

Movement distance and depth in soil

Net displacement was calculated from bearing and movement distance measurements, total path length was calculated as the sum of all movement distances, and straightness was calculated as net displacement/total path length. All movement variables and depth in soil were not normally distributed. The effects of experimental block and the two main factors (distance of release and presence/absence of banana pseudostem tissue) and on the distance moved per night, and depth in soil were analyzed with a three-way rank-based ANOVA (available at http://www.stat.wmich.edu/slab/RGLM/). The number of weevils arriving at the banana pseudostem tissue (Braimah 1997) was compared between 1 and 2 m release distances with a Wilcoxon signed-rank test (SAS Institute, 2001).

Environmental variables

Average wind speed, temperature, rainfall, and humidity were calculated for each night. Average wind direction for each night was calculated by converting wind speed and direction to a vector with x, y components and calculating the true vector average of all measurements for that night (http://www.ndbc.noaa.gov/wndav.shtml). Angular dispersion in wind direction was calculated as the mean vector length, $r = \sqrt{(x^2 + y^2)}$, where x and y are the average cosine and sine values of the sample of angles (Batschelet 1981). The average wind direction over all nights was calculated, and the six positions of release were categorized with respect to wind direction as upwind, downwind, or perpendicular to wind. The effect of release position with respect to wind direction on movement variables was analyzed with a three-way ANOVA with presence/absence of banana pseudostem tissue, release distance, and release position as factors and including interaction terms (SAS Institute, 2001).

Pearson correlation coefficients were determined for wind speed, temperature, rainfall, and humidity and the following movement parameters: distance moved per night, depth in soil, net displacement, straightness, and distance from center. Correlation between bearing and wind direction was determined using a circular correlation coefficient (Jammalamadaka and Sarma 1988, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS) over all treatment combinations and separately for presence and absence of banana pseudostem tissue.

Movement patterns

Autocorrelation in move length was analyzed by determining the first-order correlation coefficient, which is the correlation coefficient between all pairs of move lengths on successive days (Turchin 1998). Autocorrelation in direction of movement was analyzed by determining a circular correlation coefficient between all pairs of bearing measurements on successive days (Jammalamadaka and Sarma 1988, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS).

The effect of presence of banana pseudostem tissue on turning angle was analyzed without respect to distance of release with a one-way circular ANOVA using the high concentration multisample F-test, assuming a von Mises distribution (Mardia and Jupp 2000, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS). Turning bias was evaluated with a binomial test on the numbers of right and left handed turns. The empirical mean vector and angular dispersion of all turning angles was calculated.

Effects of release position, direction, and tagging

Correlation in the direction of release and direction of movement in the first night after release was analyzed by determining a circular correlation coefficient (Jammalamadaka and Sarma 1988, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS). The effect of position of release in the hexagonal array (positions 1-6) on movement distance, depth, net displacement, and straightness was analyzed with a three-way ANOVA with presence/absence of banana pseudostem tissue, release distance, and release position as main factors and including interaction terms (SAS Institute, 2001). The effect of position of release on angle to center and bearing was analyzed without respect to distance of release with a circular ANOVA over all treatment combinations and separately for plots with and without banana pseudostem tissue (Mardia and Jupp 2000, available at http://statweb.calpoly.edu/ulund/index.html#CircSAS). The effect of position of release on the number of weevils from each position arriving at banana pseudostem tissue was analyzed with a Kruskal-Wallis test (SAS Institute 2001). In the double-marking experiment, numbers of tagged and untagged weevils arriving at banana pseudostem tissue were compared with a signed-rank test (SAS Institute 2001).

Results

Orientation towards banana pseudostem tissue

The average bearings for weevils in each position of release are shown in Fig. 5.2 a-d. The angle with respect to the center of the hexagonal array was significantly smaller in the presence of banana pseudostem tissue ($P = 0.0014$, three-way rank-based ANOVA) (Fig. 5.3). Distance of release (1 or 2 m) did not have a significant effect on the angle with respect to center ($P=0.43$, three-way rank-based ANOVA). Similarly, when analyzed with a one-way circular ANOVA, the mean angle to center was significantly smaller in the presence of banana pseudostem tissue (64.9°) than in the absence of banana pseudostem tissue (102.4°) ($P=0.00053$) and there was no effect of distance of release on the angle to center ($P=0.60$). The angle with respect to center was significantly different from 90° at the release distance of 1 m with banana pseudostem tissue ($P = 0.0085$, 95% CI's 44.2 to 84.5), indicating oriented movement, but was not different from 90° at 2 m with banana pseudostem tissue ($P=0.069$, 95% CI's 52.0 to 92.1) or without banana pseudostem tissue at 1 m ($P=0.22$, 95% CI's 81.7 to 119.5) and 2 m ($P=0.16$, 95% CI's 85.2 to 123.0).

Movement distance and depth in soil

The mean distance moved per night over all blocks and treatment combinations was 51.3 ± 5.4 cm, with a maximum distance of 380 cm. The distance moved per night was significantly greater in the presence of banana pseudostem tissue (P=0.0034) (Fig. 5.4). Distance of release (1 or 2 m) did not have a significant effect on the distance moved per night (P=0.43). The depth of weevils buried in the soil during the day was significantly more shallow in the presence of banana pseudostem tissue (P = 0.00018) (Fig. 5.5), but distance of release had no effect (P=0.33) on burrowing depth. In the plots with banana pseudostem tissue, the distance of release (1 or 2 m) did not have a significant effect on the number of weevils arriving at the piece of banana pseudostem tissue (P = 0.50).

Environmental variables

The average nightly temperature was 19.5 °C, and the average humidity was 93.8%. Average soil moisture was 21.9%, and ranged from 12.6% to 29.1%. Soil moisture was lower than expected due to an unusually strong dry season. Rainfall occurred on 5 of the 17 nights, with an average of 2.8 mm per night for those five nights. Wind speed was generally low, and was highest in the early evening. On most nights, wind speed ranged from 0.4 to 2.7 m/s between 18:00 and 19:40 hours and was either zero or too low to be recorded by the anemometer for the rest of the night. On two nights, wind speed was recorded throughout the night, and on several nights no wind movement was detected. Average nightly wind direction was consistently from the northeast. The average wind bearing was 38.4. Angular dispersion around the mean was r = 0.92, indicating that wind bearing values were concentrated close to the mean.

There was a weak but significant negative correlation between distance moved per night and nightly average wind speed (R^2=0.027, P=0.035) and the maximum wind speed for each night (R^2=0.033, P=0.0079). No correlations were detected between movement parameters and temperature, humidity, or soil moisture. The bearing of movement was not correlated with wind direction over all treatment combinations (R^2=0.0076, P=0.13), in the presence (R^2=0.014, P=0.081) or in the absence (R^2=0.0011, P=0.69) of banana pseudostem tissue. Position of release with respect to wind direction (upwind, downwind, or perpendicular) had no effect on movement distance (P=0.23), bearing (P=0.62), angle to center (P=0.55), depth (P=0.11), angle with respect to wind (P=0.78), net displacement (P=0.94), or straightness (P=0.38). Within plots with banana pseudostem tissue, position of release with respect to wind direction had no effect on the angle to center (P=0.24) or the angle of movement with respect to wind (P=0.28). Position of release with respect to wind direction also had no effect on the angle to center (P=0.44) in plots without banana pseudostem tissue.

Movement patterns

There was no correlation between the bearing of movement on successive pairs of nights (R^2=0.005, P=0.38) or between movement distances on successive nights (P=0.58). Turning angles were uniformly dispersed (r=0.06) with a mean angle of 90.4° calculated from the empirical mean vector. There was no right or left bias in the turning angle (P=0.59). There was no effect of presence of banana pseudostem tissue on turning angle (P=0.58).

Effects of release position, direction, and tagging

Bearing of movement measured on the first day after release was not correlated with the direction of release (R^2=0.03, P=0.08). Position of release in the hexagonal array (positions 1-6) had no effect on movement distance (P=0.70), depth (P=0.39), net displacement (P=0.58), or straightness (P=0.31). Position of release had no effect on angle to center analyzed over all treatment combinations (P=0.24) or for plots with banana pseudostem tissue (P=0.46) and without banana pseudostem tissue (P=0.14). In the presence of banana pseudostem tissue, position of release had no effect on the number of weevils from each position arriving at the pseudostem tissue (P=0.65).

Over all treatment combinations, the mean direction of movement calculated from the empirical mean vector of bearings was 173° with an angular dispersion of r=0.09. Since the angular dispersion is close to uniform and the standard deviation from the mean includes 180°, these data indicate no bias in the direction of movement due to factors outside the experimental plots. The mean direction of movement in the absence of banana pseudostem tissue was 121°, with angular dispersion of r=0.05, and in the presence of banana pseudostem tissue the mean direction of movement was 185°, with angular dispersion of r=0.15. In the double-marking experiment, there was not a significant difference between the number of tagged weevils (2.75 weevils per plot) and untagged weevils (2.25 weevils per plot) arriving at the banana pseudostem tissue ($P = 1.0$).

Discussion

Female weevils oriented towards banana pseudostem tissue when released at 1 m, and the angle to center was smaller in the presence of banana pseudostem tissue at both 1 and 2 m. This indicates that banana weevils can orient to host plant tissue under field conditions, and at greater distances than previously observed in olfactometer bioassays. Weevils released at both 1 and 2 m responded to host plant volatiles with increased movement (positive orthokinesis). These results contrast with the locomotion compensator study (Tinzaara et al. 2003), which found no increase in walking speed or total path length in the presence of banana pseudostem tissue compared to a control of clean air. While movement at the 2 m release distance in our tests was not oriented towards the banana pseudostem tissue, the response of positive orthokinesis indicates that volatiles can trigger a behavioral response at that distance. Weevils also responded to host plant volatiles at both 1 and 2 m distances by burrowing more shallowly than in the absence of their host plant. Additionally, foraging success was similar for weevils released at 1 and 2 m from banana pseudostem tissue, indicating that banana weevils can locate their host plant equally well from either distance.

Our results show that the banana weevil responds to banana pseudostem volatiles at a distance of at least 2 m. Attraction to volatiles from banana corm tissue at 50 cm (Cerda et al.

1996) and senescing leaf tissue at 10 cm (Braimah and van Emden 1999) has also been shown in the laboratory, but the maximum distances at which banana weevils respond to volatiles from different parts of the banana plant are not known. The radius of attraction of lures emitting the aggregation pheromone traps for the banana weevil has been estimated at approximately 10 m (Tinzaara et al. 2005). An additive response of increased movement and upwind fixation to pseudostem and pheromone volatiles has been observed compared to either pheromone or host plant volatiles alone (Tinzaara et al. 2003). The banana weevil is also known to exhibit thigmotaxis (Cuille 1950, cited in Gold et al. 2001; Treverrow 1994) and attraction to water (Roth and Willis 1963). It is likely that the process of host plant finding by the banana weevil includes several different modalities, each of which may operate at different distances.

We did not find evidence of anemotaxis in response to the presence of host plant volatiles. Downwind weevils did not reach the banana pseudostem tissue with greater frequency than weevils upwind or perpendicular to wind direction, and we observed no effect of wind direction on the direction of weevil movement, either for absolute direction (bearing) or direction with respect to banana pseudostem tissue (angle to center). These results contrast with those of the locomotion compensator study, in which weevils at 2 m from an odor source with constant airflow demonstrated positive anemotaxis and not orthokinesis (Tinzaara et al. (2003). Under field conditions of variable airflow, we observed orthokinesis but no anemotaxis at 2 m from banana pseudostem tissue. This may be due to variability of wind direction or absence of wind for most of the night. Since wind speed and direction were high enough to be recorded only in the first hour and a half after weevil release, weevil movement during the rest of the night may have been influenced by small-scale changes in the direction of wind speeds too low to record, or movement may have occurred in the absence of a consistent wind direction. However, the consistent direction of wind from the northeast (38°) indicates a general direction of wind in the experimental plots to which weevil movement can be compared.

Female banana weevils displayed oriented movement (chemotaxis) and orthokinesis at 1m, and orthokinesis only at 2 m. These responses are consistent with patterns observed for other insects in which chemotaxis occurs in response to steep concentration gradients of volatiles near the odor source, but not at longer distances due to dispersion of odors by turbulent eddies (Visser 1986). Many insects exhibit odor-conditioned anemotaxis upon perception of an odor stimulus at longer distances from an odor source (Visser 1986). Although we did not observe anemotaxis, it is interesting that we observed positive orthokinesis in the field, when it was not observed in the laboratory. It is possible that banana weevil responses to odor stimuli at longer distances are different in the presence or absence of wind, as has been observed for the grain beetle *Trogoderma variabile* (Tobin and Bell 1986). For example, upon perception of an odor stimulus a banana weevil might respond with positive anemotaxis in the presence of a constant wind direction, and with positive orthokinesis if no wind direction is perceptible. We also observed no anemotaxis in the absence of host plant volatiles, which is consistent with the results of Tinzaara et al. (2003), who found no orientation to a stream of clean air. This indicates that the banana weevil does not use anemotaxis to search for chemical cues in the absence of a stimulus. However, movement may be affected by wind speed. The slight negative correlation between wind speed and distance moved per night suggests that banana weevils move shorter distances at higher wind speeds.

We observed a mean movement distance of 51 cm per night, with a maximum per night of 380 cm. Previous measurements of banana weevil movement include maximum rates of 15 m per night (Cendana 1922), 60 m in five months (Delattre 1980), 35 m in three days (Gold and Bagabe 1997), and 21 m in 14 days (Wallace 1938). These rates correspond to 15, 0.4, 11.7 and 1.5 m/night, respectively. Some weevils remained inactive throughout the days of location following release, and some were inactive on the first night or few nights but moved on later nights. These results are consistent with previous observations that banana weevils may remain inactive for a period of time (Gold et al. 2001). There was no autocorrelation in movement distance or direction of movement of individual weevils from night to night. Turning angles were not biased to the right or to the left, and were not affected by the presence of banana pseudostem tissue. Since movements were measured for each night, with approximately 12 h of daylight separating one movement from the next, this lack of correlation is not surprising; we did not measure a continuous track, but the result of all movements over an entire night separated from the next night. These results indicate that banana weevils searching for their host plant do not maintain the same direction from night to night. This behavior may avoid an unproductive searching direction (Bell et al. 1995).

This study presents the first use of harmonic radar under tropical conditions of heat and humidity. While the range of tag location is limited on ground (O'Neal et al. 1994), this method is appropriate for studying insect movement on the ground at short (1-4 m) movement distances. We observed no effect of tagging on banana weevil movement as determined by foraging success. Although this did not directly measure the effect of tagging on the distance moved and orientation to the banana pseudostem tissue, the result that tagging did not affect the ability of weevils to arrive at the pseudostem indicates that tagging did not have a large effect on weevil movement.

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Figure 5.1. Release of weevils in a hexagonal array and measurement of movement parameters.

Solid circles 1-6 indicate release positions. θ_B = bearing; θ_1 = angle to center of first move; θ_2 = angle to center of second move; θ_{TA} = turning angle; d_1 = distance moved on first night after release, d_2 = distance moved on second night after release.

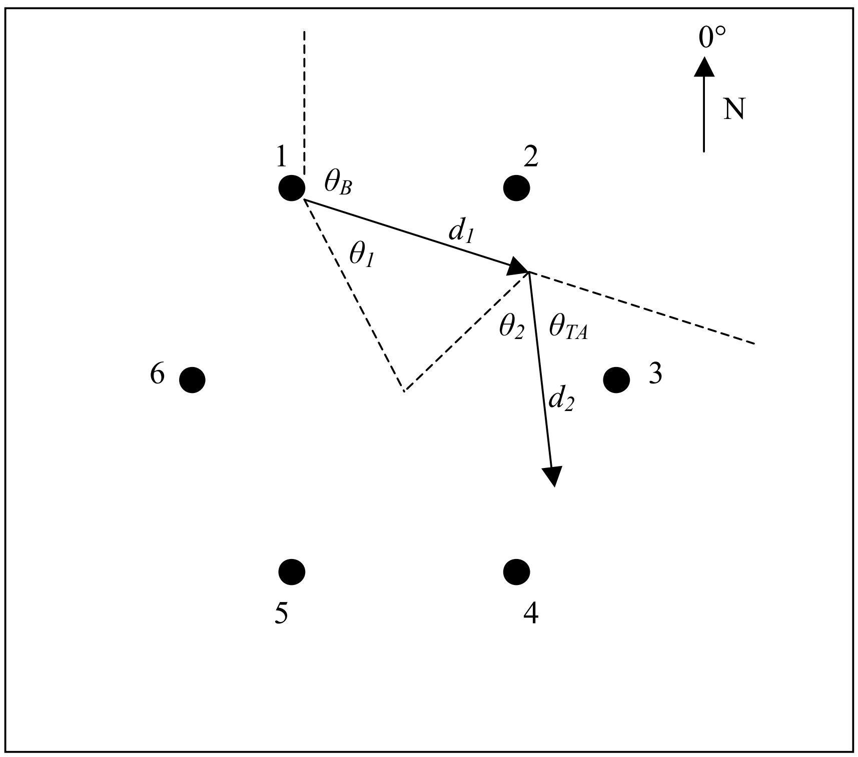


Figure 5.2. Average bearing and distance for weevils at each release position for each combination of treatment factors.

A) Release at 1 m with banana pseudostem tissue in center; B) Release at 1 m with nothing in center; C) Release at 2 m with banana pseudostem tissue in center; D) Release at 2 m with nothing in center. Origin of graphs corresponds to center of hexagonal arrays.

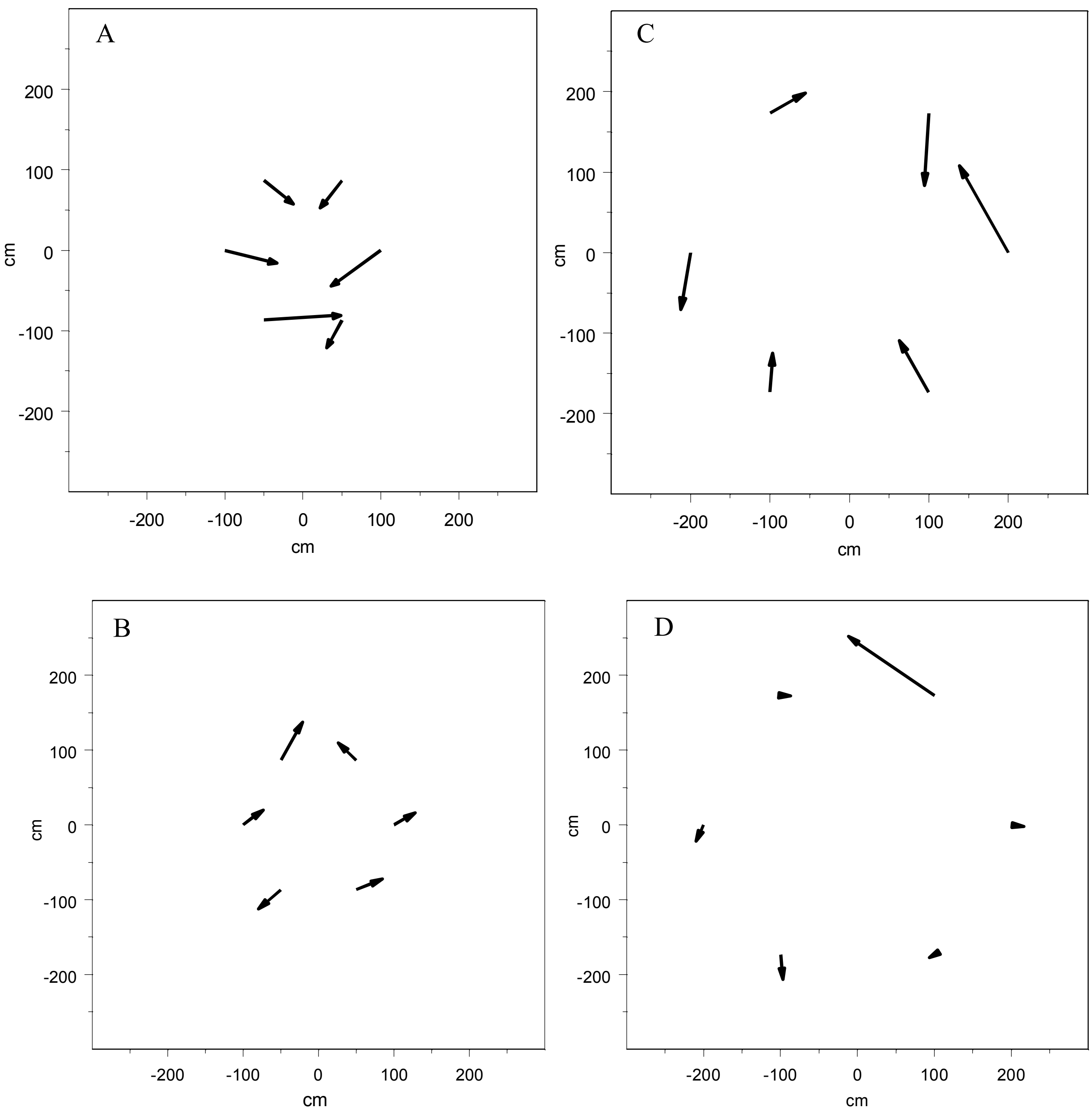


Figure 5.3. Effect of banana pseudostem tissue on angle of movement with respect to center of hexagon.

Angle to center is calculated as an absolute value between 0 and 180.

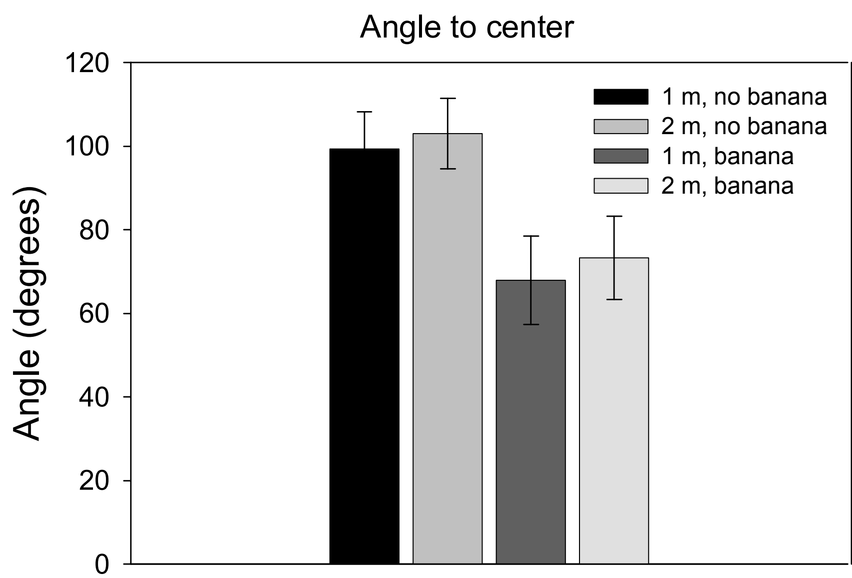


Figure 5.4. Effect of banana pseudostem tissue on distance moved per night.

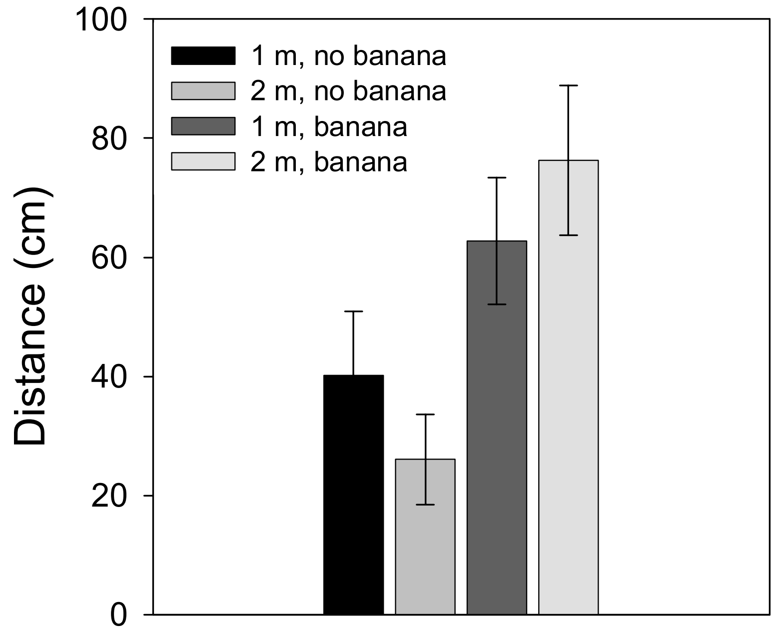
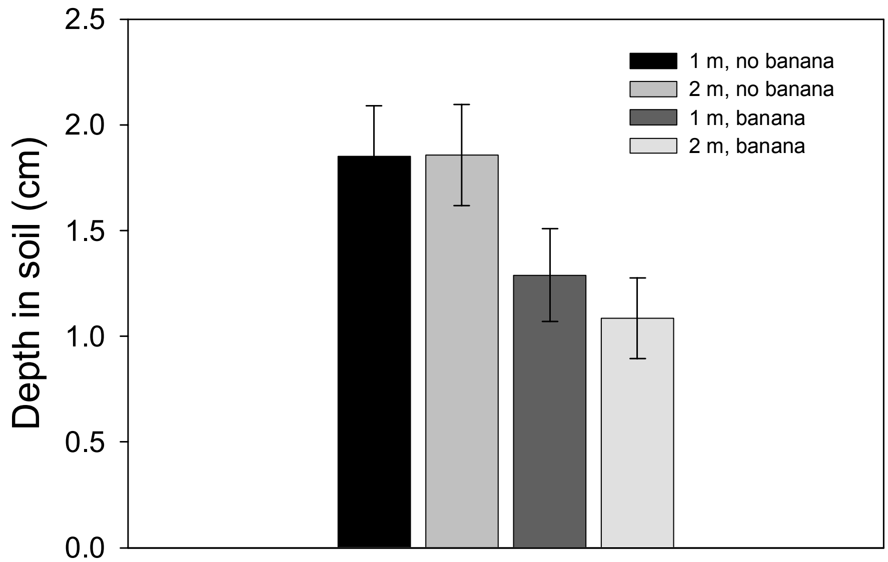


Figure 5.5. Effect of banana pseudostem tissue on depth in soil.



Concluding Remarks

Pest management in the Bribri-Cabécar Indigenous Territories occurs in a context of limited access to infrastructure, pesticide alternatives, and markets for both organic and conventional crops. Management of the banana weevil in organic banana is limited to general farm sanitation practices assumed to function as cultural controls, except for occasional use of botanical pesticides by a few farmers. Banana weevil management in plantain relies heavily on pesticide use, which is tied to markets and management practices outside the indigenous territories. Serious health and environmental risks are associated with pesticide use in the indigenous territories, particularly as unsafe pesticide application practices are often used. Organic banana and cacao agroforestry systems are less profitable than plantain monoculture, and many social and economic factors contribute to a trend of conversion of agroforestry systems to plantain. In this context, the need for alternatives to pesticides is apparent, as well as the need to improve productivity of organic agroforestry systems.

Pheromone traps were effective in reducing banana weevil damage in smallholder plantain farms after approximately one year of trapping. These traps are an alternative to pesticides that could be feasible for plantain farmers in the indigenous territories, although difficulties could arise in distribution of lures and technology transfer. Since technology transfer and sale of inputs currently occurs through plantain middlemen and cooperatives, alternative market links would have to be identified in order to make pheromone lures available. Other alternative management practices mentioned by farmers in the rapid rural appraisal are not likely to be widely adopted: for example, pseudostem traps require an extremely high labor investment, and the skin irritant properties of jabillo latex (*Hura crepitans*) make accidental exposure more undesirable in the short term than exposure to pesticides. Alternatives not mentioned in the rapid rural appraisal include hot water treatment of suckers and biological control with entomopathogenic fungi or nematodes. These should not be ruled out as potentially applicable in Talamanca, but further research would be necessary to evaluate their effectiveness. However, pheromone traps are likely to be the most feasible alternative for plantain production since their cost is comparable to that of pesticide application, they are produced within Costa Rica, and recommendations for their use already exist. Additionally, the use of pheromone traps has no known environmental risks.

Results of the assessment of banana weevil damage in organic banana agroforestry systems suggest that improved farm sanitation and management of fungal diseases may be more important than banana weevil management to increase crop productivity. Given the effort required to promote improved management practices in a context of traditionally low farm management intensity, the time of extension agents working in organic banana agroforestry systems may be more effectively spent on the practices currently being promoted rather than additional practices for banana weevil management. However, once farm sanitation and disease management become widely adopted, improved banana weevil management practices could provide an additional yield increase.

Banana weevil attraction to volatiles is the basis of mass trapping control methods such as pheromone or pseudostem traps. An improved understanding of the host plant finding process, which likely involves both host plant volatiles and the banana weevil aggregation pheromone, would be helpful in increasing trap efficiency and in understanding patterns of trap catches in different cropping systems and geographical locations. Mated females responded to the aggregation pheromone in the study of plantain farms, indicating that pheromone traps are not less attractive to mated females as occurs for some species. Given the additive attraction to the pheromone and host plant volatiles, it has been suggested that adding *Musa* volatile compounds to lures would increase pheromone trap efficiency. We found that female banana weevils respond to host plant volatiles with oriented movement and increased movement at a distance of 1 m, while movement was increased but not oriented at 2 m. The relative distances at which banana weevils respond to pheromone and to host plant volatiles may be of importance in designing efficient lures with both components. Additionally, these distances may have implications for movement of weevils among farms, and particularly for movement of weevils into farms using traps.

Results of this research have been provided to various organizations and individuals in the indigenous territories, including APPTA, ADITIBRI/ADITICA, and ACOMUITA. Important issues that could be addressed by governmental or non-governmental organizations within the territories include the need for safe pesticide application and storage practices and the need for improved infrastructure for organic agriculture and access to pesticide alternatives such as pheromone traps. Extension training to improve farmer awareness of banana weevil biology, natural enemies, and management practices would also be beneficial. There is opportunity for continued research on banana weevil management in smallholder farms in the indigenous territories. Future research efforts could focus on quantifying the relative contribution of banana weevil, other pests, and soil fertility on yield reduction. Work remains to be done in understanding movement of banana weevil adults with the heterogeneous landscape of the territories, and in understanding the process of host plant location.