SOIL BIOGEOCHEMICAL PATTERNS IN THE TALAMANCA FOOTHILLS, COSTA RICA: LOCAL SOIL KNOWLEDGE AND IMPLICATIONS FOR AGROECOSYSTEMS

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by

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AUTHORIZATION TO SUBMIT DISSERTATION

This dissertation of Leigh Winowiecki submitted for the degree of Doctor of Philosophy with a major in Soil and Land Resources and emphasis in Agroforestry Systems titled "Soil biogeochemical patterns in the Talamanca foothills, Costa Rica: Local soil knowledge and implications for agroecosystems", 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

Smallholder farmers in the Bribri and Cabécar indigenous territories in southeastern Costa Rica face many socio-economic and biophysical constraints that limit the success of their subsistence and cash-crop agriculture. The indigenous territories lie within the MesoAmerican Biological Corridor and are an active site for biodiversity conservation projects. Despite this, very little is known about their local ecological knowledge and very few efforts have included farmers' knowledge in agricultural extension projects. The objectives of this research are four-fold: 1) Understand how indigenous Cabécar farmers in three communities express local soil knowledge in their crop allocation; 2) Assess soil biogeochemical properties of the Talamanca foothills to provide useful information for agroecosystems; 3) Quantify the base cation nutrient reserves in aboveground and belowground pools in a cacao agroforestry and a shifting cultivation system to make predications about long-term sustainability; and 4) Utilize a livelihood's approach for the incorporation of socio-economic factors in biodiversity conservation projects. Several methods were employed including: participatory methods for local soil knowledge data collection; spatially balanced sampling design of soils along toposequences; and monitoring of soil primary, exchangeable, and soluble base cation pools in two agroecosystems. Farmers identify three distinct soil types within the foothill region. Each soil type is correlated with a specific landscape position and crop suitability. Soil biogeochemical patterns conclude that Typic Hapludults occupy both ridgetop and midslope landscape positions, Typic Dystrudepts and Dystric Eutrudepts occupy the footslopes, and Udifluvents and Fluventic Eutrudepts occupy the floodplain. Total Si, Ca, and K contents increase downslope. Soil under the diverse cacao agroforestry system is nutrient-poor, yet leaflitter inputs provide the necessary requirements of Ca and Mg for annual cacao harvest. A deficit of K exists due to the high K concentrations in harvested cacao husks. Land management techniques on these nutrient-poor Ultisols are needed to enhance biocycling, incorporate continuous organic matter inputs into the soil, and minimize leaching losses. A livelihood's approach identified changing trends in socio-economic factors affecting land-use decisions, including the conversion of a subsistence-based economy to cash-crop agricultural systems. Farmers are concerned about their survival amidst the current socio-economic conditions and the nutrient-poor soils they farm.

RESUMEN

Pequeños agricultores en los territorios indigenas de Bribri y Cabécar en el sureste de Costa Rica enfrentan cantidad de limitaciones socioeconómicas y biofísicas que limitan el éxito comunitario y agrícola. Los territorios indígenas se encuentran en el Corredor Biológio Mesoamericano, un lugar caracterizado por sus projectos en la conservación de la biodiversidad. Sin embargo, muy poco se sabe sobre el conocimiento ecológico de los agricultores y muy pocos esfuerzos han incluido el conocimiento de estos agricultores en proyectos agrícolas. Los objetivos de esta investigación estan resumidos en cuatro puntos: 1) Entender como los agricultores indígenas Cabécares en sus tres comunidades expresan sus conocimientos locales de suelos mediante la ubicación de sus cultivos, 2) Determinar propiedades biogeoquímicas de los suelos localizados al pie de monte de Talamanca para proveer información importante sobre el ecosistema agrícola, 3) Cuantificar la reserva de cationes básicos en reservas arriba y abajo del suelo en una sistema agroforestale de cacao y la cultivación de granos básicos (slash-and burn) para hacer predicciones en cuanto a sostenibilidad a largo plazo; y 4) Realizar acercamientos realistas para la incorporación de factores socioeconomicos en los proyectos de conservación de biodiversidad. Métodos diferentes han sido empleados, incluyendo: metodos participativos para colectar datos sobre el conocimiento local de suelos, muestreo de suelos espacialmente balanceados a lo largo de las sequencias topograficas, y el monitoreo de cationes basicos del suelo en las siguientes formas: primarias, intercambiables, y solubles en los dos agroecositemas. Los agricultores han identificado tres tipos de suelo en la region del pie de monte. Cada tipo de suelo esta relacionado con una localizacion distintiva y cultivo ideal. Los patrones biogeoquímicos del suelo nos permiten saber que Typic Hapludults se encuentra en los cumbres de las montañas y las medias cuestas, Typic Dystrudepts y Dystric Eutrudepts son encontrados cuesta abajo, y Udifluvents y Fluventic Eutrudepts son encontrados en los llanos alluviales. El contenido de Si, Ca, y K se incrementa a medida que se va cuesta abajo. El suelo bajo el sistema agroforestale diverso de cacao es pobre en nutrientes, pero la hojarasca puede proveer los requerimientos necesarios de Ca y Mg para el cultivo anual de cacao. Al contrario, existe un deficit en K debido por la alta cotenido de K en la casara del cacao. Técnicas en manejo de suelo son necesarias en estos Ultisoles con muy bajo contenidos de nutrientes para incrementar el bioreciclaje, incorporar materíia orgánica contunuamente, y minimizar pérdidas por lixiviación. Un acercamiento realista ha identificado cambios en tendencias socioeconomicas que afectan desiciones en el uso del suelo, incluyendo la transioción de una economia de subsistencia a una economia agricola capitalista. Los agricultores temen por su subsistencia en medio de la corrientes condiciones socioeconomicas y las pobres condiciones del suelo.

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DEDICATION

This dissertation is dedicated to all farmers, everywhere.

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1.1 Abstract

Farmers have developed soil knowledge through conducting long-term, observational experiments on their farms. Utilizing these experiential-based insights and incorporating the knowledge of local people living and depending on the land can improve communication between researchers and farmers, identify relevant research projects, and improve the success of extension projects. In remote landscapes, tapping into local soil knowledge and working with local farmers can also help alleviate the limitations of working in data-poor regions. The objective of this study was to understand how farmers in three Cabécar indigenous communities in southeastern Costa Rica use local soil knowledge to allocate crops across the foothill region of the Talamanca Mountains. These farmers practice no-input subsistence and cash-crop farming, employ no on-farm mechanization techniques, and plant both annual and perennial crops on their multi-parceled farms. Twenty-three randomly selected households were interviewed. Participatory methods of data collection were used and included participant observation (1.5 yrs), semi-structured interviews, farm mapping exercises, and farm-transect walks. Results of the interviews indicate that farmers identify three distinct soil types using primarily soil color, texture, and landscape position. Farmers' understanding of soil properties is tied directly to site suitability for specific crops. *Red soil* was described as hard, dry, and suitable for acid-tolerant crops. *Red soils* are found on ridgetops and shoulders and are classified as Ultisos (Acrisols). *Black soil* was described as smooth, moist, and found in upland depressions or low-lying areas near rivers. *Black soil* is sought after by the farmers, as all crops are reported to grow well in it, including the nutrient-needy banana. The average sum of bases in *Black soil* is 6 times greater than in

Red soil. Mean Al saturation is 6 times less in the *Black soil* compared to *Red soil*. *Black soils* are classified as Inceptisols (Cambisols). The third soil type identified in the region was *Sandy soil*, found only in the alluvial floodplains. Farmers report that banana and plantain do especially well in *Sandy soil*. These soils classify as Entisols (Fluvisols). While farmers identify limitations of the *Red soil*, they often have to farm this soil as it may be the predominant soil type on their farm. These data and experiences will be used to aid future agricultural development work in the region, including projects promoting the restoration of unproductive soils, providing alternatives to burning, and incorporating organic amendments to crops.

1.2 Introduction

Integrating local soil knowledge with scientific knowledge builds a unique bridge between two complementary learning systems with the potential to enhance both research and the livelihoods of local people. Local knowledge is developed over time, is dynamic in nature, and incorporates both a historical and cultural context (Oudwater and Martin, 2003; Winklerprins, 1999). Local soil knowledge is often passed down orally, is developed through experience (Sillitoe, 1998), and is embedded in land-management practices (Krogh and Paarup-Laursen, 1997). Local soil knowledge reflects the natural, cultural, and social realities of the environment and society. Benefits of integrating local soil knowledge data include: addressing the immediate needs of the local people (Winklerprins, 1999); increased success of sustainable development projects (Barrios and Trejo, 2003; Winklerprins, 2001); and the development of GIS soil databases that incorporate both local and scientific soil classifications to create land-use suitability indexes (Barrera-Bassols et al., 2006; Gobin et al., 1998; Gobin et al., 2000). Understanding what criteria farmers use to classify or describe soil is the first step in identifying patterns in local land-management practices and crop allocation related to soil type (Talawar and Rhoades, 1998). Local soil knowledge studies have shifted from documenting soil classification systems of local farmers to incorporating farmers' knowledge in order to develop more holistic soil management projects (Barrios et al., 2006; Talawar and Rhoades, 1998).

The Talamanca Mountains in southern Costa Rica provide an excellent study area to investigate local soil knowledge within the Cabécar indigenous territories. These mountains encompass large tracts of forests, two national parks, three indigenous territories, and smallholder subsistence and cash-crop farmers who live within this matrix. The northern foothills of the Talamanca Mountains are part of the proposed Meso-American Biological Corridor, which aims to conserve and connect coastal ecosystems with montane ecosystems. The indigenous territories within this corridor have been the center of several development projects promoting agricultural diversity (Dahlquist et al., 2007) and biodiversity conservation in cacao agroforestry systems (Andrade and Detlefsen, 2003; Somarriba et al., 2003) as a means to preserve structural connectivity within the corridor. Despite more than 20 years of extension efforts in the area, little is known about the local ecological knowledge of the Cabécar Indigenous people (Whelan, 2005).

1.3 Study Area

Talamanca is a region rich in culture, political turmoil, and economic strife. The Cabécar indigenous territories were established in 1977 by the Costa Rican government. The Cabécar territory is 23,000 ha in size and supports a population of 3,500 (Andrade and Detlefsen, 2003). Cultural remains indicate that the Cabécar and other indigenous peoples have existed in the Talamanca region for over 3000 years (Borge and Castillo, 1997), yet their struggle to maintain their presence in the region increased with the arrival of Spanish conquistadors in 1540 (Villalobos and Borge, 1998). In 1909, Chiriquí Land Company (later know as United Fruit Company) converted the region to commercial monoculture banana plantations and forced the native inhabitants to retreat from their farms on the flat floodplains into higher regions or cross over to the Pacific Slope of the Talamanca Mountains (Borge and Castillo, 1997). The company left the area after repeated floods inundated the Talamanca Valley in the 1930s, weakening crop resistance to disease (Somarriba, 1993). Between 1940 and 1970 the Cabécar returned to the Talamanca valley and foothills to reestablish their farms and livelihoods, only to encounter new battles with petroleum, mining, and hydroelectric companies (Villalobos and Borge, 1998). Currently, the indigenous Cabécar smallholder farmers inhabit the Talamanca Mountain foothills and small portions of the alluvial valley. They practice both subsistence agriculture and cash-crop production, including organic banana (*Musa* AAA.) and cacao (*Theobroma cacao*) agroforestry systems, shifting cultivation (rotation of basic grain crops and fallow) systems, as well as chemical-intensive plantain (*Musa* AAB production (Somarriba and Harvey, 2003). Talamanca is the poorest canton in Costa Rica (Municipalidad of Talamanca, 2003) and farmers continue to face marginalization due to limited infrastructure and limited access to markets and health care (Gomez, 2001).

Geomorphically, the Atlantic slope of the Talamanca Mountains contains three distinct regions: the Talamanca valley, which covers about 12,000 ha (18% of the territories) and contains 80% of the population within the Bribri and Cabécar indigenous territories (Borge and Castillo, 1997); the foothills, ranging in elevation from 100-600 m; and mountainous terrain above 600 m. Average annual temperature of the study region is 25 °C and annual precipitation is between 2200 - 3100 mm (Kapp, 1989). The Talamanca Mountains and associated foothills are rugged, remote, and prone to natural disasters such as landslides and flooding; and yet, farmers cultivate the land throughout the entire region. It has been suggested that smallholder farmers working in diverse landscapes have a fine-scale knowledge of the local soil types and develop corresponding agricultural practices to successfully cultivate the complex hill slopes (Habarurema and Steiner, 1997; Steiner, 1998). The Talamanca foothills provide an excellent example to better understand how small farmers work in a diverse landscape.

Many biophysical, cultural, and socio-economic factors influence the farmers' selection of crops and the development of land-management practices over time (Dove, 1985; Schusky, 1989). These factors include local, regional, and international economies and markets, cultural knowledge, site suitability, climate, native soil fertility and soil characteristics, availability of labor and land, the influence of extension agents, and the sharing of knowledge among farmers. All of these factors may be considered simultaneously during agricultural decision-making process. Acknowledging and incorporating local soil knowledge, and the numerous factors included within it, can allow for more effective extension outcomes, more applied research projects, and improved relations between the indigenous farmers and researchers.

1.4 Objectives

The objectives of this research are threefold: 1) to assess if and how farmers distinguish between different soil types on the landscape; 2) to understand how farmers express soil knowledge through crop allocation; and 3) to offer suggestions on how organizations, researchers and extension agents can incorporate these data into development projects and/or land-management strategies.

1.5 Methods

1.5.1 Selection of Communities and Households

Three Cabécar communities (Sibuju, San Miguel, and San Vicente) located in the foothills of the Talamanca Mountains of southeastern Costa Rica were selected for the study (Figure 1.1). These are relatively remote and dispersed communities with limited infrastructure. Communities were selected based on the following criteria: 1) ample, available land resources to practice subsistence, rotation, and cash-crop agriculture; 2) close proximity (~7 km) to each other with similar landforms; 3) homogenous ethnicity; and 4) willingness to accept us into their community.

Stratified random sampling of Cabécar households was employed. Random sampling of a population yields more representative results that have stronger statistical value than non-random samples (Neuman, 1999). The three Cabécar communities combined have approximately 75 households. All households were stratified into three categories using age of head of household: 20-40-, 40-60-, and over 60-years old. A total of 23 households were randomly selected for interviews for the categories. Due to an unequal distribution of households within each age category, we drew random samples from each category to capture at least 25 % of each age group.

1.5.2 Participant Observation and Open-ended, Semi-structured Interviews

Communities, farms, and farmers were visited repeatedly over the course of 1.5 years (June 2005 to December 2006) to observe farming practices, soil properties, management strategies and converse with farmers. Five preliminary interviews were conducted with farmers during this stage to help design future interview questions.

Semi-structured, open-ended interviews were conducted with 30% of the total number of households (23 of 75 households) in the three Cabécar communities between January and March 2006. The main objectives of the interviews were to determine if farmers distinguish between different soil types in the region, how farmers describe soil, if crops perform better on certain soil types, what factors are considered in crop allocation, and what management strategies farmers utilize for each crop (Table 1.1). Basic information (size of household, land area farmed, etc.) about each household was also gathered. Interviews were conducted in a farmer's home or on the farm. Average length of the interview was ~2 h. Several members of the family often accompanied the head of household during the interview.

1.5.3 Participatory Mapping Exercise: Current and Historical Land use

Participatory maps of each farm and each parcel within the farm were drawn by the household. The location and size of each cropping area was indicated. Landscape attributes were also noted such as if there was a steep slope or a depression. Land-use history of each parcel was recorded. For example, if a parcel currently was in fallow, we asked how long it has been in fallow, what crop existed before the fallow, what crop was planted before that, and if the land was burned for each rotation. Finally, areas of different soils, as recognized by the farmers, were indicated on the farm map.

1.5.4 Farm Transect Walk

Transect walks provided another opportunity to discuss soil and crops in the field. We asked the farmers to show us the different soils on their farm that they described in the interview. We examined the soil to a 30-cm depth with the farmer and extracted soil samples to describe. We compared the farmer's color designation with Munsell color charts in the field. Discussion of crop allocation and productivity also occurred at this time. We asked the farmer why they planted each crop where it was and what were the characteristics of the soil at that particular site.

1.5.5 Farmer Workshop: Triangulation and Confirmation

In addition to participant observation and farm transect walks, a community workshop was held to triangulate results from the interview data. Interview data were presented to the communities in the form of a workshop as well as in a written document. The workshop was held at a local community center. All community members were invited, including farmers who were not interviewed. Additional questions were asked at the workshop (Table 1.2). The objectives of this workshop were to: 1) assess if we accurately interpreted the farmers' knowledge; 2) determine if farmers agreed on the different soil types in the region and the crop allocation patterns on these soil types; and 3) provide an additional forum (semi-formal community meeting) for farmers to share their soil knowledge with researchers and community members.

1.5.6 Qualitative Data Analysis

Extensive notes were taken during all interviews and the workshop. All interviews were transcribed and typed. Data were compiled, analyzed, and interpreted according to basic qualitative procedures (Creswell, 2003). Data (responses) were organized into categories and themes were identified. Responses under each theme were quantified.

1.5.7 Soil Analyses

Nine soil pedons were sampled on nine different farms to represent the soil types identified by the farmers. Samples were taken by horizon and transported to the University of Idaho Pedology laboratory. Particle-size analysis was conducted using wet sieving, centrifugation, and the pipette methods (Gee and Bauder, 1986). Soil samples ground to 0.50 µm were analyzed for total C by dry combustion (Nelson and Sommers, 1996) using a C, N Elementar analyzer. pH was measured on a 1:1 (soil:deionized water) slurry with standard pH electrode (Thomas, 1982). Exchangeable cations (Ca, Mg, and K) were extracted using NH_4OAc and concentrations in extracts were analyzed by inductively coupled plasma (ICP) spectroscopy (Sumner and Miller, 1996). Exchangeable Al was extracted using 1 M KCl and analyzed using ICP spectroscopy (Bertsch and Bloom, 1996). Soil chemical data from each soil type were compared for statistical differences using two sample t-tests. Soils were classified using both Soil Taxonomy (Soil Survey Staff, 2006) and World Reference Base for soil resources (IUSS Working Group WRB, 2006).

1.6 Results

1.6.1 Demographic Information

The 23 interviews conducted in the three selected Cabécar communities (Sibuju, San Vicente and San Miguel), represented 30% of the total number of households. Ninety-one percent of the interviews were conducted with men as head of the household and 2 widowed women were head of household. Data will be expressed in terms of head of household, despite the fact that several household members may have been involved in any one interview. Head of household age ranged from 26 to 75 years old, with 6 households in the 20-40-year-old category, 11 in the 40-60-year-old category and 6 in the over 60-year-old category. Average number of household members is 5 with a standard deviation of 2.5. Seventy percent of the Cabécar farmers interviewed were not born in the community where they currently live. Length of time the head of household has lived in the current community ranged from 4 to 45 years, with a mean of 27 years. Principal crops identified by farmers include rice (*Oryza sativa*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), cacao (*Theobroma cacao*), banana (*Musa* AAA.), and plantain (*Musa* AAB

1.6.2 How Farmers Describe Soil

Talamanca foothill farmers use primarily color and texture to distinguish between soil types. Farmers were specifically asked, "What types of soil exist on your farm?" Ninety-six percent identified two distinct soil types and called them *Red soil* ("tierra colorada") and *Black soil* ("tierra negra"). The remaining four percent did not identify a *Red* or *Black soil*. When asked what soils exist in the larger region, seventy percent of farmers described a *Sandy soil* ("tierra arenosa") located in the large alluvial floodplain. It was often challenging for a farmer to describe the soil without relating it to a crop or landscape position. Yet, 74% of the farmers described *Red soil* as being hard. Terms such as dry, sticky, clayey, sterile, and occurring on sloping lands or ridgetops were also used (Table 1.3). Fifty-two percent of the farmers described *Black soil* as smooth. Other descriptors included loose, moist, sandy, and found in low-lying areas of the landscape (Table 1.3). All participants who identified *Sandy soil* described it as sandy, best for plantain production, and occurring in the alluvial floodplain. Since many of the households moved from and farmed on the opposite side of the Talamanca Mountains, farmers were asked to describe the soil there. Pacific-slope soils were described as dry, sterile, and less productive than soils of the Atlantic Slope. Smallholder farmers in southwestern Nigeria used texture and color, as well as visual perception of drainage and soil density to classify soil (Osunade, 1988). Soil classification of rural farmers in Mexico and Burikna Faso was based on soil color, texture, consistency, and moisture retention (Dialla, 1993; Williams and Ortiz-Solorio, 1981). These studies agree that farmers designate different soil types using soil characteristics that are visually observable or physically discernable.

Fifty-six percent of households acknowledged that the soil had different horizons ("capas"). Farmers acknowledged the presence of a black cap above *Red soil* after observing the soil after a tree has fallen or a landslide occurred. This site of disturbance exposes the subsoil and allows an opportunity to observe subsurface soil. The remaining 44% did not mention any soil horizonation. Talamanca farmers do not plow or use mechanization on the farm and they rarely examine soil below 30-cm, this is due to the nature of the crops planted. Basic grains are planted by merely pushing away the top few centimeters of soil with a round-edged stick. Banana and cacao are planted as small saplings and require digging only to a depth of ~10 cm. Exposed riverbanks, scarce road cuts, landslides, and tree falls are the most common opportunities for farmers to witness subsurface soil.

1.6.3 Crop Suitability

Farmers commonly discussed each soil type within the context of crop suitability. Through experimentation, farmers have learned that pasture, rice (*Oryza sativa*), peach palm (pejibaye) (*Bactris gasipaes*), coffee (*Coffea robusta*), pineapple (*Ananas comosus*), and oranges (*Citrus aurantium*) are suitable crops for *Red soil* (Table 1.4). *Red soil* is also suitable for houses and other structures. In contrast, the Black and *Sandy soil*s were viewed as highly productive and fertile soils that support the cultivation of most local crops including beans (*Phaseolus vulgaris*), maize (*Zea mays*), banana (*Musa* AAA), cacao (*Theobroma cacao*), and cassava (*Manihot esculenta*) . Farmers also associated crop success with each soil type. For example, farmers acknowledged that while a specific crop may grow on the *Red soil*, its yield may be too low to try planting a second time. In contrast, farmers repeatedly stated that crops grow vigorously on the *Black soil*. While farmers in the foothill region prefer *Black soil* over *Red soil* for crop cultivation, they are often forced to farm the *Red soil* due to lack of available land and accessibility. Therefore, farmers cultivated crops that were able to grow successfully on the *Red soil*, which tended to be acid-tolerant crops. Farmers stated that they have to look for the *Black soil* as it is sought out for crop cultivation. When asked specifically how they know which crop prefers which soil type, the farmers responded that they learned both from their elders and through on-farm experimentation. Farmers often showed us mini-experiments on their farm such as growing yucca under banana or planting cacao saplings in a new location.

Talamanca farmers are not alone in establishing soil types that are strongly correlated to crop suitability. Farmers in Burkina Faso associated each soil type with site suitability for specific crops (Dialla, 1993). Habarurema and Steiner (1997) noted that farmers in Rwanda classified soil based on agricultural suitability, and little correlation was found between farmers' soil classification scheme and Soil Taxonomy (Habarurema and Steiner, 1997). Farmers of central Honduras used similar soil physical characteristics that US soil scientists use to classify and describe soil, yet the farmer's perspective was directly related to agricultural productivity (Ericksen and Ardon, 2003). Despite the relatively short time smallholder farmers in Dominican Republic have farmed the mountainous region of the island (60 yrs), they were able to determine and communicate site suitability for crops based on-farm experimentation (Ryder, 2003).

1.6.4 Landscape Position

Foothill farmers have developed an intimate relationship with the landscape that has allowed them to identify patterns between landscape position and soil types. The foothill region is topographically diverse with springs and streams dissecting the undulating hills. Farmers, often discouraged, described the landscape as broken (“quebrada”), uneven or hilly. Yet despite its complexity, many farmers identified patterns of soil type occurrence in relation to landscape position. Specifically, 61% of farmers referred to the *Red soil* as the soil that is on the ridgetops. Fifty-seven percent of farmers described the *Black soil* as existing in the low-lying lands or upland depressions. Seventy percent of farmers specifically described the *Sandy soil* as existing in the alluvial floodplain in the valley. In summary, farmers described the landscape as consisting of uplands with *Red soil* that is good for pasture and lowlands with *Black soil* that is good for all crops. A few farmers explained their understanding of this landscape-soil relationship by illustrating how rain washes (“se lava”) the *Black soil* away from the ridgetops and slopes and deposits it in these low-lying areas (“bajuras”). Similarly, farmers in Burkina Faso described 4 different soil types in their region that were linked to directly to different landscape positions (Gray and Morant, 2003). Smallholder farmers in the Brazilian Amazon noted differences in moisture retention and texture among soils formed on different topographic positions on the floodplain island of Ituqui and planted crops accordingly; though all soils were classified as Entisols in Soil Taxonomy (Winklerprins and McGrath, 2000).

1.6.5 Land-use Trajectory

Talamanca farmers have multiple farms scattered across the different communities. Foothill farmers have between 1 and 5 farms with an average of 2.7 farms per head of household and an average farm size of 47 ha. In addition to having several different farms, Talamanca farmers divide their farm into different parcels. Foothill farmers manage between 4-13 parcels within their farms and each parcel may have a different land use, land-management strategy, history, and soil type. Figure 1.2 illustrates the land-use trajectory of one foothill farmer. The 52-ha farm is currently divided into 5 different parcels. Topographically, this farm is very diverse, containing ridgetops, steep slopes, and a footslope at the river’s edge. Historically, all parcels were managed similarly for the cultivation of basic grains, that is a forested area of 0.25-1 ha was cut down, burned, planted with rice, harvested, then allowed to go to fallow. Then a new parcel of land was selected for basic grain cultivation, until almost all of the native forest was cut and burned. In summary, this 52-ha farm was slowly slashed and burned, one hectare at time, until after several years, the entire farm had been subjected to cultivation. A shift in this land-use pattern occurred when perennial crops were introduced onto this farm. Site selection of perennial crops is an important decision for the farmer, as the crop will likely exist on the site for 5 to 50 years. Farmers use knowledge from past production of the basic grains to help decide where to plant the perennial crop. For example, beans and maize are considered more sensitive crops than rice and require less-steep land. Therefore if beans and maize produced well on a particular site, the farmer assumes that perennial crops will also produce well. This is not true for rice, which farmers will grow on very steep slopes and on *Red soil*. When the option exists, perennial crops are planted on soils that are viewed as being more fertile (e.g. *Black soil*). Thus, current crop allocation has followed soil type patterns on the farm.

1.6.6 Soil Chemical and Physical Characteristics

Morphological, physical, and chemical differences exist between the three soil types identified by farmers. As the names suggest, *Red* and *Black soil* have moist soil colors that are considerably different (Table 1.4). Textural classes also differ between the soil types. Mean clay concentrations in each soil type are significantly different from each other ($p<0.05$), with the *Sandy soil* having the lowest mean clay concentration (22%), followed by the *Black soil* (45%), and the *Red soil* (54%). *Red soil*, described by farmers as clayey, has an argillic horizon (needed for an Ultisol classification) and clay textual classes throughout the profile (Table 1.4). In contrast, *Sandy soil* has coarser textures and most *Black soils* lack an argillic horizon (Table 1.4). The *Sandy soil* has the highest mean sand concentration (40%), and the *Red* and *Black soil* both have a mean of 20% sand. There is considerably more variability in the clay and sand content in the *Sandy soil* compared to the *Black* and *Red soil* (Figure 1.3). This is likely due to the naturally high variability associated with Talamanca floodplain soils (Polidoro, 2007).

Carbon content for horizons in the Red and *Black soil* is very similar and decreases dramatically with depth (Figure 1.4). Despite obvious color differences between the Red and *Black soil*, there is no statistical difference ($p<0.05$) in carbon concentrations between the two soils. The Red and *Black soil* have 4 to 5 times more carbon in the top 10 cm than the *Sandy soil*. Two of the *Sandy soil*s show irregular decreases in C with depth, which is a characteristic of Fluvents (Fluvisols) (Soil Survey Staff, 2006). These data compare with previous studies on soil carbon storage which showed that despite the high carbon content in the A horizon of foothill soils of Talamanca, soils from the alluvial floodplain store more carbon with depth (Polidoro et al., 2008).

Mean pH values range from 4.5 for the *Red soil* to 6.9 for the *Sandy soil* (Table 1.5). A comparison of pH values of all horizons within the *Red* and *Black soil* yielded no statistical difference ($p<0.05$), and pH values are sufficiently low to suggest that Al concentrations may be high. Soil pH within the *Sandy soil* is significantly higher than in the *Red* and *Black soils* and is near neutral for the entire profile. Sum of bases indicate a soil's ability to exchange and supply essential plant nutrients, calcium (Ca), magnesium (Mg), and potassium (K). Comparison of quantities of base cations in each soil type, shows a significant difference ($p<0.05$) between soil types. *Sandy soil* has an average sum of bases of 35 $\text{cmol}_c\ \text{kg}^{-1}$, the *Black soil* 22 $\text{cmol}_c\ \text{kg}^{-1}$, and the *Red soil* only 8 $\text{cmol}_c\ \text{kg}^{-1}$ (Figure 5). *Black soil* profiles have at least 2 times more bases compared to the *Red soil* profiles. These data have important implications for fertility of soil and availability of nutrients. For example, due to the low storage and exchange capacities of the *Red soil*, management techniques that encourage efficient biocycling and minimize losses due to leaching are needed in order to continue to farm on the *Red soil*.

Apparent effective cation exchange capacity (ECEC) per kg of clay is a measure of the clay fraction's contribution to the cation exchange and storage capacities of the soil. A low apparent ECEC value of 12 cmol_c per kg of clay or less is needed for a soil to qualify for a kandic or oxic horizon, indicating a soil dominated by low-activity, kaolinitic clay (Soil Survey Staff, 2006). Despite the low sum of bases of the *Red soil*, none of the *Red* *soil* horizons qualify for a kandic or oxic horizon, due in part because the exchange capacity is dominated by Al (Table 1.5). *Sandy soil* has the highest mean apparent ECEC, indicating high-activity clays present (Table 1.5).

Aluminum saturation in the *Red soil* increases dramatically with depth to values between 82-94% (Figure 1.6). *Black soil* also displays an increase in Al saturation with depth, but values are half those of the *Red soil* (Figure 1.6). In sharp contrast to the *Red soil*, the *Black soil* does not have Al saturation values above 50% within the rooting zone. High Al saturation can negatively affect root growth and nutrient uptake in plants. For example, soil aluminum saturation of 26 % in soil under cacao inhibit uptake of base cations and increase nutrient-use efficiency (Bailgar and Fageria, 2005). The *Sandy soil* has Al concentrations below the detection limit of the ICP, indicating that Al saturation is not a concern for the *Sandy soil*.

Soil chemical characteristics are reflected in crop productivity. Farmers state that neither banana, plantain, maize, nor root tubers produce well in the *Red soil*. This could be due to high clay content inhibiting growth of fine roots, low base status of the soil not satisfying the nutrient requirements of the crop, or high Al saturation inhibiting root growth. While farmers have no way to chemically measure soil fertility, their observations of crop productivity give an accurate perception of the fertility of the soil. Farmers perceive *Black soil* as being better for crop production than the *Red soil*. Though pH values of *Black soil* are still considered acidic, and clay content is comparable to the *Red soil*, the higher sum of bases and lower Al saturation of the *Black soil* are more suitable for most crops compared to the *Red soil*.

The three soils types identified by farmers are classified differently using Soil Taxonomy and World Reference Base. Due to their low base status, clay-rich subsoil, and high Al saturation, *Red soil*s are classified in Soil Taxonomy as Ultisols (Udults) and Acrisols using the World Reference Base. *Black soil*s are classified as Inceptisols (Udepts) and Cambisols, as they lack an argillic horizon and have a base saturation greater than 50 %.

*Sandy soil*s are classified as Entisols (Fluvents) and Fluvisols due to their high base status and that they form in alluvial sediments.

1.6.7 Changing Soils

Cabécar farmers clearly identified three distinct soil types in the Talamanca region primarily using color, texture, and landscape position; and allocate crops accordingly. In addition to the current characteristics of the soil, farmers were asked if the soil had changed since they started farming their tract of land (< 40 years ago). Seventy percent of households interviewed said that the soils had changed over time, and these changes were viewed as negative. Thirty-nine percent of the farmers indicated that landslides had a large impact on the land. The foothill region is quite susceptible to frequent rain and earthquake-induced landslides. In addition to landslides, 56 % commented that soil had changed due to the practice of burning for cultivation of basic grains. Of this 56%, half of the farmers commented that burning led to soil sterilization and low productivity due to overuse. All of the farmers in the over 60-year-old category referred to the soil on Pacific Slope as sterile due to over-burning. Despite this, 96% of the farmers burned regularly. During the community workshop, farmers actively debated the necessity of burning. The most common argument for burning was weed control. Yet, other farmers suggested a labor-intensive alternative of chopping the vegetation into small pieces and planting the crop within this mulch layer.

Talamanca foothill farmers repeatedly referred to *Red soil* as *tired* ("cansada"). On these soils, farmers convert the land use to pasture or allow natural vegetation to regenerate. Pasture is seen as a final/climax land use as farmers did not report converting pasture to any other land use in this region. Over time, as more land is converted to pasture, active land management practices will be needed to put these lands back into production. Despite the limited fertility of some foothill soils, Talamanca farmers do not add amendments to improve soil conditions. No active management (other than allowing the land to remain in pasture) is applied to improve soil conditions.

Farmers mentioned that trees provide several benefits: timber, shade, fruit, protection for natural springs (water sources), maintaining soil moisture, prevention of erosion, and supplying compost through the leaves. However, no active tree planting to promote these benefits was observed. Most farmers keep shade trees on their farm for their timber value, as they provide a local source of construction materials. In similar studies conducted in Chiapas, Mexico, organic coffee farmers remarked that shade trees provide litterfall, which contributes to soil formation, yet farmers did not recognize the role of trees in maintaining soil moisture or enhancing nutrient uptake (Grossman, 2003). There could be several explanations for the lack of soil management techniques employed: no extension efforts have promoted the application of organic amendments; market values for crops are too low to encourage applying or paying for amendments; and only inorganic fertilizers on available on the local market which are not suitable for organic cacao and banana production.

Extension agents exist in order to improve agricultural practices for the benefit of farming communities. Recognizing gaps in local knowledge is the first step in designing useful trainings and dissemination material for farmers. For example, reinforcing the benefits of trees on the landscape and incorporating management techniques that enhance organic matter inputs to the farm. Once knowledge gaps are identified, utilizing and acknowledging common vocabulary is necessary to create effective dialogues and changed behavior (Eigenbrode et al., 2007). An example being, farmers use the words *tired* or *sterile* to describe unproductive soil and *vitamin*, not nutrient, to describe nutrients needed by crops. It is important to use the local agricultural vocabulary to better communicate soil data and research results to the farmers. Management techniques that are informed by cultural agricultural practices of the region and incorporate scientifically based extension programs will aid in developing land-management practices that improve human and soil conditions in the region.

1.7 Summary and Recommendations

As smallholder farmers continue to abort diverse agricultural systems to adopt seemingly lucrative (often monoculture) cash crops, effective dialogue between farmers and research and extension scientists are needed to develop innovative agricultural solutions that increase production. Understanding how farmers view the land and soil is an initial step to encourage effective communication and trust between involved parties to accomplish these goals. Subsistence farmers have developed knowledge of soil and its site suitability as it directly impacts their survival. In Talamanca, this dialogue has begun. In this study farmers communicated their knowledge, asked questions, and shared ideas and concerns. Future project themes and workshops identified by farmers for Talamanca include: nutrient (*vitamin*) cycling; effects of fire on soil; and improvement of degraded lands. Talamanca farmers are concerned about the productivity of the land within indigenous territories and about how their children and grandchildren will survive financially amidst the current socio-economic conditions. Outreach information and research must acknowledge farmers reliance on productive soil, incorporate the local agricultural vocabulary, and address the concerns of soil degradation and low crop productivity.

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Table 1.1: Abbreviated list of questions for semi-structured interviews.

Topic	Questions
Basic household information	How long have you lived in Talamanca?
	What are the principal crops on your farm?
	How many children do you have?
	How many farm parcels do you have?
Soil Characteristics	What types of soil exist on your farm? Where are they?
	What types of soil exist in the Talamanca region?
	What are the characteristics of these different soils?
	What is the depth of each soil?
Crops	What crops grow best on the different soil types?
	How do you decide where to plant each crop?
	How do you manage your fallow?
	Have the soils changed since you began farming them?

Table 1.2: Abbreviated list of questions for community workshop.

Topic	Questions
Historical information on communities	Why did you come to Talamanca? What were key events in the history of your communities? What was the climate like when you came to Talamanca? Have you attended other agriculture-based workshops?
Soil Characteristics	What are the different soil types in the region? What are some differences between the soil of Talamanca versus the region you moved from? What are the characteristics of these different soils? What is the depth of each layer of soil?
Crops	What crops grow best on the different soil types? How do you decide where to plant each crop? How do you manage your fallow? What is the role of trees on the farm?

Table 1.3: Descriptive words (in Spanish with English translation) used by farmers to describe the three soil types. Data are based on the 23 interviews.

Soil types (% of households who identified)	**Description (Spanish)**	**Description (English)**	**% of respondents using descriptor**
Red soil (96)	duro	hard	74
	pegajoso	sticky	48
	arcilloso	clayey	35
	seco	dry	22
	esteríl	sterile	9
	altas, montana	steep sloping land	61
Black soil (96)	suave	smooth	52
	suelto	loose	39
	arenoso	sandy	35
	húmedo	moist	17
	bajuras, bajos	low-lying areas	57
Sandy soil (70)	arenoso	sandy	70
	suelto	loose	17
	arena mesclado con tierra	sand mixed with soil	13
	la isla	floodplain	70

Table 1.4: Morphological characteristics for a representative pedon of each soil type. (M= medium, GR=granular, SBK= subangular blocky, SGR= single grain, C=clay CL= clay loam, SICL= silty clay loam, SL= sandy loam).

Soil type	Horizon	Depth (cm)	Moist color	Structure	Textural Class (Lab)
Red soil	A	0-10	10YR 4/4	MGR	C
	BA	10-30	7.5YR 5/6	MSBK	C
	Bt1	30-70	7.5YR 4/6	MSBK	C
	Bt2	70-110	7.5YR 5/6	MSBK	C[a]
	BC	110-160	7.5YR 5/8	MSBK	C
Black soil	A1	0-10	10YR 2/2	MGR	CL
	A2	10-30	10YR 4/3	MGR	CL
	Bw1	30-60	10YR 4/4	MSBK	CL
	Bw2	60-90	10YR 4/6	MSBK	C
	Bw3	90-120	10YR 4/6	MSBK	C[a]
Sandy soil	A1	0-15	10YR 4/2	MGR	SICL[a]
	A2	15-30	10YR 4/3	MGR	SICL
	A3	30-50	10YR 4/4	MGR	CL
	C1	50-70	10YR 3/2	SGR	SL[1]
	C2	70-100	10YR 3/2	SGR	SL

[a] hand textured in field

Table 1.5: Mean pH values and apparent effective cation exchange capacities (ECEC) per kilogram of clay for soil horizons in each of the three soil types identified by farmers.

	pH			**ECEC (cmol_c kg clay^{-1})**		
soil type	**n**	$\bar{x}$	**range**	**n**	$\bar{x}$	**range**
Red	18	4.5	4.2-4.7	11	30.4	16.9-58.3
Black	15	5.0	4.4-6.3	11	48.9	25.6-71.7
Sandy	18	6.9	5.6-7.7	8	169.4	109.1-294.5

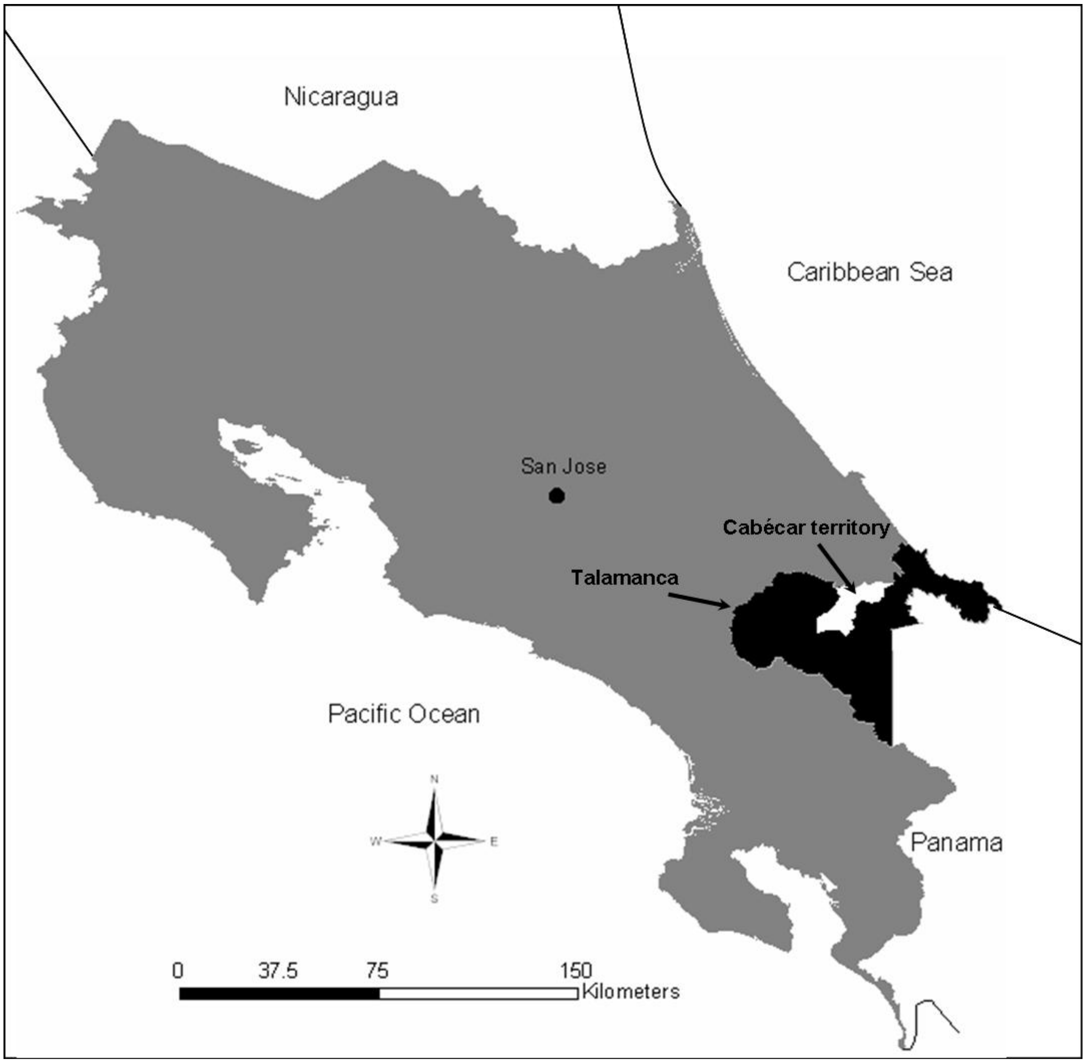

Figure 1.1: Map of Costa Rica with the southeastern canton of Talamanca in black. Cabécar indigenous territory is highlighted in white.

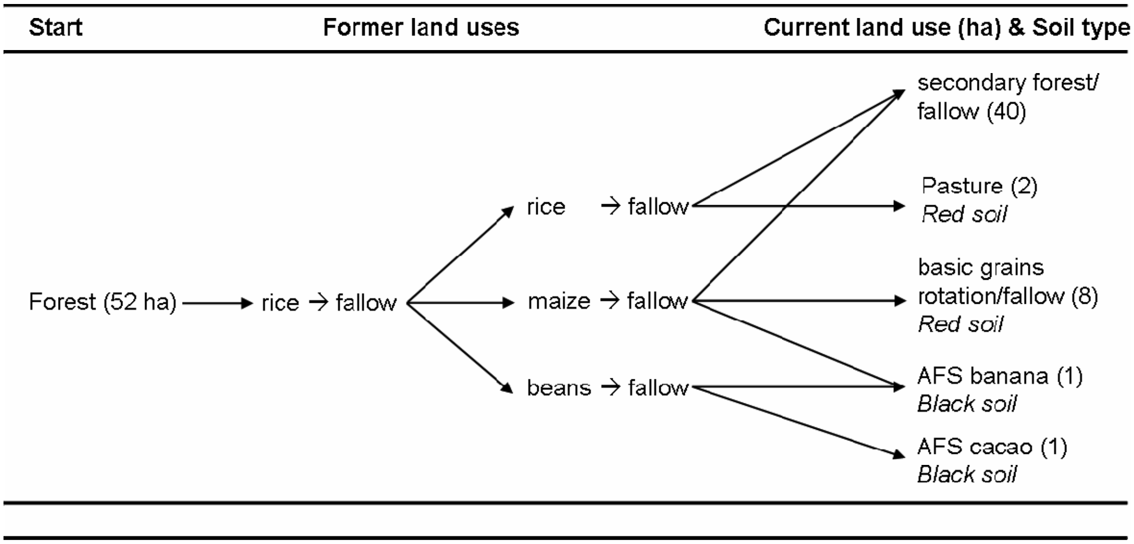

Figure 1.2: Land-use trajectory of a typical farm in the foothills of Talamanca. The farm is divided into 5 parcels, all of which were managed similarly until the inclusion of perennial crops and pasture. AFS is agroforestry system.

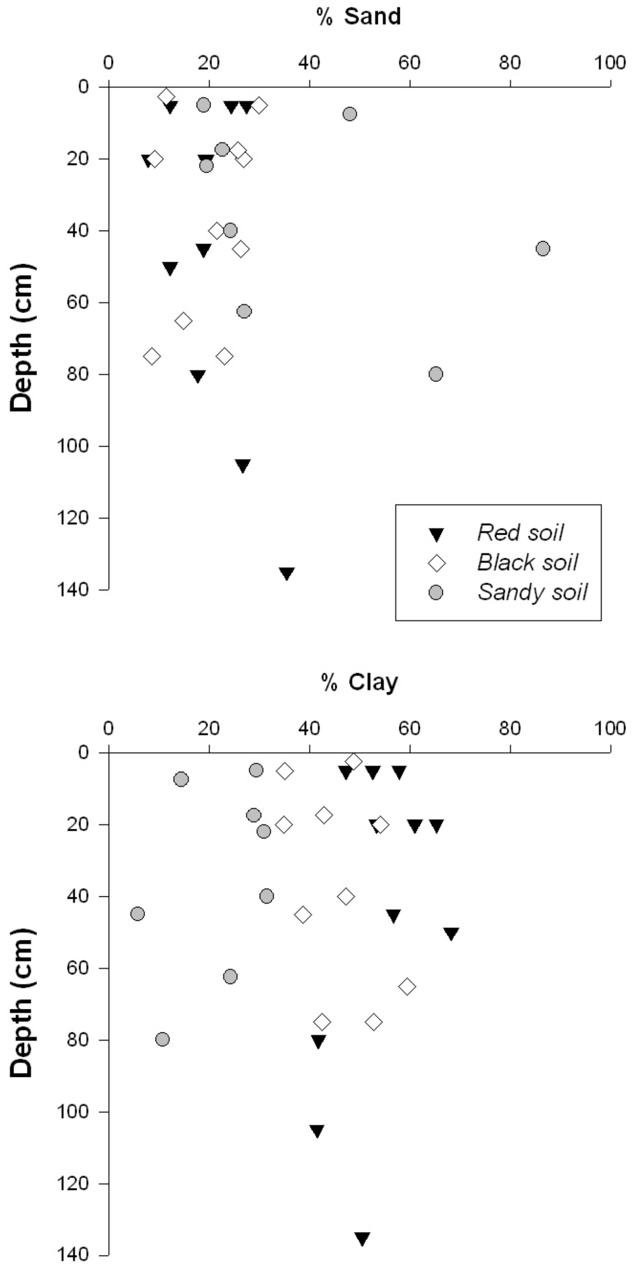

Figure 1.3: Percent clay and sand from horizons from each of the three different soil types.

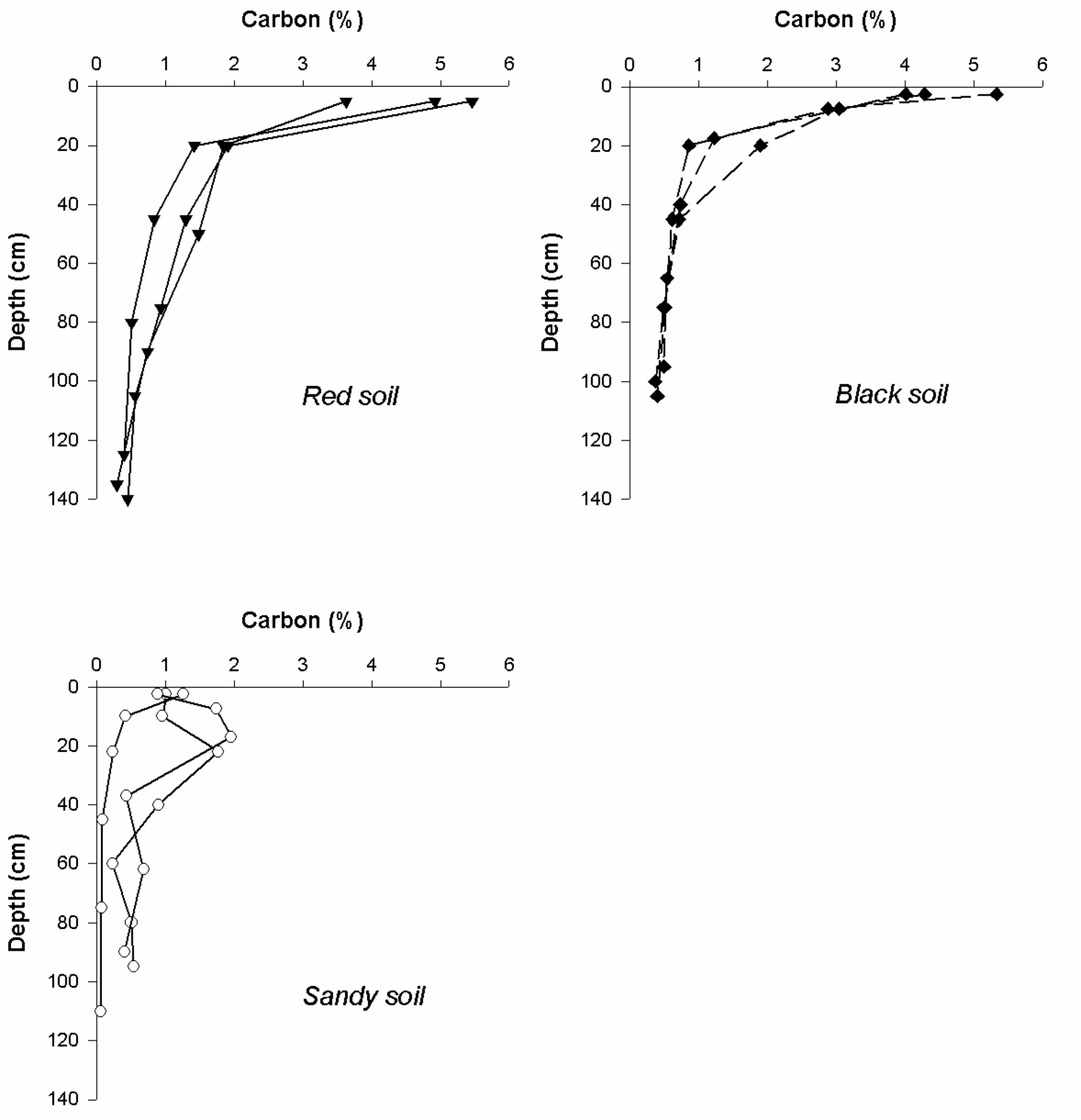

Figure 1.4: Percent carbon in soil horizons from three *Red soil*s, three *Black soil*s and three *Sandy soil*s. Points are plotted at the center of the horizons.

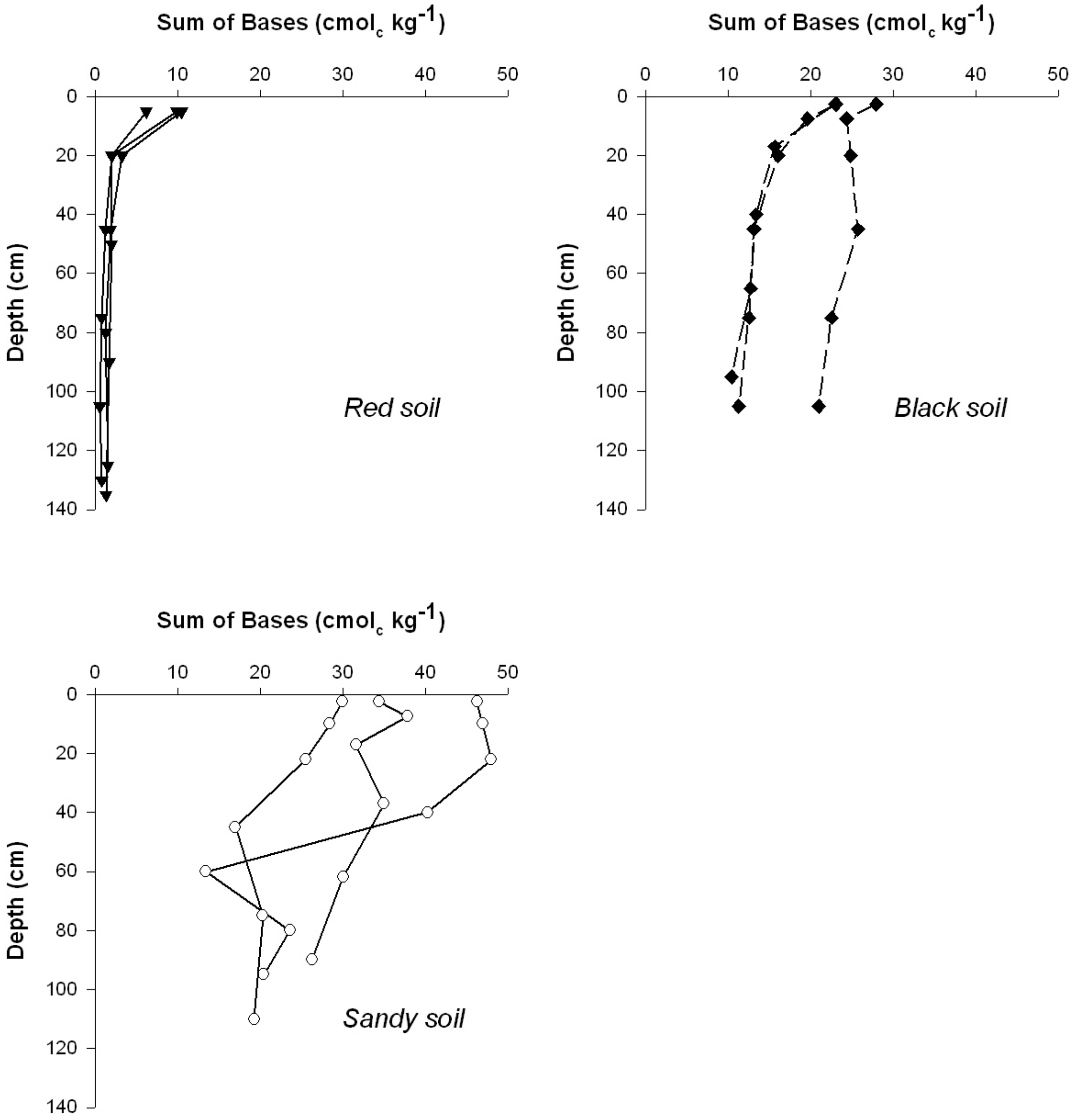

Figure 1.5: Comparison of the sum of bases (Ca, Mg, K) in three Sandy soils, three Black soils and three Red soils. Points are plotted at the center of the horizons.

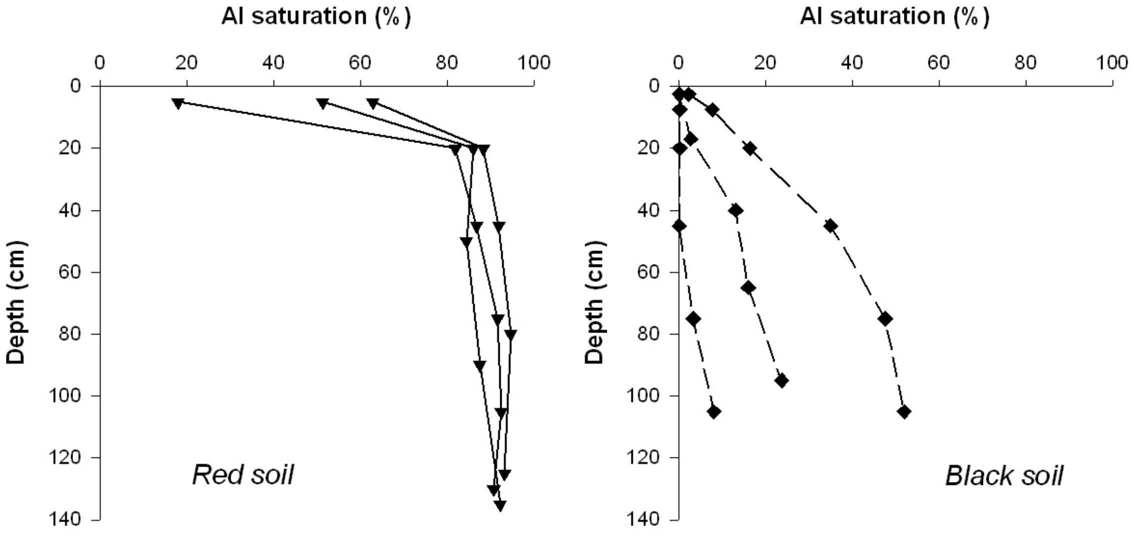

Figure 1.6: Al saturation in three *Red soil*s and three *Black soil*s. Points are plotted at the center of the horizons. Data from *Sandy soils* are not shown as Al concentrations were below detection limit of instrument.

2 CHAPTER TWO: SOIL BIOGEOCHEMICAL PATTERNS IN THE FOOTHILLS OF THE TALAMANCA MOUNTAINS, COSTA RICA: IMPLICATIONS FOR FARMERS

2.1 Abstract

Soil-forming processes operate at the landscape scale and result in geochemical separations according to topographic position. High year-round rainfall, temperatures, and humidity in tropical environments often speed the degree of weathering and soil development. Yet, very little data exists for soils formed in Tertiary sediments in the humid tropics. This study aims to identify soil geochemical patterns across the Talamanca foothill landscape. Specific objectives are: 1) to characterize physical, chemical, and mineralogical characteristics of the Talamanca foothill soils and 2) provide practical information regarding nutrient management on these soils. Seventeen sampling sites were randomly selected using topographic position index to sample ridgetop, midslope, and footslope landscape positions. In the field, footslopes were further divided into upland depressions, colluvial footslopes, and alluvial floodplain sites. Sum of bases, Al saturation, total elemental (Fe, Al, Si, Ti, Mn, Ca, Mg, K) content, texture, clay mineralogy, and sand grain morphologies were determined on seventeen pedons. Principal component analyses demonstrate that total elemental contents explain 54 % of the variation in the data and that data from ridgetop, midslope, and footslope soils are split across this axis. Ridgetop and midslope soils have the lowest sum of bases ($p<0.05$) and highest Al saturation ($p<0.05$). No statistical difference ($p>0.05$) was observed in total elemental Ca and K between ridgetop and midslope soils. Distribution of carbon is similar in all profiles except for floodplain soils ($p<0.05$). Ridgetop soils are the only samples with gibbsite present in the clay fraction and midslope soils are dominated by kaolinite. All footslope soils are dominated by smectitic clays. The ratio of Fe and Al to Si decreases downslope, indicating that soils formed on

ridgetop and midslope positions are highly weathered. Ridgetop and midslope soils classify as Typic Hapludults, due to the leaching of cations and illuviation of clay. Footslope and upland depression soils classify as Typic Dystrudepts and Dystric Eutruedpts. Floodplain soils classify as Udifluvents and Fluventic Eutrudepts. Farmers cultivating ridgetop and midslope soil need to incorporate soil management techniques that minimize leaching losses, lower Al saturation, and maximize organic matter inputs. These techniques include cultivating acid and aluminum-tolerant crops, applying mulch, composting post-harvest residue, and incorporating deep rooting trees to help stabilize steep slopes.

2.2 Introduction

Topographic position has an important influence on soil genesis (Jenny, 1941) and often explains soil variations across mountainous landscapes. Topography influences transport and redistribution of material and water both downslope (Sommer, 2006) and downward through the soil profile (Jenny, 1941). Internal drainage through the soil is an important determinant of pedogenesis as it promotes weathering of primary minerals and leaching of soluble ions, which directly affects chemical and mineralogical properties of the soil (Chadwick and Chorover, 2001). These soil characteristics have been used to explain topographic influences on soil development in tropical environments (Birkeland et al., 2003; Osher and Buol, 1998; Simas et al., 2005), assess effects of land-use change on the soil ecosystem (Holscher et al., 1997; Wilcke and Lilienfein, 2002), understand vegetation variations across the landscape (Dubbin et al., 2006), and explain past climatic or geologic conditions (Hotchkiss et al., 2000; Ruhe and Scholtes, 1956).

Tropical geomorphology in the Talamanca region of Costa Rica is greatly influenced by the constant hot and humid climate, which results in the formation of saprolite and development of highly weathered soils (Thomas, 1994). Talamanca foothill farmers acknowledge the relationship between landscape position and soil type (Winowiecki et al., In Review), yet little detailed information exists on how geomorphology influences soil development and soil properties across the foothills of the Atlantic-slope of the Talamanca Mountains. Though it is difficult to decipher the history of soil formed in Tertiary sediments compared to soils formed in young glacial or loess materials (Birkeland, 1999), these landscapes are prevalent in tropical environments and are often farmed by smallholders, such as in Talamanca.

Understanding mineralogical, chemical, and physical characteristics of soil has significant implications for soil productivity and predicting the effectiveness of management practices. Once landscape patterns and relationships are identified, appropriate management strategies can be developed. The overall objective of this research is to determine the influence of landscape position on soil geochemistry and soil development in the northeastern foothill region of the Talamanca Mountains. Specific objectives include: 1) Determine chemical, physical, and mineralogical characteristics of Talamanca foothill soils and 2) Suggest land-use strategies for each soil type.

2.3 Methods

2.3.1 Study Region

2.3.1.1 Geology

The Talamanca Mountain Range is the oldest and longest Mountain Range in Costa Rica. It stretches north-south, extending from Panama to the center of Costa Rica (Figure 2.1). The Range formed as an island arc due to the subduction of the Cocos plate underneath the oceanic Caribbean plate (Denyer and Kussmaul, 2000). Repeated deposition of marine sediments and upthrust onto the continent continued until the Pliocene when the mountain range began to rise (Denyer and Kussmaul, 2000). The Talamanca Mountains have a complex geology of intercalated marine sediments (limestone, shale, mud) and volcanic rocks (andesite, basalt) with Holocene alluvial deposits (Bergoeing, 1998; Weyl, 1980).

The Atlantic-slope of Talamanca Mountains has three distinct geomorphological classifications: steep mountains (> 600 m), foothills (100-600 m), and the Talamanca valley (< 100 m). The specific study area is in the northeastern foothill region (Figure 2.1). Different geologic formations have been identified and mapped within the study region and differ mostly in their time of formation (Oligo-Miocene, Miocene, and Pliocene and with regard to the influence of volcanic rocks versus sedimentary rocks (Sprechmann, 1984). Due to the broad time frame assigned to each formation and the complex geology great variations can occur within the defined unit. Mapped anticline and syncline formations, seismically induced landslides, and rill and gully erosion in the foothills further complicate the landforms.

2.3.1.2 Climate, Vegetation and Land Use

The Atlantic-slope of the Talamanca Mountains lies within the humid tropics of Costa Rica. Average annual temperature of the study region is 25 ^{o}C with 85% relative humidity (Kapp, 1989). Annual precipitation is between 2200- 3100 mm and falls year-round (Kapp, 1989). The soil moisture regime classifies as udic and the soil temperature regime is isohyperthermic (Soil Survey Staff, 2006). The Holdridge life zone for the Talamanca foothills is Very Humid Tropical Forest (Kapp, 1989).

Land use is varied within the territory and includes monoculture plantain production (*Musa* AAB), organic cacao (*Theobroma cacao*) agroforestry systems, organic banana (*Musa* AAA), agroforestry systems, secondary forest, and rotational crops (which includes fallow and annual grain crops). The foothills are dominated by smallholder subsistence and cash-crop farmers.

The Atlantic-slope of the Talamanca Mountains encompasses three indigenous territories, two national parks, and is part of the MesoAmerican Biological Corridor.

Several non-governmental organizations and universities operate in the region and have active agricultural and biodiversity extension programs. Despite the long-term development-based programs in the region, little to no ecological base-line data exists. To reconcile this data gap, this project attempts to classify and describe soils in the northeastern foothill region of the Talamanca Mountains within the Cabécar territories.

2.3.2 Field Procedures

Seventeen sample sites were randomly selected within a ~30 km^2 study region using a topographic position index to create a spatially balanced sampling design. The topographic position index was generated using a 90-m digital elevation model (DEM) of the area to identify the following landscape positions: ridgetops, midslopes, and footslopes (Weiss, 2006). Sampling points were allocated accordingly. Sites were located in the field using a Garmin V GPS unit. Once in the field, the footslope landscape positions were further divided into three distinct categories: colluvial footslopes (sites located at the base of a hill), alluvial footslopes (sites located within the alluvial floodplain, labeled as floodplain soils), and upland depressions (micro and macro depressions in the landscape). Randomly selected sites allow for a greater area of inference, for example, other foothill regions in Talamanca or elsewhere in the tropics with similar geology. Pedons were excavated to ~ 1.5-m depth, described using standard descriptors, and sampled by genetic horizon (Schoeneberger et al., 2002).

2.3.3 Laboratory Procedures

Soil samples were transported to the University of Idaho Pedology Laboratory. Soil was air-dried, gently crushed, and sieved to < 2 mm**.** Sand, silt, and clay contents were determined using wet sieving, sonification, and pipette methods (Gee and Bauder, 1986). pH was measured on a 1:1 (soil:deionized water) slurry and on a 1:1 (soil:1 N KCl) slurry with a standard pH electrode (Thomas, 1982). pH (in 1 N KCl) values below five suggest that measurable amounts of Al are in soil solution and contribute to acidity of the soil (NRCS, 2004). Delta pH values are used to determine dominant charge characteristics of the soil and is calculated using Eq. [1] (Mekaru and Uehara, 1972):

$$\Delta\ pH = pH_{KCl} - pH_{H_2O} \qquad \text{Eq. [1]}$$

Negative delta pH values suggest that soil colloids exhibit a dominant negative charge and positive delta pH values suggest that the soil may exhibit anion exchange capacity (Mekaru and Uehara, 1972). Exchangeable cations (Ca, Mg, Na, and K) were extracted using NH_4OAc at pH 7 (Sumner and Miller, 1996); and cations were analyzed using inductively coupled plasma (ICP) spectroscopy. Exchangeable Al was extracted using 1 N KCl (Bertsch and Bloom, 1996) and analyzed using ICP spectroscopy. Total elemental concentrations of Fe, Al, Si, Ca, Mg, and K were determined via ICP-emission spectroscopy following a $LiBO_2$ fusion and dilute nitric digestion at ACME Analytical Laboratories. Soil samples ground to 0.50 µm were analyzed for total C by dry combustion (Nelson and Sommers, 1996) using an Elementar C, N, S analyzer. Clay mineralogy was determined on clay fractions using 4 different treatments: Mg-saturated and air-dried, Mg-saturated with glycerol, K-saturated, and K-saturated heated to 500 ^{o}C and analyzed using X-ray diffraction (Whittig and Allardice, 1986) on a Siemens Diffraktometer D5000 XRD instrument. Energy dispersive X-ray spectroscopy was used to determine elemental atom percent of individual very fine sand grains and to qualitatively assess their degree of weathering. Very fine sand grains were examined optically with a petrographic microscope. Soils were classified according to Soil Taxonomy (Soil Survey Staff, 2006) and World Reference Base for soil resources (IUSS Working Group WRB, 2006).

2.3.4 Statistical Analysis

Principal component analyses were conducted with SAS to determine important soil characteristics to further analyze. One-way ANOVAs were run in SAS to compare landscape position and variable of interest. Differences are considered statistically significant using 95% confidence interval ($p<0.05$).

2.4 Results and Discussion

2.4.1 Principal Component Analysis

Principal component analysis using C, N, pH, sum of bases, ECEC, and Al saturation demonstrates that 89 % of the variability of the data is represented with the first two axes. Eigenvectors for axis one are pH: 0.48, ECEC: 0.49, and sum of bases: 0.53. Eigenvectors for axis two are C: 0.67 and N: 0.67. Landscape positions are split along the first axis (the x-axis), which represents 54% of the variation on the data (Figure 2.2). Principal component analysis using total elemental data of Si, Al, Fe, Mg, Ca, Na, K, Ti, P, Mn demonstrates that 73% of the variability of the data is explained by the first two axes and 88 % of the variability in the data is explained by the first three axes. Eigenvectors for axis one are Si: 0.36, Mg: 0.32, Ca: 0.38, Na: 0.38, K: 0.41. Eigenvectors for axis two are Ti: 0.33, P: 0.60, and Mn: 0.63. Eigenvectors for axis three are Fe: 0.63, and Mg: 0.35. Landscape position is nicely split according to axis one with the ridgetop and midslope soil on the left and the footslope soil data on the far right (Figure 2.3).

2.4.2 pH

Talamanca foothill soils high have acidity (Table 2.1). Ridgetop soils are more acidic than soils formed on other landscape positions ($p<0.05$). Ridgetop pH values range between 3.0 and 4.5 in the A horizon to between 3.9 and 4.7 at 1 m. Midslope soil pH values vary between 3.3 and 5.2 and most pedons have increasing pH with depth. Footslope and upland depression soils have pH values between 4.4 and 6.3 also with variable pH values with depth. In low pH soils, such as these, protonation of pH-dependent functional groups of minerals such as kaolinite or metal oxides encourages the development of a positive charge and decreases the cation exchange capacity of the soil (Sparks, 1995). Several inter-related factors influence charge development on soil colloids. For example, organic matter was demonstrated to lower soil pH while sequioxides were responsible for raising soil pH in Oxisols in Malaysia (Anda et al., 2008). Therefore, it is very likely that these low-pH Talamanca foothill soils may have low cation exchange capacities. Floodplain soils have the highest pH values in the region, approaching neutral and varying between 5.7 and 7.7, most likely due to the influx of fresh sediment. Floodplain pH values have irregular patterns with depth, due to the continual deposition of alluvial material from flood events.

Soil with low pH values and pH-dependent charges can often exhibit anion exchange capacities, which correlate with a positive delta pH (Becquer et al., 2001; Mekaru and Uehara, 1972). pH (1 N KCl) values were all below 5, suggesting that measurable amounts of Al are in soil solution. Most delta pH values were negative, indicating that most soil horizons in this study exhibit a cation exchange capacity. A few midslope soil horizons within the profile have positive delta pH values indicating that these soils may exhibit positive charge (Table 2.1). In contrast to the majority of Talamanca foothill soils, subsurface horizons in Oxisols in southeastern Brazil had positive delta pH values (Soares et al., 2005). These positive delta pH values in Bo horizons also coincided with low ECEC values, high effective anion exchange capacities (EAEC), low organic matter content and the presence of gibbsite, and iron oxide clay coatings (Soares et al., 2005). The negative delta pH values in Talamanca soils suggest that these soils have a net negative charge, despite the low pH values.

2.4.3 Sum of Bases

Sums of bases (Ca, Mg, K, Na) from all horizons from each landscape position are plotted as box plots to demonstrate the variability within and between landscape positions (Figure 2.4). Box plots demonstrate the spread of the data. The 25th and 75th quartiles are depicted as the edges of the box and the median is indicated by the line within the box. Points outside the box are considered outliers. These data demonstrate that soils formed on ridgetop landscape positions have the lowest concentrations of base cations compared to the other landscape positions ($p<0.05$) and have the least variability (Figure 2.4). Soils formed on midslopes have the second lowest sum of bases ($p<0.05$)

and exhibit greater variability than ridgetop soils. We suspect that soils formed on ridgetop and midslope landscape positions are more highly weathered and have incurred more leaching of soluble cations. Though not shown, base cation concentrations decrease with depth in ridgetop and midslope soils indicating the importance of biocycling in maintaining exchangeable forms of these nutrients. Floodplain and foothill soils have the highest base concentrations ($p<0.05$). These data are not surprising, as floodplain soils receive continuous inputs of alluvial sediment, presumably rich in base cations. Median values of sum of bases in footslope soils (28 $cmol_c\ kg^{-1}$) were in between the floodplain (30 $cmol_c\ kg^{-1}$), and upland depression soils (22 $cmol_c\ kg^{-1}$). Footslope, floodplain, and upland depression landscape positions experience similar processes of simultaneous processes of soil formation and cumulization.

2.4.4 Aluminum Saturation

Patterns in Al saturation vary with landscape positions (Figure 2.5). Floodplain soils have Al values below the detection limit, due to the near-neutral pH. Footslope and upland depression soils have the next lowest Al saturation values, with considerable variability. Midslope Al saturation values are quite variable among pedons, but all pedons have increasing Al saturation with depth. Ridgetop soils have the least variability in Al saturation among pedons and all Al values reach 80 % by 20-cm depth. Aluminum dominates the exchange sites of subsurface horizons in ridgetop and midslope soils. These data have important implications for crops as Al toxicity is common acid soils and phytotoxicity can occur with micromolar concentrations of Al, inhibiting root growth and uptake of nutrients (Delhaize and Ryan, 1995). Cacao, an important cash crop in Talamanca, was shown to have decreased nutrient uptake by seedlings when grown in soil with Al saturation values of 26 % and higher (Baligar and Fageria, 2005). Soil organic matter was shown to regulate Al solubility in subsurface mineral horizons (Berggren and Mulder, 1995) as well as buffer against Al toxicity in low-pH soils (Brown et al., 2008).

2.4.5 Carbon

Total carbon concentrations decrease regularly with depth in all foothill soil profiles except the alluvial floodplain soil (Figure 2.6). Floodplain soils have four times less C in the top 10 cm compared to the other soils. Two floodplain pedons have an irregular C decrease with depth, which is partially indicative of Fluvents (Soil Survey Staff, 2006). Similar patterns of C distribution throughout the profile are observed in all landscape positions except the floodplain soil. Carbon content of A horizons in ridgetop soils have 4.9 to 5.5 % C, midslope soils have 2.5 - 4 % C and upland depression soils have 4.3 to 5.3 % C (Figure 2.6). Statistically, only floodplain soils were calculated to have different C concentrations across the landscape ($p<0.05$). Talamanca midslope and floodplain soils were calculated to store substantial quantities of organic carbon and have an important role in carbon storage throughout the landscape (Polidoro et al., 2008). Despite the red color of ridgetop soils, they have relatively high C concentrations. This is partially because humic acids do not always contribute a darkening (brown or black) to the soil (Deng and Dixon, 2002) as well as the fact that even small amounts of Fe oxides have a large influence of the red, orange, or yellow hue of the soil. Similar to our ridgetop soils, Oxisols formed on ridgetop landscape positions in Brazil had the highest C concentration in the A horizon compared to the other soils of the catena (Botschek et al., 1996). Red-hued, high-clay content Oxisols in the Brazilian Amazon have high C contents and store comparatively more organic carbon than tropical Ultisols and Alfisols, and have similar C contents compared to temperate Mollisols (Sanchez, 1976).

2.4.6 Total Elemental Concentrations

Major elements undergo transformations over time and their concentrations may indicate degree of soil development (Birkeland, 1999). Soils that have undergone more weathering should exhibit lower concentrations of elements in easily weatherable minerals compared to soils that have experienced less weathering, assuming parent material is the same. Total concentrations of base cations from three profiles from ridgetop, midslope, and footslope landscape positions show a trend of increasing Ca and K concentrations downslope (Figure 2.7). Calcium concentrations in the ridgetop and midslope soils are low, have little variability between pedons and decrease with depth. In contrast, Ca concentrations in the footslope soils vary between pedons and have 0.5 to 3 times higher concentrations with depth compared to upslope soils ($p<0.05$). The low total Ca and K concentrations in the ridgetop and midslope soils indicate low primary mineral reserves of these elements and suggest the importance of maintaining inputs of organic matter to the system as a source of base cations. No statistical difference is observed between midslope and ridgetop Ca and K concentrations ($p>0.05$). Magnesium concentrations is different across all three landscape positions ($p<0.05$), with considerable variation between pedons in the footslope and ridgetop soils. A toposequence of soils in northeast Thailand also had ridgetop and midslope soils with low base cation contents and uniform patterns with depth compared to footslope soils (Thanachit et al., 2006). These data from Thailand (and Talamanca) suggest that soils formed on ridgetop and midslope landscape positions in tropical environments are highly weathered and have low base cation reserves compared to soils formed in depositional landscape positions (Thanachit et al., 2006).

A comparison of total Fe and Al in three profiles from each landscape position was used to identify trends across the landscape. Total Fe decreases downslope ($p<0.05$): ridgetop (10.2 +/- 0.77 % Fe); midslope (9.2 +/- 0.4 % Fe); and footslope (7.7 +/- 1.2 % Fe). No statistical difference ($p<0.05$) in total Al concentrations is observed between ridgetop (13.2 +/- 1.5 % Al) and midslope (14.0 +/- 1.1 % Al) soils. Footslope soils have lower ($p<0.05$) total Al concentration (11.0 +/- 1.1 % Al) compared to upslope soils. Fe and Al concentrations do not always vary with time as these elements may be transformed from primary minerals to secondary minerals through weathering, with very little loss over time. Yet, under anoxic conditions, Fe (II) can be lost from the system, decreasing total Fe concentrations. In addition, soils that have lost Si may appear to have higher Fe and Al concentrations as they are reported on a mass basis. It is possible that footslope soils have poor drainage and Fe is lost from the soil due to reduction of Fe(III). Data from a Brazilian Oxisol toposequence showed total Fe concentrations decrease with downslope landscape positions, and authors suggested that weathering of soluble base cations has left higher concentrations of Fe in the more highly weathered soils on the ridgetop (Birkeland, 1999).

Another way to assess weathering of the soil is to compare the ratio of Fe and Al to Si (Birkeland, 1999). Si is more readily translocated through the soil profile than Fe and Al, and Si concentrations should decrease in soils subjected to greater weathering. Figure 2.8 demonstrates that ridgetop soils have a higher ratio of Al + Fe to Si, indicating a more weathered soil. Footslope soils have a lower ratio compared to ridgetop soils, suggesting less-developed soils (Figure 2.8). The variability in midslope soil alludes to the potential variability in parent material and suggests that this variation is better expressed on midslopes. Layering of intercalated parent material may allow contrasting components to be closer to the surface or outcrop at certain points along the landscape (e.g. at different slope positions).

2.4.7 Texture

Foothill soils, in general, have high clay content (Figure 2.9). Mean soil clay content in the A horizons of ridgetop soils is 53% and clay content increases with depth. Midslope soils also have high mean clay content in the A horizon (50%) and clay content increases with depth. No statistical difference is observed in clay content between ridgetop and midslope soils ($p>0.05$). Argillic horizons are present in all midslope pedons, though the depth at which argillic horizons begin varies between 10 and 60 cm. The presence of argillic horizons in the midslope soil suggest that even though midslope landscape positions are susceptible to erosion, substantial development has occurred, indicated by the illuviation of clay within the profile. Upland depression soils have clay content ranging from 27-54 % and footslope soil clay content ranges between 27- 45 %.

Floodplain soils have the overall lowest clay (between 6 and 32 %) and highest silt and sand concentrations, due to the continual deposition of alluvial material. Despite the high clay content and relative stability of upland depressions, argillic horizons have not formed, possibly due to poor water infiltration in these soils limiting the elluivation of clay. In highly weathered soils of Brazil, no strong relationship between slope position and clay content exists, as all Bo horizons had > 58 % clay (Birkeland, 1999). The lower clay content in the A horizon of Talamanca upland depressions and footslope soils may make these soils more suitable for crops such as plantain, banana, maize, and root crops.

2.4.8 Clay Mineralogy

Clay mineralogical data are presented in relation to topography (Figure 2.10). Kaolinite is present in all sampled pedons. These data are not surprising as kaolinite is an extensive mineral in soils throughout the world. Kaolinite in the clay fraction can be inherited from the parent material (kaolin-rich rock or sediments) or form from weathering of primary or secondary minerals (e.g. feldspars) (White and Dixon, 2002). Two ridgetop pedons have gibbsite in the clay fraction of ridgetop soils. This distinction is indicative of the highly weathered characteristic of ridgetop soils. Gibbsite, an Al-oxide, is common in highly leached soils (Huang et al., 2002). The ridgetop sites with gibbsite also have the highest Al saturation. In addition to gibbsite and kaolin in ridgetop soils, hydroxy-interlayered clay minerals (HIM) are also present. The HIMs are 2:1 layer silicates that have an interlayer partially filled with a hydroxy-Al sheet. HIMs are common in highly weathered Ultisols (Kretzschmar et al., 1997) and Alfisols, and their abundance in the soil profile usually decreases with depth (Schulze, 2002). One ridgetop site has hydroxy-interlayered-smectite as the dominant clay mineral with minor amounts of kaolin and a kaolin-mica intergrade in both surface and subsurface horizons. The presence of (HIS) in the ridgetop soil may suggest a soil formed on slightly different parent material than the other ridgetop soils, for example a geologic formation rich in Si. This alludes to the variation in parent material across the region.

Several midslope pedons have kaolinite as the only clay mineral present (Figure 2.10). This is indicative of a soil that is highly weathered of all 2:1 phyllosilicates. Other midslope profiles have kaolinite as the dominant clay mineral with minor amounts of either poorly crystalline smectite or HIM in the Bt horizon. The presence of HIM and smectite suggest that some of the midslope soils are less developed than the kaolin-dominated soils. Smectite was the common and dominant clay mineral in the footslope and alluvial floodplain soils, with minor amounts of mica and kaolin. Smectite is a Si and Ca-rich 2:1 layer silicate that can (and often does) form in depositional environments (Birkeland, 1999). A soil dominated by smectite indicates higher concentrations of Si.

Four pedons (1 ridgetop, 1 midslope, 1 footslope, and 1 upland depression) had broad peaks extending from 7.3-8.8 nm, suggesting the presence of a kaolin-mica intergrade. These intergrades occur when mica acts as a source/site for kaolinite formation (White and Dixon, 2002). Graham and Buol (1990) observed pseudomorphs of biotite (with vermiculite or kaolinite) that form during periods of minimal illuviation and occurred in every pedon sampled in southeastern US, regardless of landscape position (Graham and Buol, 1990). Other Ultisols sampled in the Piedmont of North Carolina also had kaolinized pseudomorphs of biotite, detected using thin sections (Kretzschmar et al., 1997). Due to the similarities between biotite and mica, we could assume similar pseudomorphing of mica is occurring in Talamanca foothill soils with kaolinite, explaining these broad peaks in the X-ray diffractograms.

Comparing the dominant clay mineral with the effective cation exchange capacity (ECEC) to a 1-m depth demonstrates patterns across the landscape (Figure 2.11). Alluvial floodplain soils and footslope soils dominated by smectite in the clay fraction have the highest ECEC ($p<0.05$). Midslopes have the greatest variability in dominant clay mineral and ECEC values. The pedons with HIM as the dominant clay mineral had the highest ECEC 23 $\mathrm{cmol_c\ kg^{-1}}$. Kaolinite is a 1:1 clay mineral that has very little isomorphic substitution, which results in low cation exchange capacities and potentially low base status. Tropical kaolinitic soils can be divided into low base status and high base status soils, e.g. Al dominating the exchange sites of the former and Ca and Mg dominating the exchange sites of the later (Juo and Franzluebbers, 2003). Talamanca midslope soils are considered low-base-status kaolinitic soils due to the high Al saturation associated with each pedon. The midslope profile that has both kaolinite and smectite has a higher sum of bases (13 $\text{cmol}_c\ \text{kg}^{-1}$) likely due to the higher cation exchange capacity of the 2:1 layer silicate, smectite. The midslope profile that has HIM as the dominant mineral also has a sum of bases of 13 $\text{cmol}_c\ \text{kg}^{-1}$. The extent of filling of the interlayer of HIM has implications for the CEC of the soil, e.g. the less the interlayer space is filled with hydroxyl-Al the greater the ability of the clay mineral to store and exchange cations. Ridgetop soils have the lowest weighted mean of bases (0.8-2.8 $\text{cmol}_c\ \text{kg}^{-1}$) regardless of dominant mineral present.

2.4.9 Morphology of Fine-Sand Grains

Scanning electron micrograph (SEM) analysis of very fine sand grains provides insight into the weathering environment of the soil and the primary minerals present. Qualitative morphological differences between sites and between depths are observed. Sand grains from the floodplain sites have the greatest variability of sand grain morphologies; varying from tabular mica to very pitted sand grains to sand grains with a framboidal appearance. Floodplain sand grains range from rounded to angular. This variability is attributed to the nature of floodplain soils, receiving fresh new material that began its weathering somewhere else.

Upland depression A horizons have moderately sorted grains in the fine sand fraction, with angular to subangular grains. Lath-like amphiboles are present, which represent a nutrient-rich primary mineral (Figure 2.11a). Most sand grains are not deeply pitted, suggesting less chemical weathering. The B horizon at the upland depression site has more rounded grains and deeper pitting and fewer lath-like amphiboles (Figure 2.11b). This suggests that greater weathering has occurred in the subsurface and that less nutrient-rich primary minerals are present. Sand grains from midslope A horizons are moderately sorted with subangular to subrounded grains. Grains varied between smooth, etched, framboidal, and lath-shaped to rounded and pitted. Sand grains from midslope Bt horizons are more rounded than the A horizon and more pitted. Quartz grains are common in midslope soils and display uniform patterns of weathering throughout the grain (Figure 2.10c). Sand grains from ridgetop sites are well sorted with two dominant morphologies: subangular smooth grains and subrounded grains with deep weathering pits. Sand grains from a Bt horizon of ridgetop soils have deeper pitting and fewer smooth grains suggesting more chemical weathering. Few sand grains from the ridgetop soil have a botryoidal appearance, characteristic of iron oxides, possibly hematite or maghemite (Figure 2.10d). In all sites, sand grains from the Bt horizon show more deeply pitted grains, more sorting of the sand grains, and more subrounded to rounded grains, suggesting greater chemical and physical weathering in the subsurface horizons.

Total elemental atom percentages of the sand grains from midslope and ridgetop positions are dominated by Si (between 29 and 81% Si), Al (6-27% Al), and Fe (4-43 % Fe). Very few sand grains in the foothills have measurable concentrations of Ca, Mg, or K. These data demonstrate the low nutrient reserves in the primary mineral pool. Petrographic microscopic analysis confirms the presence hematite and quartz in sand fraction of midslope and ridgetop soils and the presence of magnetite and maghemite was confirmed using a magnet. All of these minerals are considered resistant to weathering. A few amphiboles and weathered feldspars were also identified. These data confirm that the foothill soils are highly weathered and lack significant quantities of Ca, Mg, and K in primary mineral form. In contrast, sand grains from the floodplain sites have higher concentrations of Ca, K, Na, and Mg compared to upslope soils. Optical mineralogy confirmed that floodplain sand fractions contain numerous feldspars and amphiboles in addition to quartz and iron oxides. A study of 12 soils from southeastern Brazil highlighted the importance primary minerals present and the state of weathering in the coarse soil fraction as this pool contributes to the soils' overall fertility in highly weathered tropical soils (Soares et al., 2005)

2.4.10 Soil Classification

Ultisols occupy the ridgetops and midslopes. Footslope and upland depression soils are Inceptisols, and floodplain soils are Inceptisols and Entisols (Figure 2.10). Ridgetop soils classify as Typic Hapludults in Soil Taxonomy and Haplic Alisols (Alumic, Hyperdystric) in World Reference Base for Soil Resources (WRB). Despite the extremely low sum of bases (0.3-3.0 cmol$_c$ kg^{-1}) in the argillic horizons, the apparent ECEC per kg clay above the requirement of these horizons do not meet the requirement of less than 12 cmol$_c$ kg clay^{-1} for a kandic or oxic horizon. Midslope soils classify as Typic Hapludults and in Soil Taxonomy and Haplic Acrisols (Alumic, Hyperdystric) in WRB. All midslope soils have argillic horizons, indicating that weathering and illuviation of clay is taking place even in colluvium. Footslope and upland depressions classify as Typic Dystrudepts and Dystric Eutrudepts in Soil Taxonomy and Haplic Cambisols (Clayic) in WRB. Floodplain soils classify as Udifluvents, Udorthents, and Fluventic Eutrudepts using Soil Taxonomy and Haplic Fluvisols (Arenic) and Fluvic Cambisols in WRB.

A fertility capability soil classification (FCC) system developed for tropical soils acknowledges the importance of considering quantitative soil data when making land-management decisions, as well as the need to scale-up from individual pedons to a landscape-scale (Sanchez et al., 2003). Descriptors used in FCC are directly related to soil limitations related to plant/crop growth (Sanchez et al., 2003), which aids the feasibility of this system when working with small farmers. Talamanca soils formed on ridgetop and midslope soils would have the following modifiers using FCC: CC(0-15%)$a^{-}k$, indicating clay content above 35% in both surface and subsurface horizons, slopes between 0-15%, high Al saturation, and low nutrient capital. Footslope and upland depression soils would have the following modifiers using FCC: LC(0-15%)*a* and floodplain soils: LL(0-5%).

2.5 Summary/Recommendations for Farmers

Soil geochemical patterns were observed according to landscape position. Tropical soils of the Talamanca foothills have high acidity, high clay content, low-base status, and high Al saturation. Landscape patterns were discernible using clay mineralogy, total elemental concentrations, and exchangeable base cation data. Differences between ridgetop and midslope soils were small due to the high amount of weathering occurring even in midslope soils formed in colluvium. Despite the presence of gibbsite in the ridgetop soils, delta pH values indicate that these soils do not exhibit a strong anion exchange capacity, most likely due to the high C content and associated organic matter. Footslope and upland depression soils had higher base status and lower Al saturation compared to upslope soils. Floodplain soils have the highest base cation status, lowest C content in the A horizon, and highest sand content throughout the profile.

Talamanca foothill farmers allocate crops on their ~ 40 ha farms according to landscape position and soil suitability. Farmers identify ridgetop soils as *Red soil* that is unproductive for most crops. Farmers prefer to farm on floodplain, upland depression, or footslope soils. Physical and chemical soil data coincide with farmers' observations and different limitations are identified for soils formed in each landscape position. Ridgetop and midslope soils have similar physical and chemical limitations. Farmers attempting to cultivate ridgetop soils will need to address the high Al saturation and either cultivate crops that tolerate high-Al soil or incorporate land management techniques that modify the Al environment. Management techniques include increasing the soil organic matter content (SOM) through the application organic compost or green manures, composting post-harvest residue, and planting woody perennials. The incorporation of woody perennials will provide continuous organic matter inputs to the soil, e.g. leaflitter as well as providing coarse roots to the subsoil. Currently, farmers clear the vegetation on ridgetop soils and leave the site with only grass species. As land becomes limited in the indigenous territories, this will no longer be a viable land-use option. Farmers will need to incorporate management techniques that improve and enhance soil conditions.

Footslope and upland depression soils are selected by farmers for planting more sensitive crops such as banana, cacao, and maize. These soils have lower clay content and higher base status than upslope soils. Floodplain soils have low water holding capacity due to high sand content, low SOM contents, and are susceptible to crop fall down due to flood events. Maintenance of tree species on the floodplain will help regulate the water balance, stabilize banks, and provide continuous organic matter inputs. Currently farmers designate monoculture, chemical-intensive plantain on the floodplain and sell it on the national market. Very few trees are incorporated into the system and no crop rotation is practiced. Farmers will need to establish riparian zones that include native woody perennials.

The farmers in the foothill region of Talamanca face several challenges regarding crop production including: steep slopes susceptible to erosion, landslides; low native fertility of foothill soils; lack of infrastructure for getting their crop to market; and lack of extension efforts in the region for soil improvement techniques; and lack of access to mechanized farm equipment. The hope of this project was to provide user-friendly baseline soil data, identify patterns soil biogeochemical patterns across the landscape, and to help aid land-use decisions within the region.

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Table 2.1: Selected soil characteristics for one pedon from each landscape position. --- indicates that sample was not analyzed.

Landscape Position	Depth	pH H_2O	pH KCl	Δ pH	Ca	Mg	K	Na	Sum of Bases	Al	ECEC	Al Sat.	Sand	Silt	Clay
	(cm)				——	——	——	——	cmol$_c$ kg^{-1}	——	——	——	%	——	——
Ridgetop	0-10	4.2	3.7	-0.5	7.22	2.04	0.61	0.05	9.92	2.18	12.1	18	24	28	47
Ridgetop	10-30	4.3	3.6	-0.8	0.94	0.59	0.44	0.04	2.00	9.09	11.1	82	20	27	53
Ridgetop	30-60	4.6	3.6	-1.0	0.17	0.60	0.46	0.04	1.27	8.34	9.6	87	19	24	57
Ridgetop	60-90	4.6	3.5	-1.1	0.06	0.49	0.19	0.04	0.77	8.51	9.3	92	—	—	—
Ridgetop	90-120	4.7	3.5	-1.2	0.02	0.43	0.10	0.04	0.59	7.28	7.9	92	27	32	41
Ridgetop	120-160	4.7	3.4	-1.3	0.05	0.49	0.25	0.02	0.82	8.04	8.9	91	—	—	—
Midslope	0-10	4.0	3.6	-0.3	2.34	1.48	0.39	0.13	4.34	3.83	8.2	47	17	27	53
Midslope	10-20	3.5	3.7	0.2	1.21	0.51	0.08	0.12	1.92	5.03	6.9	72	16	30	55
Midslope	20-33	3.6	3.7	0.1	0.99	0.42	0.35	0.12	1.88	5.27	7.1	74	13	30	57
Midslope	33-48	3.8	3.7	0.0	0.62	0.22	0.01	0.11	0.95	6.34	7.3	87	16	34	50
Midslope	48-65	4.0	3.7	-0.3	0.32	0.16	0.06	0.06	0.60	4.92	5.5	89	5	32	63
Midslope	65-85	4.2	3.8	-0.4	0.35	0.21	0.01	0.11	0.68	3.82	4.5	85	8	29	63
Midslope	85-120	4.3	3.8	-0.5	0.18	0.09	0.10	0.10	0.47	3.49	4.0	88	—	—	—
Footslope	0-9	4.4	4.3	-0.1	17.43	7.01	0.73	0.17	25.34	0.22	25.6	0.9	24	40	36
Footslope	9-23	4.6	3.8	-0.8	18.57	8.95	0.50	0.25	28.28	1.35	29.6	5	18	48	34
Footslope	23-45	4.5	3.8	-0.7	18.79	9.11	0.49	0.26	28.65	1.60	30.2	5	13	45	42
Footslope	45-90	4.7	3.8	-1.0	21.30	11.71	0.57	0.37	33.94	0.96	34.9	3	20	47	33
Upland Depression	0-5	4.7	4.0	-0.7	15.06	6.02	1.87	0.19	23.14	0.57	23.7	2	11	40	49
Upland Depression	5-10	4.5	3.6	-0.9	12.74	5.17	1.51	0.22	19.65	1.66	21.3	8	—	—	—
Upland Depression	10-30	4.6	3.6	-1.1	10.21	4.43	1.22	0.22	16.08	3.17	19.2	17	9	37	54
Upland Depression	30-60	4.5	3.4	-1.1	7.97	4.21	0.79	0.19	13.16	7.11	20.3	35	—	—	—
Upland Depression	60-90	4.4	3.3	-1.2	7.39	4.58	0.39	0.19	12.55	11.5	24.0	48	9	39	53
Upland Depression	90-110	4.5	3.3	-1.2	6.65	4.27	0.24	0.16	11.33	12.3	23.6	52	—	—	—
Alluvial Floodplain	0-5	7.6	6.6	-1.0	30.11	3.18	1.07	0.08	34.45	0.00	34.5	0	19	52	29
Alluvial Floodplain	5-10	7.6	6.6	-1.0	33.11	4.30	0.37	0.11	37.88	0.00	37.9	0	—	—	—
Alluvial Floodplain	10-25	6.7	5.7	-1.0	26.56	4.64	0.26	0.17	31.62	0.00	31.6	0	23	48	29
Alluvial Floodplain	25-50	6.8	5.3	-1.5	28.59	5.57	0.73	0.14	35.03	0.00	35.0	0	—	—	—
Alluvial Floodplain	50-75	6.7	5.4	-1.3	24.92	4.55	0.48	0.13	30.08	0.00	30.1	0	27	49	24
Alluvial Floodplain	75-100	6.9	5.3	-1.6	22.25	3.66	0.19	0.20	26.30	0.00	26.3	0	—	—	—

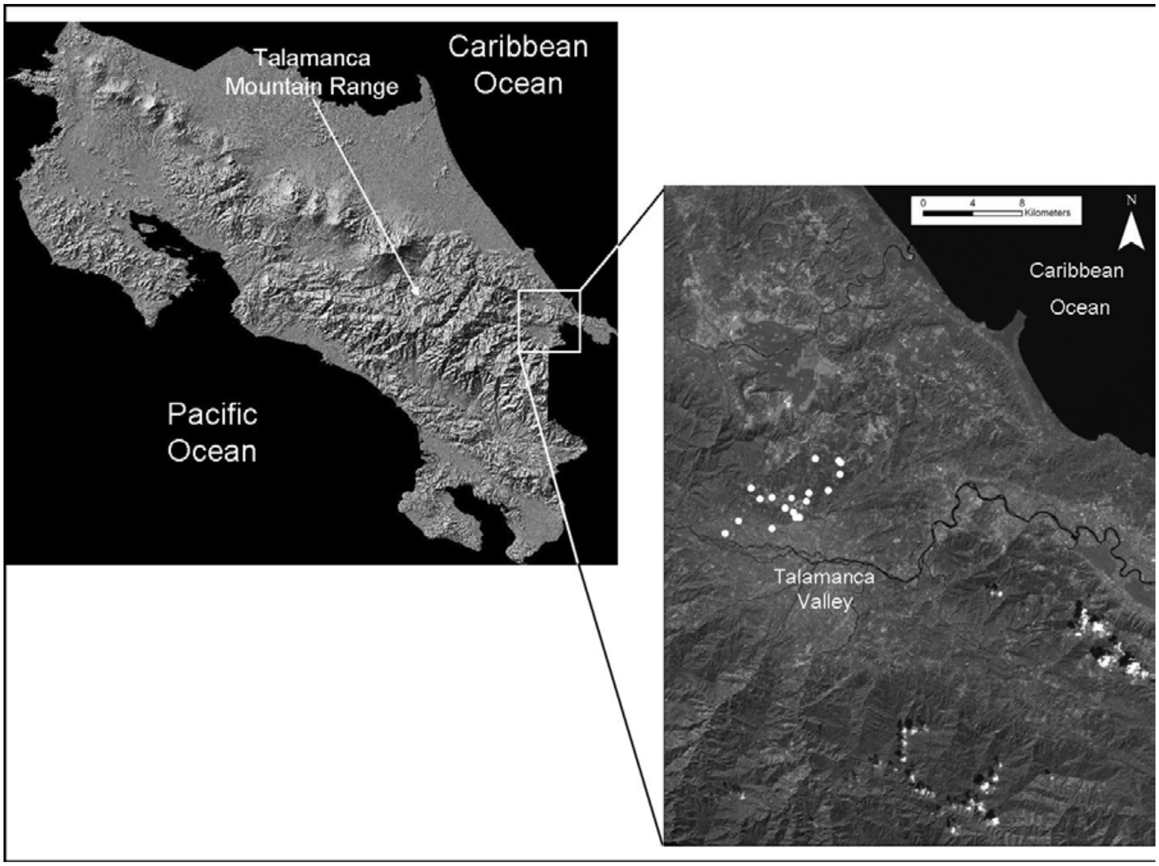

Figure 2.1: Digital elevation model of Costa Rica with Talamanca Mountains labeled. Area within the box is enlarged on the right. Arial photograph of the Talamanca Valley and northern foothill region is shown on the right. Pedon sites are indicated with white circles.

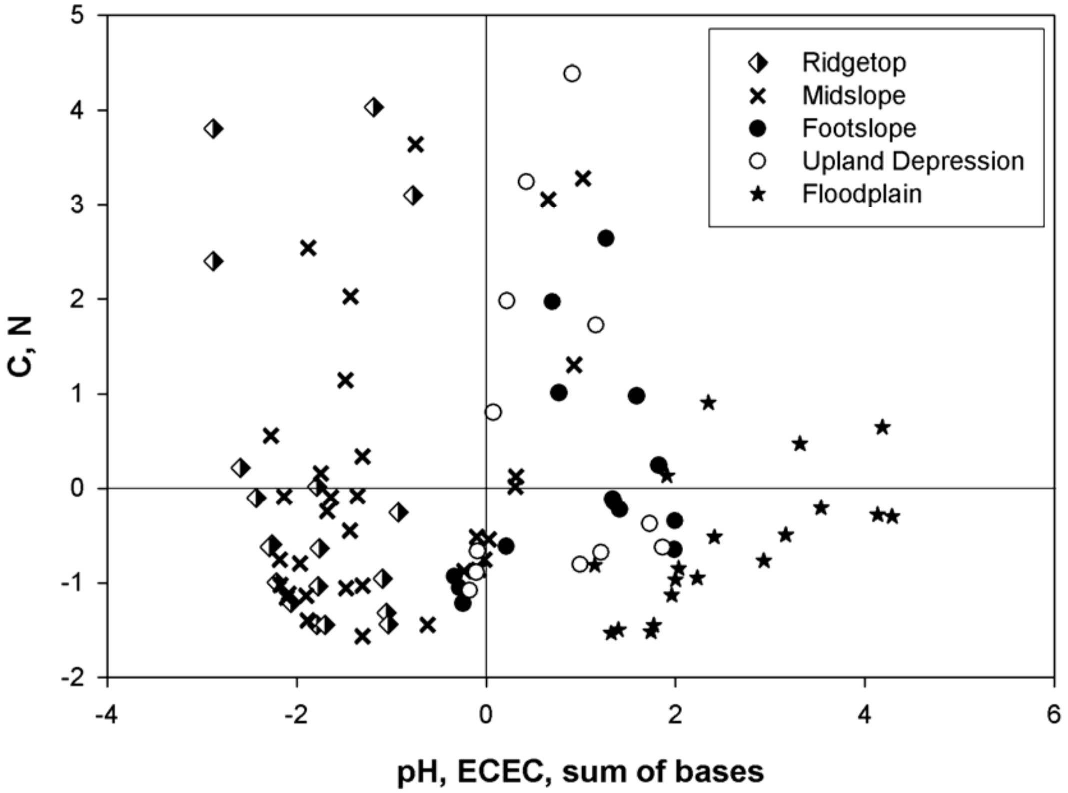

Figure 2.2: Principal component analysis for extractable sum of bases, pH, effective cation exchange capacity (ECEC), C, and N according to landscape position.

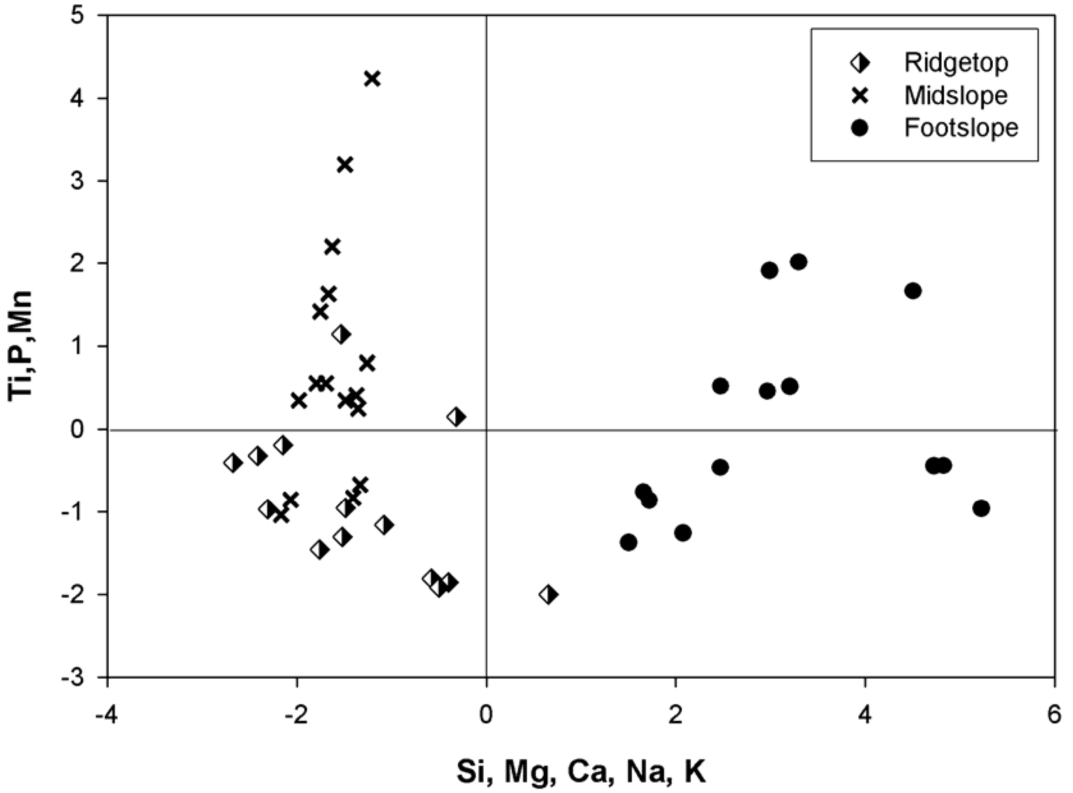

Figure 2.3: Principal component analysis of total elements and landscape position.

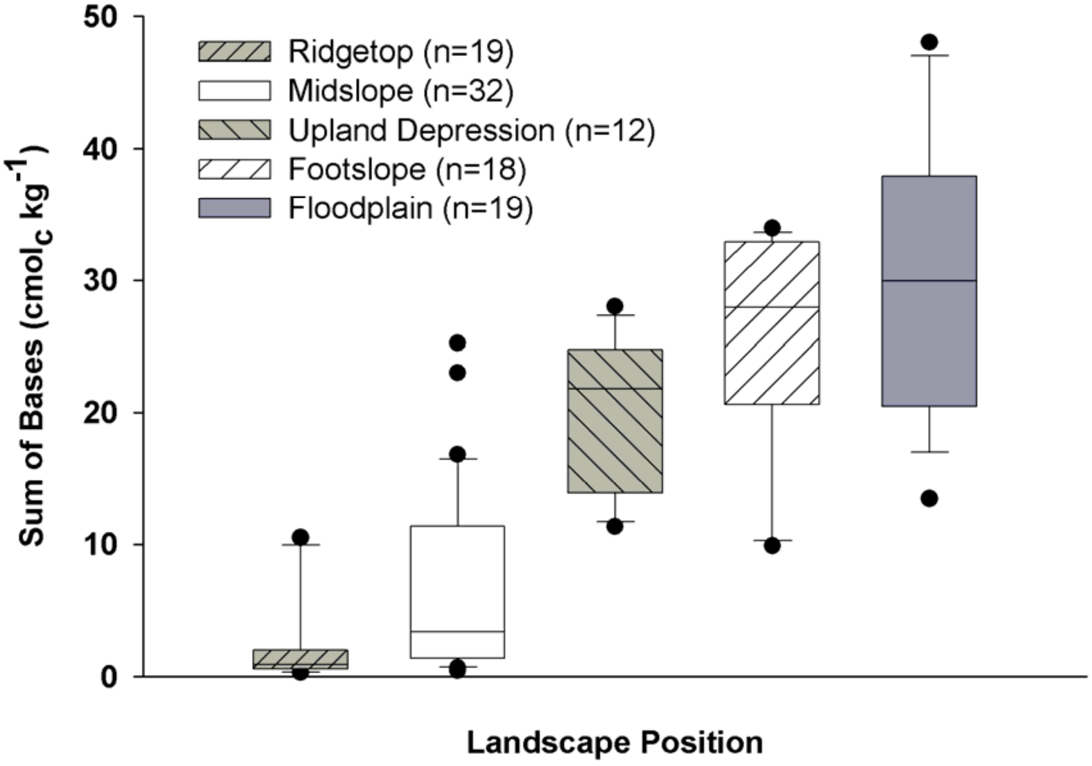

Figure 2.4: Sum of bases (Ca, Mg, K, Na) for all horizons in each of the five landscape positions.

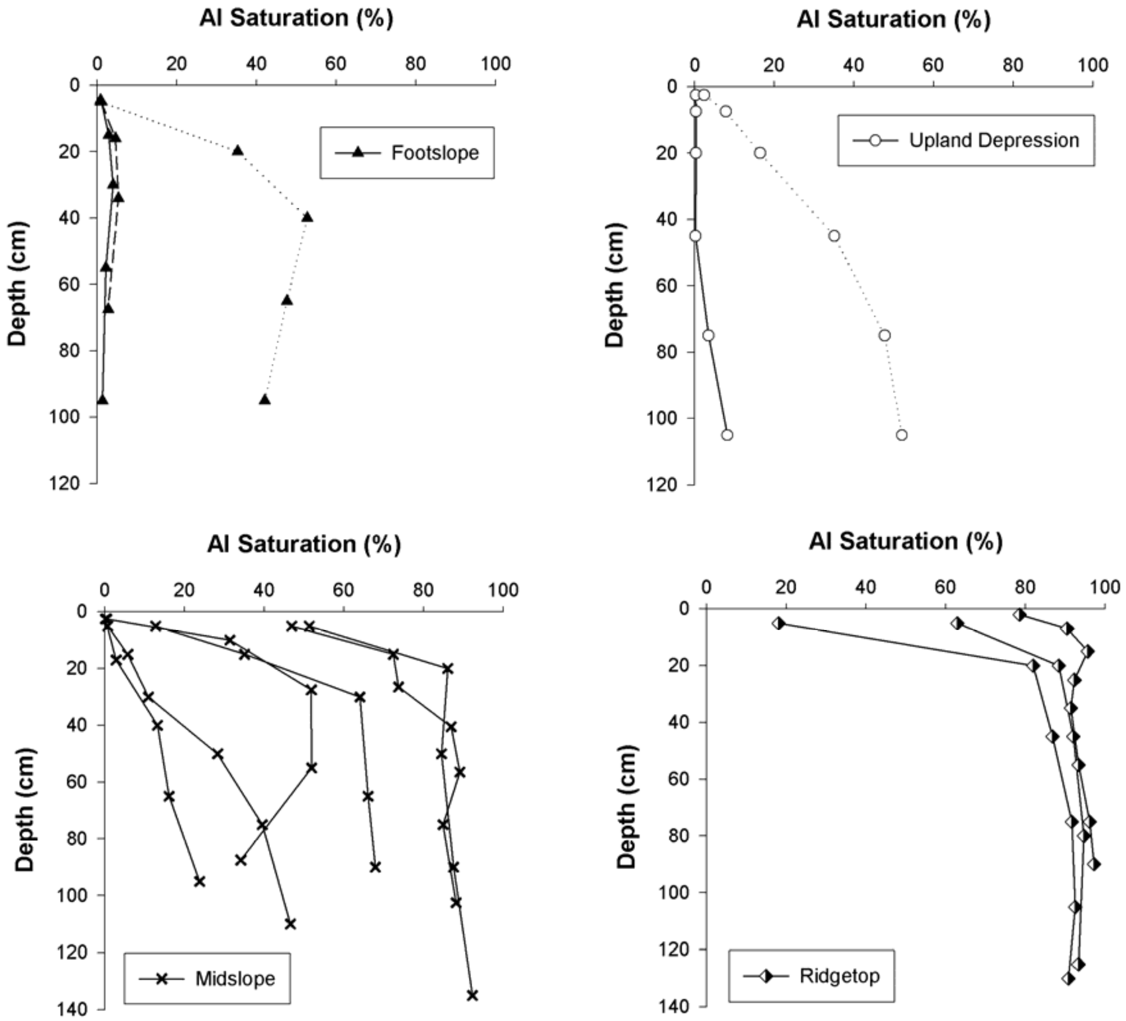

Figure 2.5: Aluminum saturation of each horizon from three footslope pedons, two upland depression pedons, six midslope pedons, and three ridgetop pedons.

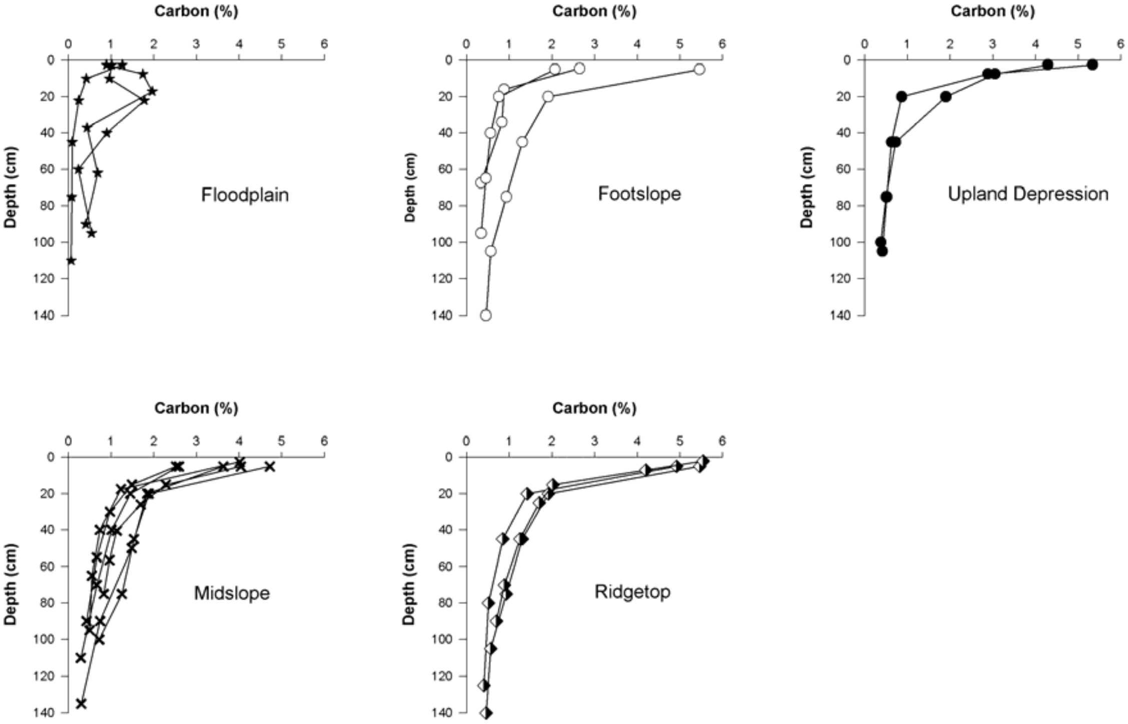

Figure 2.6: Total carbon for each horizon from three floodplain profiles, three footslope profiles, two upland depression profiles, six midslope profiles, and three ridgetop profiles.

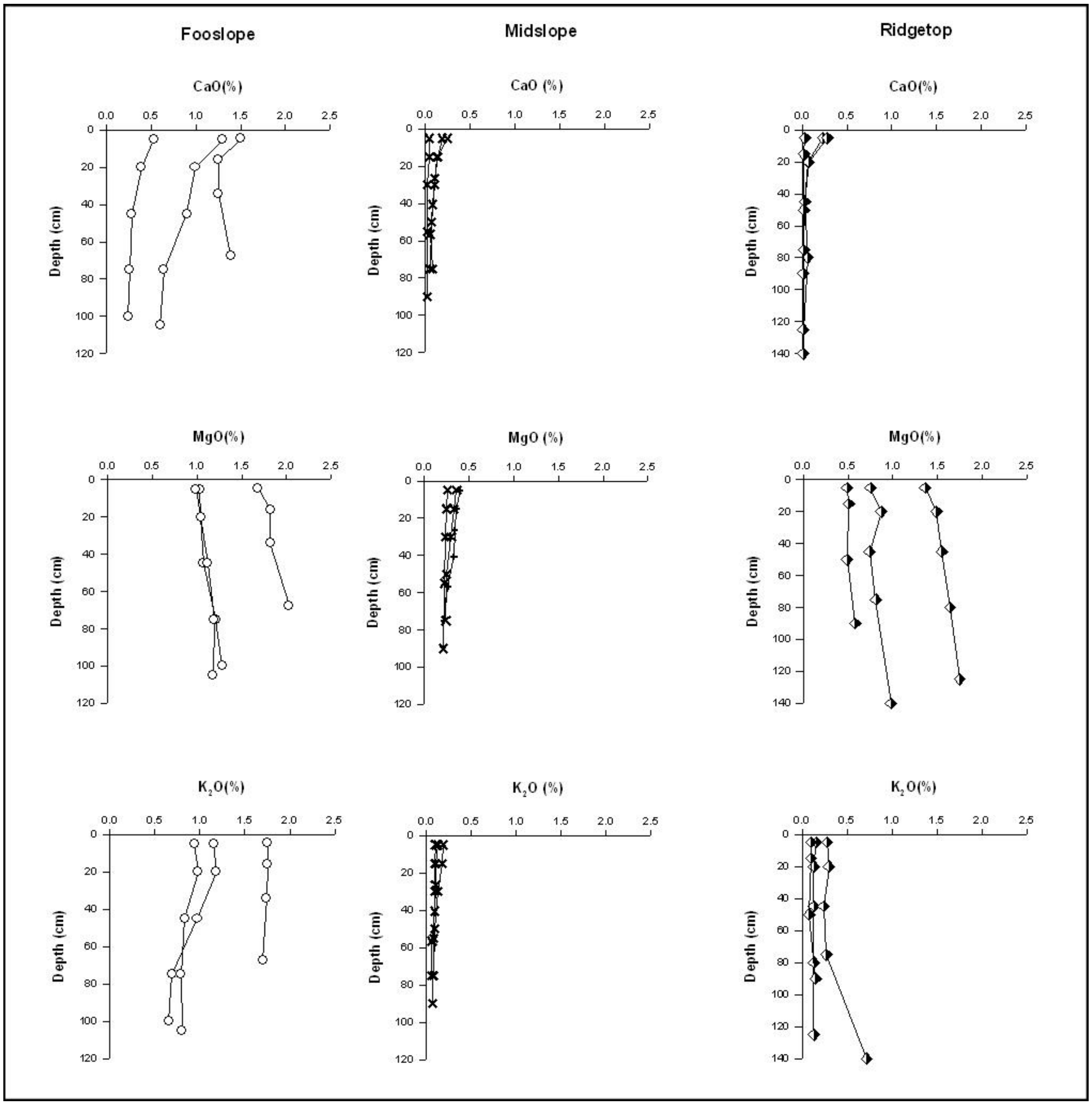

Figure 2.7: Total Ca, Mg, and K concentrations for each horizon in three footslope pedons, three midlslope pedons, and three ridgetop pedons.

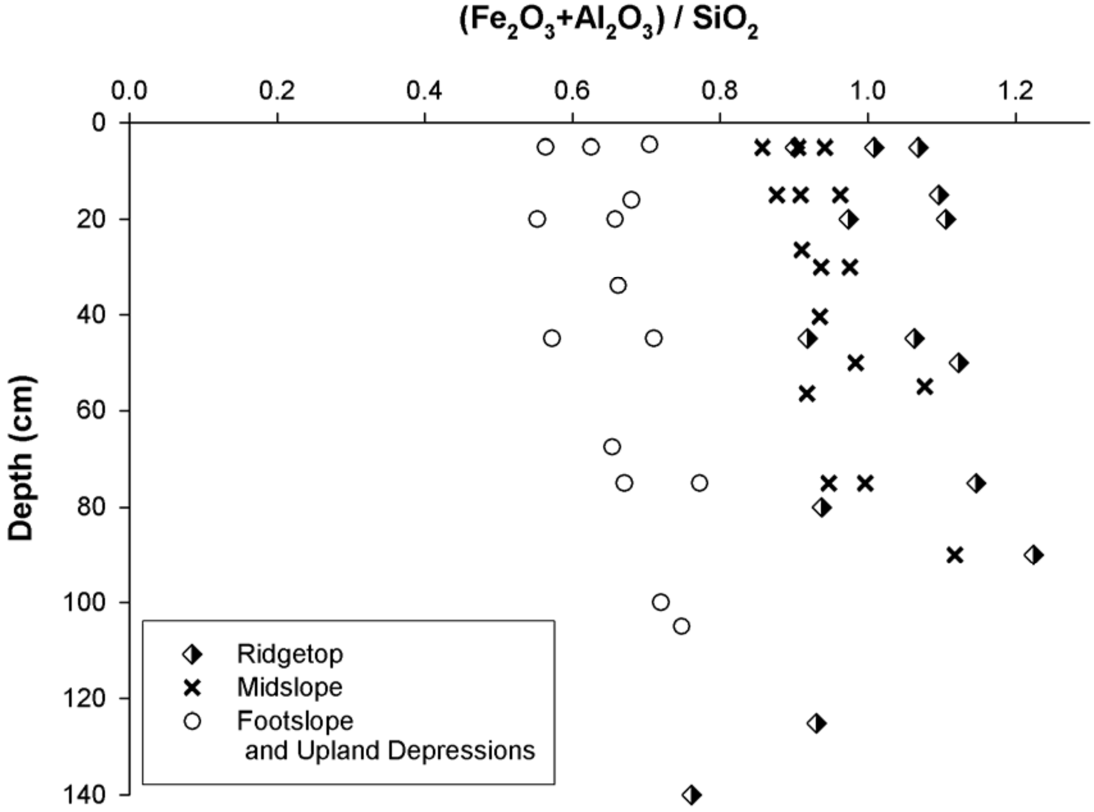

Figure 2.8: Ratio of the sum of Fe and Al oxides to Silica for each horizon for three ridgetop profiles, four midslope profiles, and three footslope and upland depression profiles. Higher ratio indicates a more developed soil.

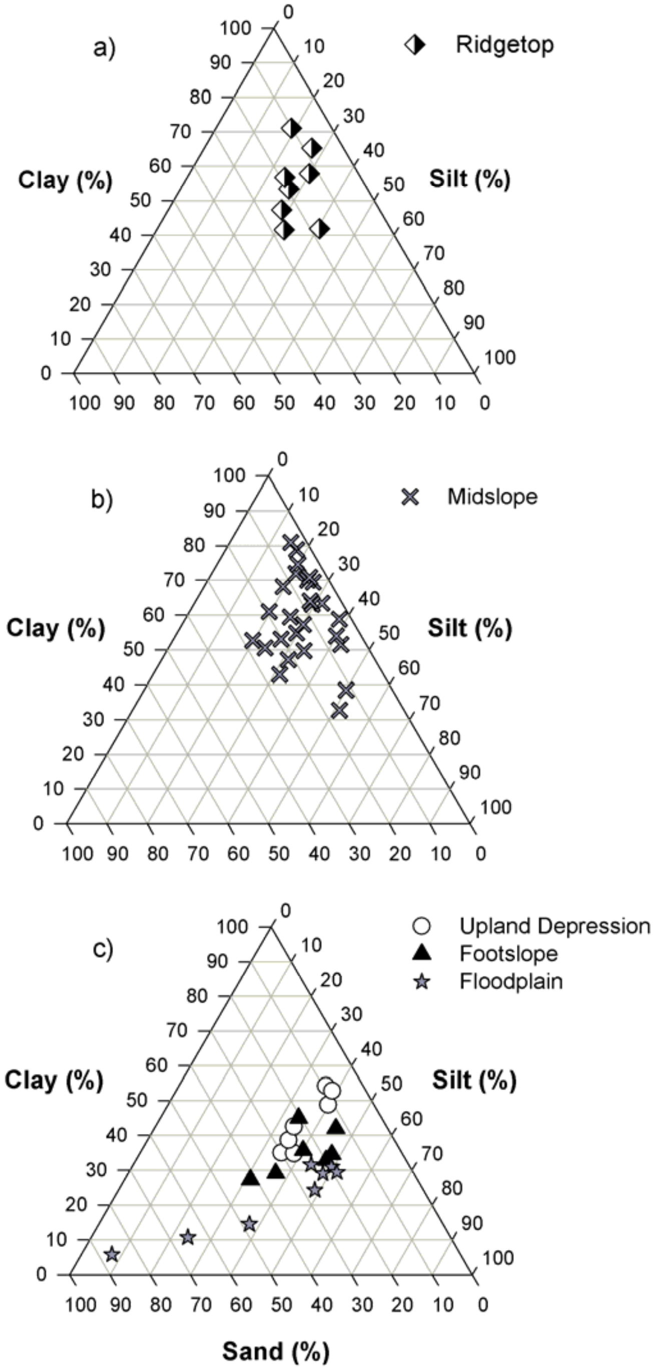

Figure 2.9: Ternary graphs of the % silt, sand, and clay of each soil horizon, organized by landscape position: a= ridgetop soils; b= midslope soils; c= upland depression, footslope, and floodplain soils.

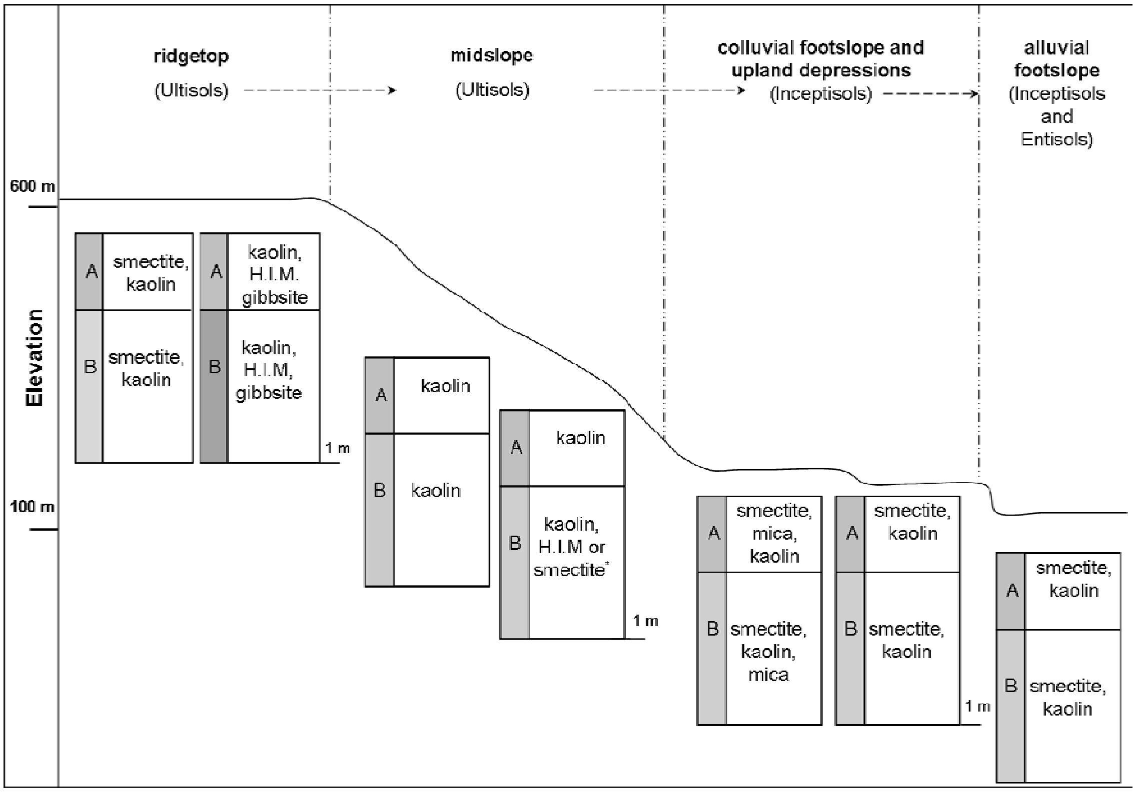

Figure 2.10: Clay minerals present in A horizon and subsurface horizon. Illustrated soil profiles are grouped by landscape position and show variability within landscape position. Not shown is the midslope profile dominated by HIM. Arrows at the top of the diagram denote soil classification according to Soil Taxonomy.

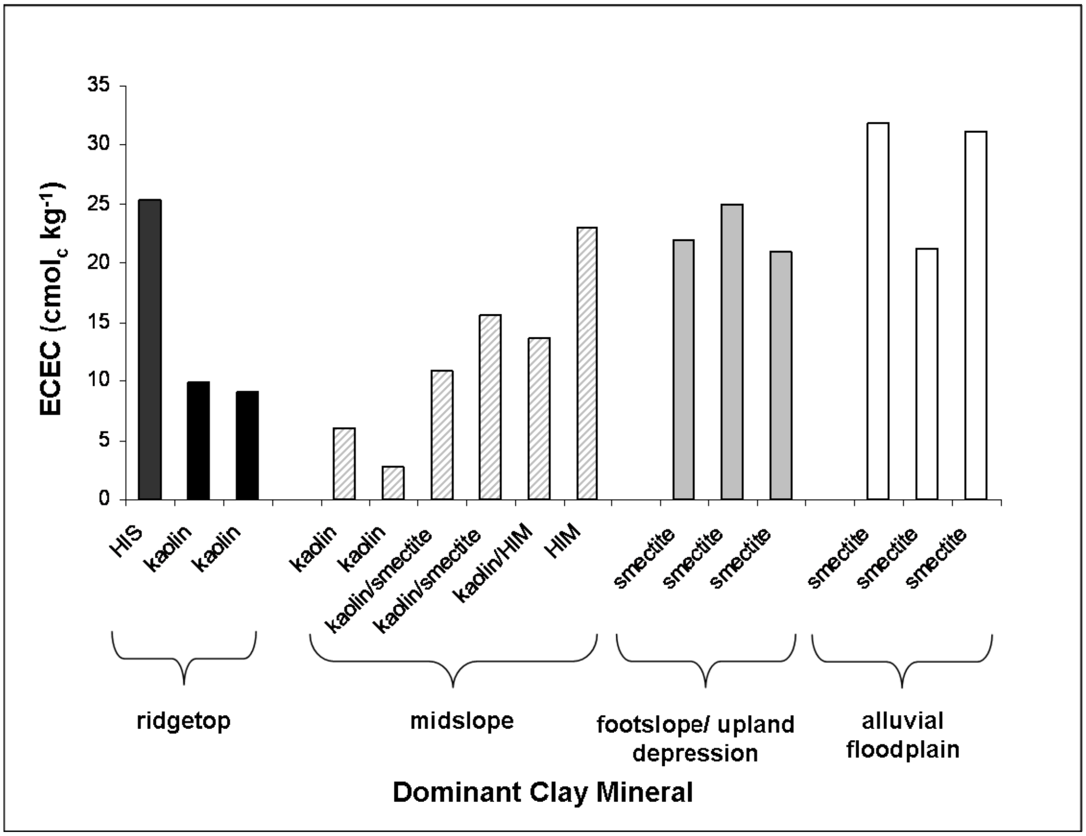

Figure 2.11: Weighted mean of effective cation exchange capacity (ECEC) to 1-m depth for each profile. Pedons are grouped by landscape position. HIS=hydroxy-interlayered smectite. HIM=hydroxy-interlayered mineral.

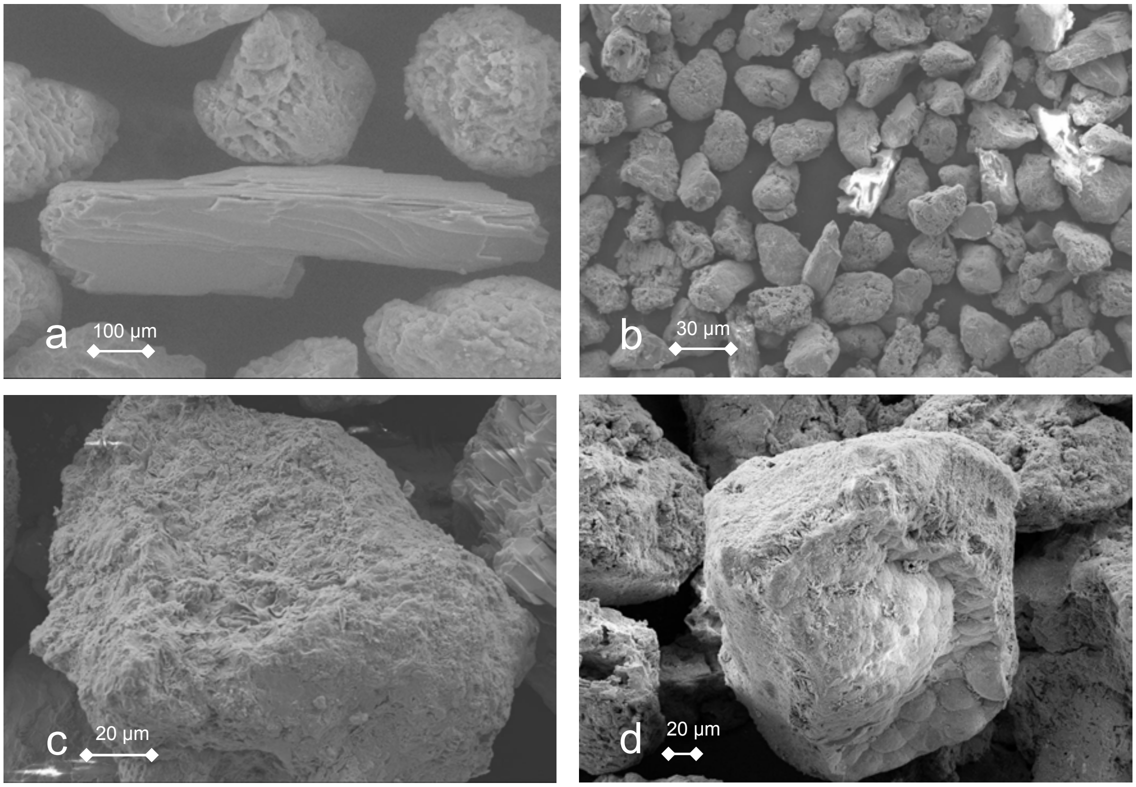

Figure 2.12: Scanning electron micrographs of sand grains demonstrating the variety of morphological features found in foothill soils: a) lath-shaped amphibole, while not common in the sand grains, is present; b) general photo of sand grains from a Bt horizon in a soil formed in an upland depression, note the two dominant grain morphologies (deeply pitted grains suggesting chemical weathering and subrounded grains suggesting of physical weathering); c) note the uniform weathering typical of quartz grains; d) note the botryoidal appearance in the lower right portion of the grain, characteristic of iron oxides, possibly hematite.

3 CHAPTER THREE: BIOGEOCHEMICAL CYCLING OF BASE CATIONS IN CACAO AGROFORESTRY AND SHIFTING CULTIVATION SYSTEMS, TALAMANCA, COSTA RICA

3.1 Abstract

Long-term sustainability of no-input cacao (*Theobroma cacao)* agroforestry and shifting cultivation systems is dependent on efficient internal nutrient cycling and the nutrient storage and exchange capacities of the soil. Understanding the effects of land use on nutrient and hydrologic cycling will provide insight for developing better management practices. Yet, data on the fluxes between nutrient pools within contrasting agroecosystems, including the revegetation stage of shifting cultivation, are sparse. Specific objectives of this study are: 1) to quantify base cation pools in a cacao agroforestry (cacao) and a shifting cultivation (arroz) system, including aboveground and belowground pools and 2) to make long-term predictions based on base cation sustainability. Field monitoring sites were selected in January 2006 in a cacao agroforestry (cacao) and shifting cultivation/slash-and-burn (arroz) system. Calcium (Ca), magnesium (Mg), and potassium (K) were measured in various soil nutrient pools. Soil porewater was sampled monthly and analyzed for Ca, Mg, and K. Litterfall was collected biweekly and decomposition of cacao leaves was measured in a litter bag study. Results indicate that both sites have low soil base cation status. The cacao site has a weighted mean sum of bases to 1-m depth of 1.2 $\text{cmol}_c\ \text{kg}^{-1}$ and the arroz site has 7.9 $\text{cmol}_c\ \text{kg}^{-1}$. Both sites have >30% Al saturation in the top 20 cm. Soil mositure content and matric potential are at or above field capacity year round, suggesting a water surplus at both sites, which has implications for potential leaching losses. Mean porewater concentrations at the 1-m depth during a 16-month sampling period at the arroz site are 1.14 mg Ca L^{-1} in contrast to 0.23 mg Ca L^{-1} under cacao. Results from the litter bag study show that 77% of the mass of cacao leaves is lost after one year. Data from this study suggest that these Ultisols have limited capacity to store and supply exchangeable

Ca, Mg, and K to plant roots, and that only small quantities of these nutrients remain in primary mineral form at the cacao site. The contribution of biocycling from leaflitter in agroecosystems on nutrient-poor soils is an important consideration in the design of agroforestry systems, as leaflitter decomposition appears to be rapid and an important source of these base cations.

3.2 Introduction

3.2.1 Costa Rica: Conservation and Agriculture – Agroforestry Practices and Shifting Cultivation

Costa Rica is well known for its conservation efforts through its creation of an extensive National Park System and the Payment for Environmental Services program. In addition to conservation-based tourism, agriculture continues to be an important part of Costa Rica's total GNP, as over 50 % of its land area is dedicated to agriculture and pastures (FAO, 2003). To coincide with Costa Rica's conservation principles, sustainable agricultural techniques continue to be evaluated, developed, and implemented across the landscape. Agroforestry is a wide-spread agricultural system throughout the tropics that holds promise for soil conservation (Sanchez, 1999; Young, 1997), biodiversity conservation (Harvey and González, 2007; Rice and Greenberg, 2000; Schroth et al., 2004; Somarriba and Harvey, 2003), mitigation against global climate change (Verchot et al., 2005), increasing aboveground and belowground biomass (Schroth et al., 2002), and improving economic viability (Alavalapati et al., 2004). A working definition of agroforestry is, "a form of multiple cropping under which three fundamental conditions are met: 1) there exist at least two plant species that interact biologically; 2) at least one of the plant species is a woody perennial; and 3) at least one of the plant species is managed for forage, annual or perennial crop production" (Somarriba, 1992).

Several studies conducted in Costa Rican agroforestry systems have advanced the knowledge base of nutrient cycling within these systems. A study comparing pastures and pastures recently (5 years) converted to agroforestry systems in the Sarapiqui region of Costa Rica concluded that soils under agroforestry systems had higher extractable P in the top 25 cm, but lower exchangeable bases and pH, and no difference in SOC or N was observed (Tornquist et al., 1999). The lack of difference could be due to the short time since land conversion. An extensive, long-term study on organic matter and nutrient cycling, as well as fruit, wood, and litter production of two different cacao agroforestry systems was conducted on CATIE's experimental farms between 1980-1990 (Fassbender et al., 1991). The systems were *Theobroma cacao* with *Cordia alliodora* and *Theobroma cacao* with *Erythrina poeppigiana.* Differences were observed in the allocation of K, Mg, and Ca in the shade trees, e.g. trunks of *Cordia alliodora* stored more Ca and Mg compared to the rest of the tree and while *Erythrina poeppigiana* allocated higher concentration of Ca and Mg in its branches (Alpizar et al., 1986). In addition, potassium concentrations in leaves, branches, stems, and fruits of the *Theobroma cacao* plants differed depending on the shade tree present (Heuveldop et al., 1988). N, P, and K leaching losses were relatively small and similar between the two systems, yet the *Erythrina poeppigiana* system leached four times more Ca and Mg than the *Cordia alliodora* system (Imbach et al., 1989). This study provides excellent data on the nutrient contribution of two common tree species planted with *Theobroma cacao* in Costa Rica.

Authors point out that though much research has been conducted within diverse agroforestry systems, many unexplored factors still need to be addressed regarding their sustainability in different climatic regions and on different soil types and landforms (Hartemink, 2005; Kang and Akinnifesi, 2000), within different political and communal structures (Alavalapati et al., 2004), with combinations of different shade tree species (Rhoades, 1995), and in direct comparison with annual cropping systems (Hartemink, 2005). In addition, agroforestry systems practiced by smallholder farmers are often more diverse and less organized than the systems depicted in research and thus warrant on-farm research trials (Somarriba et al., 2001).

In contrast to diverse agroforestry systems, shifting cultivation is cited as contributing to tropical deforestation and creating unproductive soils (Sanchez et al., 2005). Despite this, shifting cultivation still occupies 22% of tropical land area (Sanchez et al., 2005) and is practiced within remote regions of Costa Rica. Slash-and-burn systems have been intensely studied with regard to nutrient cycling and nutrient losses due to burning (Ewel et al., 1981; Juo and Manu, 1996; Nye and Greenland, 1960) and carbon fluxes (Palm et al., 2005) over time. Research has also focused on the fallow vegetation including: an assessment of nutrient stocks in fallow vegetation to predict nutrient inputs and losess (Hartemink, 2004), evaluation of appropriate tree species used in fallow and improved fallow vegetation (Kass and Somarriba, 1999), and mapping fallow vegetation succession to make recommendations on fallow length for maximum organic matter inputs to the soil (Styger et al., 2007). Researchers had suggested that fluxes between nutrient pools be evaluated and understood in order to further the state of knowledge of slash-and-burn systems (Palm et al., 1996). While research has been conducted within both agroforestry and slash-and-burn systems, few studies have compared on-farm biogeochemical and hydrologic cycling within agroforestry systems and an annual cropping system to determine their sustainability (Hartemink, 2005; Kang and Akinnifesi, 2000). This project attempts to combine agronomy, soils, and hydrology to address sustainability issues with regard to base cation cycling in cacao agroforestry and shifting cultivation/slash-and-burn systems.

3.2.2 Biogeochemical Cycling

Biogeochemical cycling of base cations plays an important role in the productivity and sustainability of agroecosystems (Kellerman and Tackberry, 1997; Schroth et al., 2001). Ecosystem processes, including base cation cycling, are often affected by land-use or vegetative changes (Schroth et al., 2002; Wilcke and Lilienfein, 2002) and are therefore a good measure for evaluating land-use systems. Understanding the cycling of plant-required base cations allows us to assess effects of land-use change on natural ecosystem processes, while evaluating if and for how long the system can support the crop of interest without external inputs.

Cycling of plant-required base cations, calcium (Ca), magnesium (Mg), and potassium (K), is influenced by biotic and abiotic processes which operate both above and below ground (Schlesinger, 1997). Base cation cycling and availability is influenced by atmospheric deposition, cation exchange, mineral weathering, mineralization of soil organic matter, leaching, and accumulation in aboveground biomass (Likens et al., 1998). Yet initial soil nutrient constraints are dependent on nutrient reserves, mineral solubility, and cation exchange capacity (Schlesinger, 1997). Base cations are released through weathering of both primary and secondary minerals and enter soil solution as an ion, which can be sorbed on the soil exchange complex, assimilated into biomass, or leached from the system (Likens et al., 1998). In the humid tropics, relatively constant temperatures and high rainfall rates allow for continuous decomposition of plant material, recycling of nutrients, and leaching losses of nutrients through the soil (Jordan, 1985). Soluble cations below the rooting zone are susceptible to leaching and can contribute to a significant portion of nutrient loss from the system (Dechert et al., 2005). Porewater concentrations are commonly used to assess sustainability of agroecosystems in terms of leaching losses (Lilienfein et al., 2000; Wilcke and Lilienfein, 2005), to assess the effects of land-use and land-management practices (Baeumler and Zech, 1998; Seyfried and Rao, 1991), to quantify the availability of nutrients for plant uptake (Smethurst, 2000), and to evaluate nutrient cycling under different vegetation types (Johnson-Maynard et al., 2005).

Litterfall plays an important role in the biocycling of base cations, as Mg and K are minimally resorbed into the perennial plant tissue before leaf senescence and Ca leaf concentrations can increase with age just before senescence (Likens et al., 1998; Ryan and Borman, 1982). Contribution of litterfall to the overall nutrient inputs in coffee agroforestry systems in Costa Rica were estimated to equal that of inorganic fertilizer inputs (Beer, 1988). In addition, litterfall can play an important role in protecting the soil surface from rain impact, retention of soil moisture, and provides habitat for beneficial micro and macro organisms, including cacao pollinators.

Most soil management projects acknowledge the importance of conserving and/or enhancing the replenishment of soil nutrients, soil organic matter and soil moisture (Juo and Franzluebbers, 2003). While these basic principles are understood, many programs assessing sustainability are limited by a lack of understanding of soil minerals present, factors affecting the release of plant-required nutrients, and leaching rates of soluble nutrients. Quantifying nutrients in the aboveground biomass and litterfall, along with soil primary mineral, exchangeable, and soluble phases of these cations will aid in determining long-term sustainability of an agroecosystems with regard to a base cation budget.

3.2.3 Talamanca, Costa Rica

Talamanca is a region in southeastern Costa Rica that borders Panama. Talamanca is home to the Bribri and Cabécar indigenous territories and is included within the MesoAmerican Biological Corridor, which connects several protected areas both within and across Central America. Talamanca farmers practice both subsistence and cash-crop agriculture. They cultivate several crops including: monoculture plantain (*Musa* AAB); agroforestry cacao (*Theobroma cacao*); agroforestry banana (*Musa* AAA); pasture; shifting cultivation with basic grains (rice (*Oryza sativa*), maize (*Zea mays)*, and beans (*Phaseolus vulgaris*)); and root crops (yucca (*Manihot esculenta*) and ñame (*Dioscorea* spp.)) (Somarriba et al., 2003). It is estimated that 1500 ha within the territories are devoted to cacao agroforestry systems, which account for 95% of the national organic cacao production (Municipalidad of Talamanca, 2003). The cacao agroforestry systems receive no fertilizers. The success of the cacao crop depends on the native fertility of the site and efficient nutrient cycling of plant-required base cations. Shifting cultivation, which entails slashing and burning the native vegetation for the cultivation of basic grains (rice, maize, and beans), is still actively practiced in the foothill and mountainous regions of Talamanca. Due the land requirement of shifting cultivation systems, it is practiced only by farmers living in remote areas with ample land.

3.3 Objectives

The objectives of this study are to: 1) quantify base cations, calcium (Ca), magnesium (Mg), and potassium (K), in aboveground and belowground pools in cacao agroforestry and shifting cultivation systems on Ultisols in Talamanca, Costa Rica to estimate nutrient fluxes between the pools; 2) compare soil porewater base cation concentrations to estimate leaching losses under both systems and; 3) make predictions about long-term sustainability of cacao agroforestry and shifting cultivation systems relative to base cation dynamics.

3.4 Methods

3.4.1 Study Area

The study area is located on the Atlantic-slope of the Talamanca Mountains (Figure 3.1). Average annual temperature of the study region is 25 ^{o}C with 85% relative humidity (Kapp, 1989). Precipitation averages between 2200 and 3100 mm, which falls year-round and the Holdgridge Life Zone classification is: Very Humid Tropical Forest (Kapp, 1989). The Talamanca Mountains are the oldest and longest in Costa Rica, and have a complex geology of Tertiary sediments, intermixed with limestone deposits and volcanic material, as well as wide valleys with Holocene alluvial deposits (Denyer and Kussmaul, 2000; Weyl, 1980). The foothill soils are a mosaic of clay-rich Ultisols and Inceptisols.

3.4.2 Field and Laboratory Methods

Two foothill sites within the Cabécar Indigenous territories were selected on Ultisols: one under a diverse cacao (*Theobroma cacao*) agroforestry system (cacao site) and one under a shifting cultivation/slash-and-burn land use (arroz site). Sites were located within 200 m of each other on midslope landscape positions. The cacao was planted in a 4.5-m by 4.5-m planting arrangement amongst a variety of native forest and planted shade trees (31 different shade tree species in total see appendix D) including: *Cordia alliodora, Inga spp., Bactris gasipaes, Psidium guajava,* and *Nephelium lappaceu*. Cacao seedlings were planted in 1988 after the land previously went through one full cycle of slash and burn and maize production that left several native tree species. The cacao is actively managed for organic production for sale on the international market. The arroz site had undergone four slash-and-burn cycles and was left in fallow for 4 years before the most recent burning. Elevation of both sites is 130 m. The slope at the cacao site is 11% and 15% at arroz site and both have easterly aspects.

Monitoring equipment was installed at the cacao site in January 2006 and in April 2006 at the shifting cultivation/slash-and-burn site the day after the field was burned. Soil moisture and matric potential were measured hourly at three depths (15, 60, and 100 cm) with Campbell Scientific CS615-L Water Content Reflectometers and UMS T-4 Transducer Tensiometers connected to a Campbell Scientific CR10X datalogger. Porous, ceramic cup soil solution samplers (lysimeters) from Soil Moisture Corp. were installed at the same three depths to collect soil solution that was analyzed monthly for Ca, Mg, and K using atomic absorption spectroscopy. Precipitation at the arroz site and throughfall at the cacao site were measured with DAVIS precipitation gauges placed 2 m above the soil surface. Random samples of precipitation and throughfall were collected and analyzed for Ca, Mg, Na, and K. Ambient air temperature was measured for a 26-day period at both sites using Hobo Temperature Sensors.

Soil pits were excavated to a depth ~ 1 m. Samples were collected by genetic horizon and transported to the University of Idaho Pedology Laboratory. Soil samples were air dried, gently crushed, and sieved to < 2mm. Sand, silt, and clay contents were determined using wet sieving, sonification, and centrifugation (Gee and Bauder, 1986). Soil pH was measured on a 1:1 (soil:deionized water) slurry with a standard pH electrode (Thomas, 1982). Exchangeable cations (Ca, M, Na and K) were extracted using

NH_4OAc at pH 7 (Sumner and Miller, 1996); leachate was analyzed using inductively coupled plasma (ICP) emission spectroscopy. Exchangeable Al was extracted using 1 N KCl (Bertsch and Bloom, 1996); leachate was analyzed for Al using ICP spectroscopy. Effective cation exchange capacity (ECEC) was calculated using NH_4OAc-extractable bases + KCl-extractable Al . Total elemental concentrations of Ca, Mg, and K were determined via ICP-emission spectroscopy following $LiBO_2$ fusion and dilute nitric digestion. Mineralogy of the clay fraction from three depths at each site was determined using X-ray diffraction (Whittig and Allardice, 1986). Soil samples ground to 0.50 µm were analyzed for total C and N by dry combustion (Nelson and Sommers, 1996) using a C, N, S analyzer (Elementar).

Litterfall was collected biweekly in four replicate, 1-m^2 plots within the cacao site. Litterfall was dried, weighed, ashed, and analyzed for nutrients. Decomposition of cacao leaves was determined using the litterbag method (Robertson and Paul, 2000). Seventy leaf litter bags were filled a known weight of dried, senesced cacao leaves and placed within the litter layer at the soil surface. Four bags were collected biweekly for 350 days. Leaves were dried and weighed to determine the rate of decomposition of cacao leaves on the farm using (Eq. [1]).

$$x_t / x_o = e^{-kt} \qquad \text{[Eq. 1]}$$

where x_t / x_o is the proportion of original mass at time t and k is the decomposition rate constant.

Nutrient concentrations of leaves were measured on a digest of the dried leaves. Aboveground biomass for cacao agroforestry site was calculated using allometric regression equations developed for Talamanca tree species, including cacao (*Theobroma cacao*) (Segura, 2005). *Theobroma cacao* tends to branch close to the soil surface, therefore aboveground biomass (Bt) models are based on the diameter of cacao trees at 30 cm above the soil surface (Eq. [2]).

$$Log\ Bt = -1.625 + 2.626 * Log\ (Diameter\ at\ 30\ cm)\ R^2 = 0.98 \qquad \text{[Eq. 2]}$$

Shade tree biomass (Bt) calculations use diameter at breast height (dbh) and were divided into two categories: fruit species (Eq. [3]) and timber species (Eq. [4]) (Andrade et al., In Preparation; Segura, 2005).

$$Log\ Bt = -1.11 + 2.64\ (Log\ dbh_{fruit}) \qquad R^2 = 0.95 \qquad \text{[Eq. 3]}$$

$$Log\ Bt = -0.51 + 2.08\ (Log\ dbh_{timber}) \qquad R^2 = 0.92 \qquad \text{[Eq. 4]}$$

Aboveground biomass for the fallow site (B) (age of four years) before vegetation was burned was calculated using (Eq. [5]), which was developed for fallow systems in Talamanca (Segura, 2005).

$$B = (1.4 + (6.3 * age))/1.3)/0.47 + 5.6 \qquad \text{[Eq. 5]}$$

We estimated that 15.8 % of aboveground biomass of cacao trees is allocated to its leaves; 2.3% of the aboveground biomass of timber tree species is allocated to leaves; and 10 % of aboveground biomass of fruit tree species is allocated to leaves. We used these percentages and the nutrient content of the leaves and trunks from each group of tree species to calculate total nutrient content in the aboveground biomass at the cacao agroforestry site.

3.5 Results and Discussion

3.5.1 Climatic Data

Measured precipitation totaled 2252 mm over 438 days, with no marked dry season (Figure 3.2). These data fall within the long-term precipitation range reported for the region. Temperature data for the two sites for a 26-day period indicate higher temperatures at the arroz site (Figure 3.2). The arroz site temperature varied between

18 and 42 ^{o}C with a maximum daily fluctuation of 20 ^{o}C. In contrast, the cacao agroforestry site varied between 19 and 28 ^{o}C with a daily maximum fluctuation of only 8 ^{o}C. These data demonstrate differences in ambient air temperature between the two sites. Though not measured, we can anticipate that temperatures at the soil surface will be higher at the arroz site compared to the cacao site. Throughfall data measured at the cacao site is calculated to be 42 % of the measured precipitation data. For example, comparing data for 156 days, 1292 mm of precipitation fell at the arroz site and 553 mm of throughfall was measured at the cacao site.

3.5.2 Soil Data

Both soils are acidic and have weighted mean soil pH values to 1-m depth of 4.1 at the cacao site and 4.4 at the arroz site (Table 3.1). These low pH values have implications for the dissolution of primary minerals, Al saturation, and crop success. At pH levels below 5, Al is solubilized and as it hydrolyzes, hydrogen ions are released, further lowering the pH. In strongly acidic soils, exchangeable Al concentrations increase with decreasing pH, which can have detrimental effects for plant growth. Al saturation is above 30% in the top 20 cm at both sites. These data have important implications for crops as Al phytotoxicity can occur with micromolar concentrations of Al, inhibiting root growth and uptake of nutrients (Delhaize and Ryan, 1995). Exchangeable Al saturation values of 26 % have shown to decrease ability of cacao, an important cash crop in Talamanca, seedlings to take up base cations due to Al stress on the plant (Bailgar and Fageria, 2005).

Both sites have low sum of bases, 3.4 cmol$_c$ kg^{-1} in the top 10 cm at the cacao site and 11.2 cmol$_c$ kg^{-1} in the top 5 cm at the at the arroz site (Table 3.1). Calcium dominates the exchange sites in both soils and the order of exchangeable base cation abundance at the both sites follow the same pattern: Ca > Mg > K (Table 3.1). These data indicate that the exchangeable base cation pool is extremely low and may have negative nutritional implications for crops, e.g. the exchangeable soil pool may not meet the requirements of the crop. Effective cation exchange capacity (ECEC) is five to ten times lower than cation exchange capacity (CEC) at the cacao site and two times lower at the arroz site (Table 3.1). This difference is because CEC determines the exchange capacity of the soil in a buffered extractant (pH 7) and thus overestimates the actual exchange capacity of acidic soils (pH<5). Base saturation, when calculated using CEC is the percentage of all possible exchange sites that are occupied by Ca, Mg, K, and Na and is extremely low at both sites. These data suggest that both sites have low exchangeable base cations and therefore, minimizing leaching losses should be considered to conserve what soil nutrients are available.

Total elemental concentrations of Ca, Mg, K, and Na at the cacao site are low, with uniform concentrations with depth (Figure 3.4). The pattern for abundance at the cacao site for total elemental concentrations is Mg > K > Ca. Potassium at the arroz site has much higher concentrations compared to all other elements and the sequence of abundance at the arroz site is K > Mg > Ca. Total elemental base cation concentrations are an important nutrient pool, as they represent the reservoir of nutrients that could potentially become available over time. However, not all of the total elements are in an exchangeable form. Patterns of percent of total element that is in an exchangeable form indicate that more than 60 % of the total Ca at both sites is in an exchangeable form (Figure 3.5). Both total Mg and K are present in the exchangeable form in lower concentrations compared to Ca. These data have implication for meeting the nutrient requirements for the crop of interest as well as indicate the low potential availability of Mg and K.

The soil clay fraction at the cacao site is dominated by kaolin to 1-m depth, as demonstrated by the peak at 0.7 nm (first order kaolin) in the Mg-air dried (25^{o}C), Mg-glycolated, and K-air dried (25^{o}C) treatments (Figure 3.6). The absence of this peak with the K-heated (500^{o}C) treatment confirms the presence of kaolin. The clay fraction at the arroz site is dominated by both kaolin demonstrated by the peak at 0.7 nm and hydroxy-interlayered minerals (HIM) demonstrated with a peak at 1.2 nm with the Mg-25^{o}C treatment that expands to 1.4 nm with the Mg-glycolated treatment (Figure 3.7). The arroz site also has mica in the clay fraction demonstrated by the 1.0 nm peaks with all treatments (Figure 3.7). The presence of mica helps explain the higher elemental concentrations of K at the arroz site, as mica is a K-bearing mineral. Clay mineralogy has important implications for CEC. Kaolinitic soils have very low CEC and soils with HIMs have moderate CEC. HIMs are 2:1 layer silicates that have an interlayer partially filled with hydroxy-Al (Schulze, 2002). Chemical properties of hydroxy-interlayered minerals are difficult to characterize as CEC values depend on extent of occupancy of the interlayer with hydroxy-Al (e.g. greater filling is associated with lower CEC values) (Barnhisel and Bertsch, 1989). Yet, the differences in clay minerals present at the arroz and cacao sites help explain CEC and total elemental K concentrations.

Textural class for the cacao site is clay throughout and the textural classes for the arroz site are silty clay loam in the A horizon and silty clay to clay in the Bt horizons (Table 3.2). Both soils have less than 20 % sand throughout the profile, with sand concentration decreasing with depth (Table 3.2). The high clay contents have implications for water infiltration, percolation, and ease of root penetration. Water infiltration and water percolation affect leaching of soluble ions (e.g. base cations). In addition, fine roots of annual crops may have difficulty penetrating through the clay, thus impeding crop growth and success.

Total C concentrations at both sites decrease with depth (Table 3.2). Despite the higher C concentration in the A horizon of the arroz site, the weighted average to 1-m depth of total C at the arroz site is 0.56 % compared to 0.92 % at the cacao site. These C concentrations represent organic carbon and therefore have important implications for CEC and Al toxicity. Often, Al will complex loosely with soil organic matter (SOM), reducing the phytotoxicity of Al in the soil (Berggren and Mulder, 1995). In addition, SOM contributes significantly to the CEC of soils, especially in soils dominated by kaolin clays. The higher soil C concentrations with depth at the cacao site could be due to the deeper rooting system of shade trees inputting organic matter at greater depth through root turnover.

The soil under both sites classify as Typic Hapludults using Soil Taxonomy. They classify differently using World Reference Base for Soil Resources (WRB). The soil under cacao is a Haplic Acrisol (Clayic, Alumic) and the soil under arroz is a Haplic Alisols (Clayic) in WRB. Acrisols are soils with low activity clays and low base saturation, while Alisols are soils with high activity clays and low base saturation. In contrast, the classification as a Hapludult does not refer to clay activity, but indicates low base saturation.

3.5.3 Aboveground Biomass, Litterfall, and Decomposition

The cacao trees at the cacao site are planted in ~4.5-by-4.5-m spacing with a density of 480 trees ha^{-1}. This is considered a low planting density for mono-cropped cacao. Cacao seedlings and fruit tree seedlings were planted within existing native forest tree species. There are 266 shade trees ha^{-1}, which is ~6-by-6-m spacing. Aboveground biomass for the entire cacao agroforestry system is 92 Mg ha^{-1}. Nutrient concentrations in aboveground biomass at the cacao site are: 556 kg Ca ha^{-1}, 146 kg Mg ha^{-1}, and 245 kg K ha^{-1} (Figure 3.8). The litterfall rate in this diverse cacao agroforestry system is 10.3 Mg ha^{-1} yr^{-1}. Based on the amount of litter fall and the nutrient content of the litterfall, average nutrient content of litterfall for the sampled year are: 214 (+/- 68) kg Ca ha^{-1} yr^{-1}, 49 (+/- 9) kg Mg ha^{-1} yr^{-1} , and 35 (+/- 19) kg K ha^{-1} yr^{-1} (Figure 3.8). Annual litterfall represents 39 % of the Ca, 33 % of the Mg, and 14 % of the K stored in total aboveground biomass in this cacao agroforestry system, while litterfall only represents 11% of the total aboveground biomass.

It is difficult to compare these aboveground biomass and nutrient data with other studies as these data depend on many factors including: tree species, planting density, age of shade trees and crop, soil fertility status, and site management (Schroth, 2003). Yet, the long-term cacao agroforestry study at CATIE provides a good comparison. The aboveground biomass of our cacao site is 50 Mg ha^{-1} higher than that reported for a *Theobroma cacao/Cordia alliodora* agroforestry system in Turrialba, Costa Rica (Alpizar et al., 1986). However, the trees in the Turrialba study were only eight years old, compared with an age of > 18 years in this study. The litterfall rate for the diverse cacao agroforestry system in our study is comparable to the reported range of litterfall rates of lowland tropical rainforests (Vitousek, 1984). Reported litterfall nutrient values in cacao agroforestry system in Turrialba are 125 kg Ca ha^{-1} yr^{-1}, 50 kg Mg ha^{-1} yr^{-1}, and 66 kg K ha^{-1} yr^{-1} (Heuveldop et al., 1988); these values represent twice as much K and half as much Ca in the litter compared to the Talamanca site. Trees in the CATIE study were strictly *Theobroma cacao* with *Cordia alliodora*, which apparently have higher litter K and lower Ca contents than the mixed leaf litter at the Talamanca site.

Litter decomposition rate determines how quickly leaflitter biomass decomposes and provides speculative information on the release of nutrients from decomposing leaflitter. The decomposition rate constant (k) for cacao leaves at the cacao agroforestry site is 1.54 yr^{-1} (Figure 3.9). In the field, we measured that 77 % of the cacao leaves were decomposed after 350 days. These data are similar to decomposition rates of cacao leaves in Ghana: 99% decomposed after 12 months in medium and heavily shaded systems and 86 % decomposed in unshaded farms in the same time period (Ofori-Frimpong et al., 2007). Using the nutrient content of the decomposing cacao over time, we calculate the mineralization of Ca, Mg, and K from the leaves (Figure 3.10). All of the Mg and K in the leaves will be mineralized and enter the soil system in one year. This is not the case with Ca; at one year we estimate that only 65 % of the Ca in the decomposing cacao leaves will enter the soil system on an annual basis. Ca contributes to the structure of the leaf, is relatively recalcitrant, and is less mobile than K. This may explain why Ca has a slower mineralization rate compared to Mg and K in the decomposing leaves. Using these mineralization rates for Mg, K, and Ca with the average nutrient content of the combined litterfall, we estimate that 139 kg Ca ha^{-1} yr^{-1}, 49 kg Mg ha^{-1} yr^{-1}, 35 kg K ha^{-1} yr^{-1} are mineralized from the litter and enter the soil system on an annual basis.

The aboveground biomass of the fallow stage (age 4 years) totaled 37.9 Mg ha^{-1} biomass for the arroz site before it was cleared and burned. Biomass was burned and added to the soil surface. This nutrient-rich ash was susceptible to wind erosion, erosion downslope via runoff, or leaching downward through the profile.

To determine annual nutrient requirement of the cacao crop we calculated annual uptake of the crop (without accounting for litterfall requirements), loss due to harvest, and the uptake for the shade trees. We estimate that 8 kg Ca ha^{-1}, 5 kg Mg ha^{-1}, and 29 kg K ha^{-1} are needed on an annual basis for the cacao and 28 kg Ca ha^{-1}, 8 kg Mg ha^{-1}, and 13 kg K ha^{-1} annually for the shade trees. It appears that litterfall can supply enough Ca, and Mg for the entire system, but there is a K deficit. Potassium must be supplied by exchangeable soil pool, throughfall, or external inputs to sustain the crop productivity. Yet due to the low soil exchangeable K pool, this export of K from the soil pool cannot be sustained on the long-term. Another potential source of K, is the composting of post-harvest cacao husks. It is estimated that cacao husks contain 15% Ca, 51% Mg, and 76 % K of the cacao pod (Fassbender et al., 1991).

In Talamanca, the high diversity of shade trees within cacao farms has several benefits. These include: a continual supply of leaflitter year round due to time differences of leaf senescence among species, variation in nutrient concentration of leaflitter from the different tree species, and various alternative crops from the different shade trees. Careful selection of shade tree species for agroforestry systems is important as the nutrient concentrations in aboveground biomass and litterfall of tree species may vary greatly. For example, common shade tree species incorporated into agroforestry systems in Costa Rica, *C. alliodora* and *E. poepegiana* have very different nutrient concentrations in their aboveground biomass and differences were also observed in the nutrient concentration of *Theobroma cacao* grown under these different shade trees

(Alpizar et al., 1986; Heuveldop et al., 1988). Despite the high diversity of shade trees, it is clear that an input of K is needed in the system. Post harvest composting of the cacao husks appear to be a viable option, if sterilization of the monilia fungal spores adequately occurs during on-farm composting. Another potentially important loss to the system is the loss of soluble nutrients due to leaching below the rooting zone of the crop.

3.5.4 Soil Moisture and Matric Potential

Soil moisture content and matric potential provide important information on water and solute movement through soil and water availability to plants. Volumetric water content at 15 cm at both sites shows the rapid response of water content to rain events (Figure 3.11). These data also demonstrate the difference in the soil moisture content at the two sites at a depth of 15 cm. The arroz site has higher volumetric water content than the cacao agroforestry site throughout the year. The higher soil moisture content at the arroz site is likely related to differences in crop characteristics. The cacao agroforestry site has a more extensive rooting system due to the presence of woody perennials, and has a higher evapotransporation compared the arroz crop. In addition, due to the lack of canopy capture, the arroz site receives over 50% more precipitation at the soil surface. Soil moisture levels at the 60 and 100-cm depths are similar at the cacao site (Figure 3.12). These data demonstrate similarities in soil properties at these two depths as well as the response of water content to rain events in the subsoil.

Matric potential is an indicator of water availability to plants and is used in conjunction with soil moisture to calculate water and nutrient fluxes in soils. When comparing matric potential data (not shown) for both sites, matric potentials are well above the wilting point (-1.5 MPa) and are at or above field capacity (-0.033 MPa) throughout the year. With these data we can assume that there is no water deficit for the crops at either site and that precipitation entering the soil will continue to percolate through the profile. These data provide a basis to make predictions on the potential for leaching losses from the system.

3.5.5 Porewater concentrations

Leaching is an important loss from agroecosystems. Calcium, Mg, and K porewater concentrations at the cacao site at 15, 60, and 100-cm depths are presented in Figure 3.12. Magnesium porewater concentrations are 2-3 times lower than Ca and K throughout the entire sampling period, but all concentrations were below 0.6 mg L^{-1} (Figure 3.12). No relationship is observed when porewater concentrations are plotted with throughfall data, timing of flowering, or senescing of cacao (data not shown). Porewater concentrations under the cacao site do not vary through time and concentrations are very low. Due to the continually high soil moisture content and high matric potential, we conclude that internal drainage of the soil water through the soil profile is high. The low cation concentrations in the porewater also suggest rapid biocycling of cations mineralized during decomposition.

Porewater concentrations at the arroz site exhibit a much different pattern over time compared to the cacao site (Figure 3.13). Porewater concentrations of Ca, Mg, and K at the arroz site remain above the porewater concentrations at the cacao site for the entire sampling period. A spike in porewater concentrations at the arroz site remains at all depths until Julian day 368. Porewater concentrations have the pattern Ca > Mg > K at the arroz site. Due to the shallow depth of the arroz roots, we assume nutrients in porewater at 60 cm are essentially lost from the system. At Julian day 368 (which corresponds to 233 days after the burn) the porewater concentrations begin to approach the porewater concentrations under cacao and stabilize with time. These dates coincide with substantial natural revegetation at the site.

The porewater concentrations at both sites are an order of magnitude lower than porewater concentrations reported under an annual cropping system and perennial cacao agroforestry system at CATIE, Costa Rica (Seyfried and Rao, 1991). The CATIE study reported concentrations an order of magnitude greater at 90-cm depth under the annual cropping system compared to the perennial system even though the study did not include the slash-and-burn part of the cycle (Seyfried and Rao, 1991). Explanatory reasons include: the native fertility of the CATIE soils are higher than the Talamanca foothills soils with regard to base cations; the CATIE soils received several inputs of inorganic fertilizers; and the CATIE soils had a fluctuating water table to within 50 cm of the soil surface. For these reasons, our results from non-fertilized plots in Talamanca are unique and represent different agroecosystems than those commonly found in the literature.

The pattern of elevated porewater concentrations at the arroz can be related to the burning of the vegetation on site. Solubilized nutrients from ash can be easily lost through leaching as no vegetation is actively growing to absorb the nutrients. Data show that soil fertility decreases over time in a slash-and-burn system, predominantly due to leaching losses (Nye and Greenland, 1960). While data show that sites with high native fertility may have greater leaching losses regardless of land use (Dechert et al., 2005), the pattern of porewater concentrations at the arroz site indicates a response to burning. Slash-and burn-plots sampled in Northeast Pará, Brazil had an immediate flush of exchangeable Ca, which decreased 4-fold within 2 months of the burn (Holscher et al., 1997). Porewater concentrations under a slash-and-burn/ shifting cultivation site in the Amazon remained elevated compared to a control site for several years after the original burn (Jordan, 1985).

3.6 Conclusions

In order to make long-term (even qualitative) predictions about the sustainability of an agroecosystem, we must evaluate the resilience of the soil to various land management practices. Total elemental and exchangeable base cation concentrations provide important insight into potentially available nutrient pools within agroecosystems. Soil data demonstrate that the cacao agroforestry site in this study has some of the lowest soil nutrient reserves found in the region, yet farmers continue to harvest cacao for sale on the organic cacao market. The low base cation reserves of these soils illustrate the fragility of these soils and their susceptibility to mismanagement. These data also stress the importance of management practices that encourage biocycling of diverse, year-round litterfall and reducing leaching losses. An additional concern for the management of agroforestry systems is the inclusion of shade trees whose leaflitter releases nutrients at the most critical time for the crops, the time of flowering. As most of the world-wide cacao production is grown by smallholder farmers with who have few resources to apply fertilizers to their crop, it is important to understand nutrient cycling in non-fertilized, on-farm cacao agroforestry systems.

In contrast to the cacao site, the arroz site does not have leaflitter biocycling occurring during the crop growing season. Instead, the slash-and-burn system experiences a flush of nutrient loss via leaching up to one year after burning. These data demonstrate that slash and burn, especially on nutrient-poor soils, could have a negative impact on long-term sustainability if leaflitter or improved fallows are not incorporated into the system.

Despite the seemingly dire nutrient situation of the Talamanca foothill soils, there are under-utilized management practices that can enhance the native soil fertility. Specifically, in the case of cacao, only the beans of the cacao pods are exported for sale, which leaves the husks as a potential post-harvest composting component. As stated above, these husks contain a significant percentage of K in the pod. Returning important nutrients to the soil will increase the long-term sustainability of the system. In order to establish this management practice within the territories, cultural reasons surrounding why farmers do not practice this technique need to be identified and addressed. With respect to slash-and-burn agriculture, alternatives to burning do exist. For example, a few Talamanca farmers practice “tapado” which means instead of burning the vegetation, the farmer slashes the vegetation and mulches it with a machete. The annual crop is planted within this mulch layer. Concerns with this practice include weed infestation, pests, and disease vectors. Yet, organic matter is continually supplied and physical protection of the soil is enhanced. Farmers are able to harvest substantial grain yields annually with this method. Again, adoption of this technique is dependent upon the willingness of the farmers to overcome the cultural practice of burning fallow vegetation for the production of annual crops.

Data from this study indicate porewater concentrations under slash-and-burn system are higher than under a cacao agroforestry system. In addition, even diverse agroforestry systems may have nutrient deficiencies if cacao husks are not composted and added to the soil. In Talamanca, the constant hot and humid climatic conditions encourage rapid decomposition and potential leaching losses, yet if employed, proper soil management techniques can enhance and sustain sufficient biogeochemical cycling of plant-important macro-nutrients.

3.7 References

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Table 3.1: Select soil chemical properties for cacao and arroz sites. Samples were collected at the arroz site the day after it was burned.

Site	Depth	pH	Ca^{2+}	Mg^{2+}	K^+	Na^+	Sum of	Al^{3+}	ECEC	CEC	B.S.	B.S.	Al
		H_2O					Bases			(pH 7)	(CEC)	(ECEC)	Sat.
	(cm)		———	———	———	———	$cmol_c\ kg^{-1}$	———	———	———	———	%	———
Cacao	0-10	3.9	1.8	1.3	0.2	0.1	3.4	0.5	3.8	39.8	8.5	88	12
	10-20	4.1	0.7	0.7	0.1	0.1	1.6	0.9	2.5	21.0	7.8	65	35
	20-40	4.1	0.4	0.3	0.1	0.1	0.9	1.5	2.4	25.6	3.4	36	64
	40-70	4.2	0.5	0.2	0.1	0.1	0.9	1.7	2.6	12.9	6.7	34	66
	70-110	4.2	0.5	0.2	0.1	0.1	0.8	1.8	2.6	13.4	6.3	32	68
Arroz													
	0-5	4.7	7.9	2.9	0.3	0.1	11.2	0.1	11.2	23.3	48.1	100	0.5
	5-15	4.3	4.0	1.7	0.2	0.1	5.9	2.7	8.6	17.7	33.4	69	31
	15-40	4.3	3.9	1.6	0.5	0.1	6.1	6.5	12.6	24.3	24.9	48	52
	40-70	4.4	4.1	1.9	0.5	0.1	6.7	7.2	13.8	30.1	22.1	48	52
	70-105	4.4	6.8	3.2	0.5	0.2	10.7	5.5	16.2	30.9	34.6	66	34

Table 3.2: Total carbon and nitrogen concentrations and percent sand, silt, and clay for each horizon at the arroz and cacao sites.

Site	Depth	C	N	sand	silt	clay
	(cm)	———	———	%	———	
Cacao						
	0-10	2.5	0.3	8	28	64
	10-20	1.5	0.2	7	21	72
	20-40	1.0	0.1	5	20	75
	40-70	0.7	0.1	4	18	79
	70-110	0.4	trace	5	25	70
Arroz						
	0-5	3.5	0.4	16	51	33
	5-15	1.1	0.2	11	50	39
	15-40	0.6	0.1	6	42	52
	40-70	0.3	0.1	6	40	54
	70-105	0.2	0.1	3	38	59

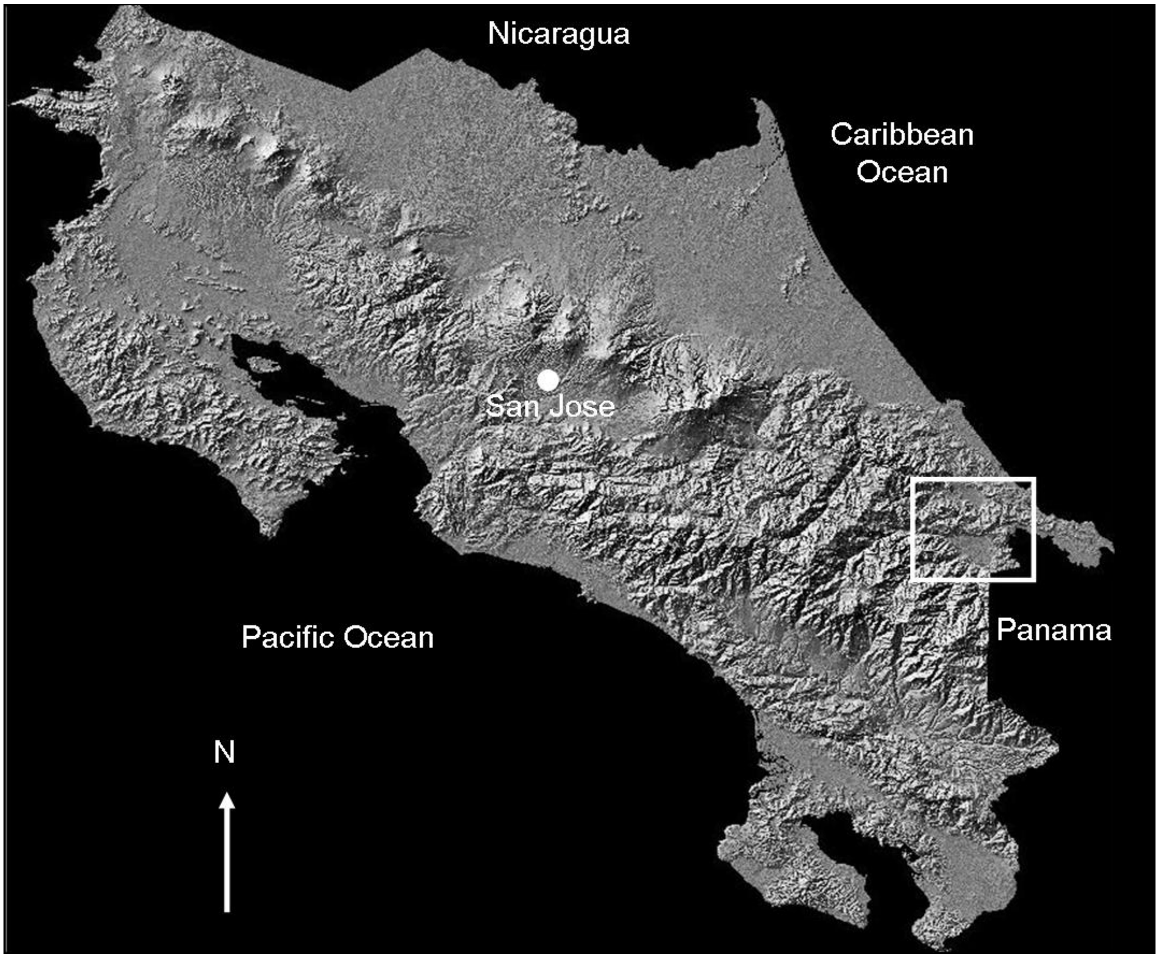

Figure 3.1: Shade relief image of Costa Rica. Talamanca Region lies within the white box. The capital of Costa Rica, San Jose is also indicated.

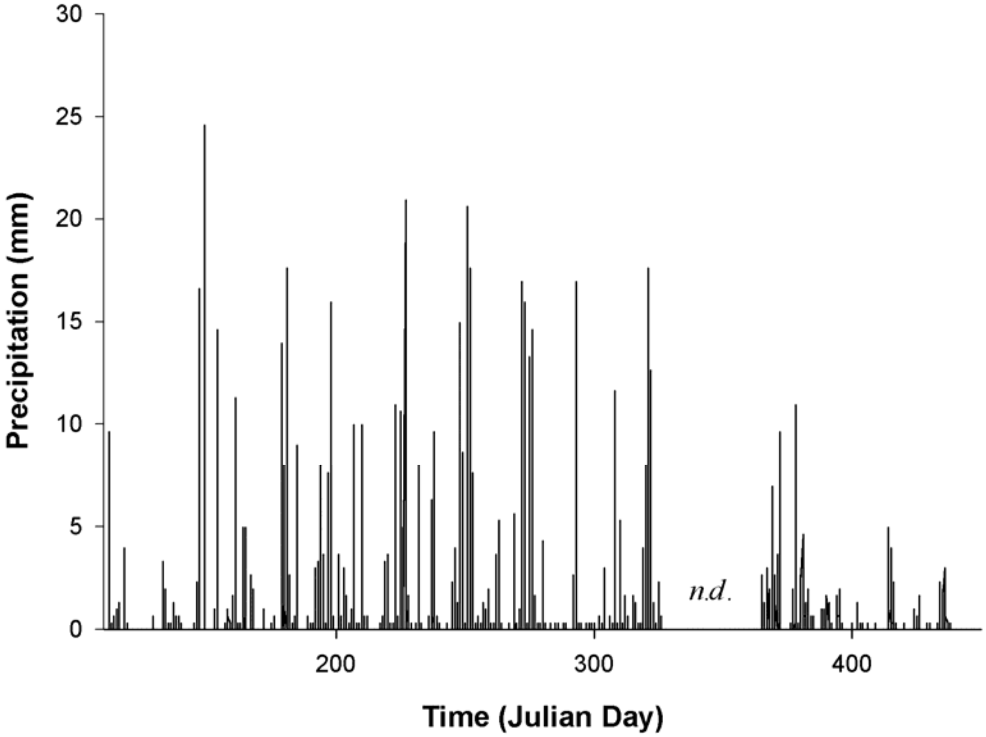

Figure 3.2: Precipitation for 438 measured days at the arroz site. n.d.= no data.

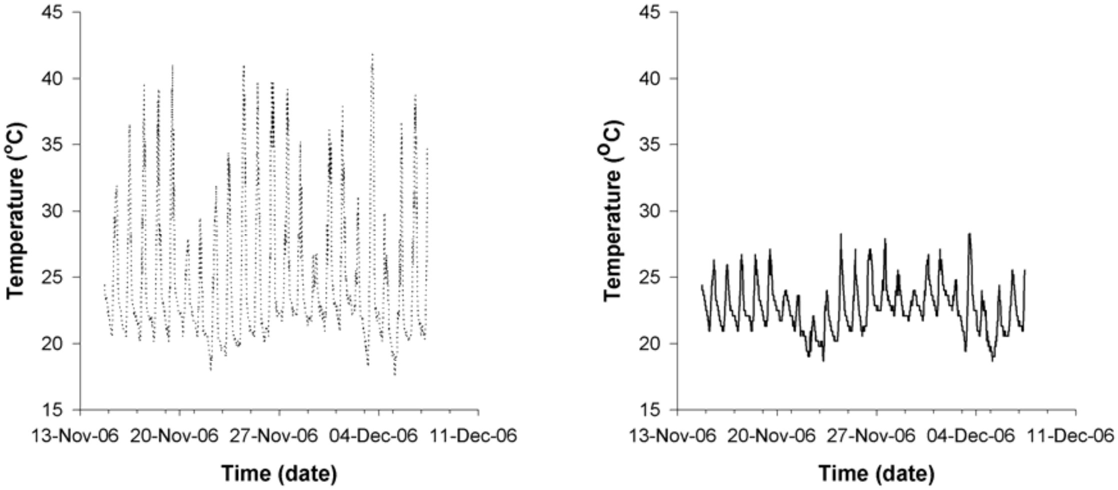

Figure 3.3: Ambient air temperature at 1-m height at the arroz site (left) and cacao agroforestry site (right).

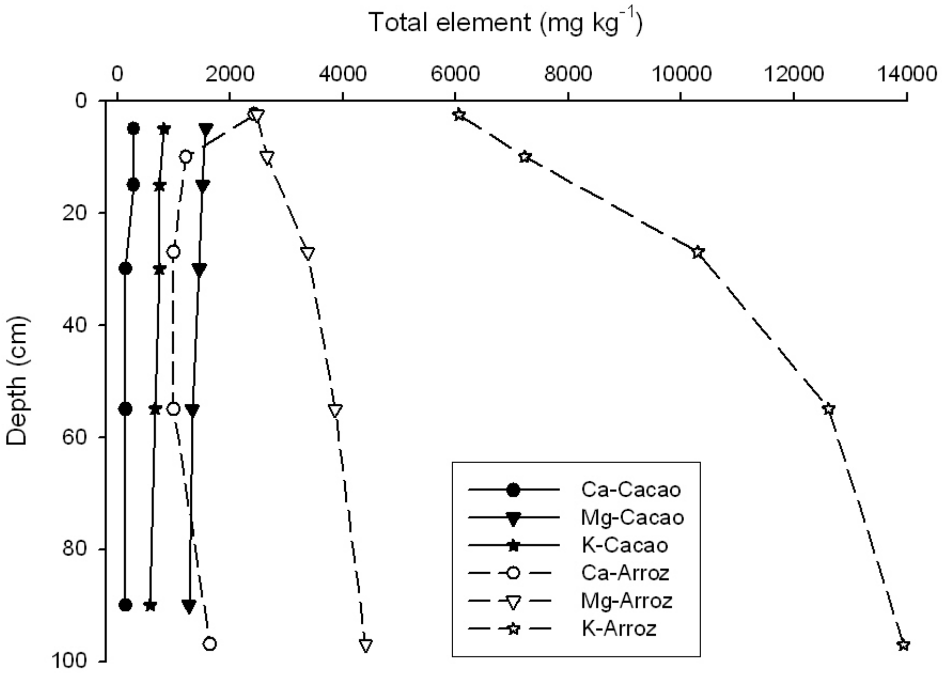

Figure 3.4: Total elemental concentrations of Ca, Mg, and K with depth at the cacao and arroz sites.

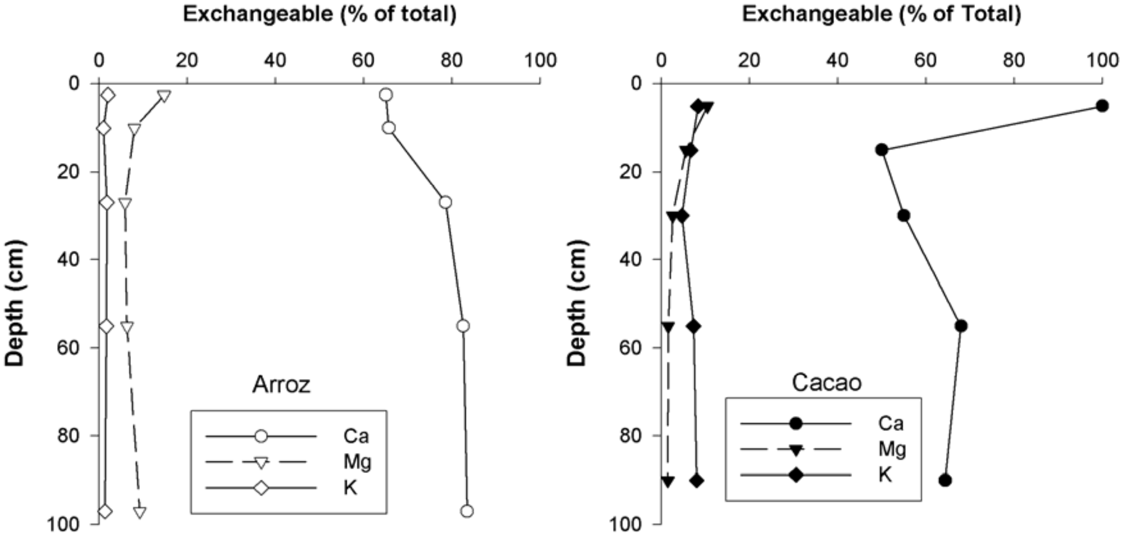

Figure 3.5: Percent of total element present in an exchangeable form.

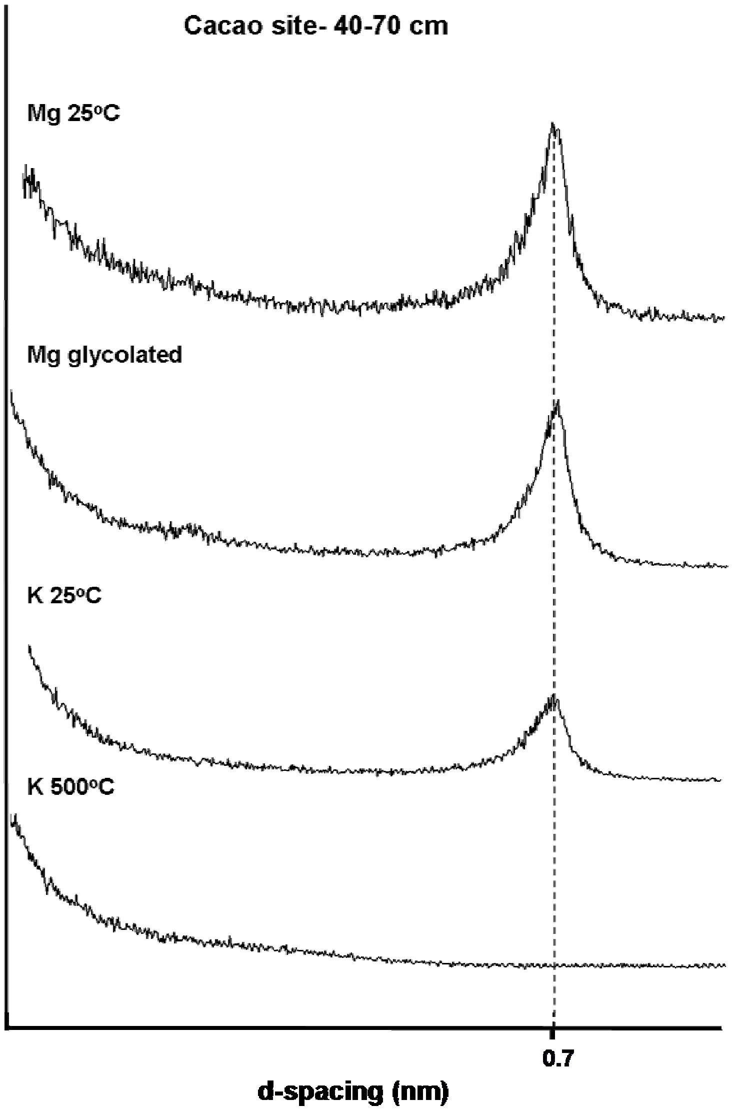

Figure 3.6: X-ray diffractograms of the clay fraction from the Cacao site at 40-70 cm.

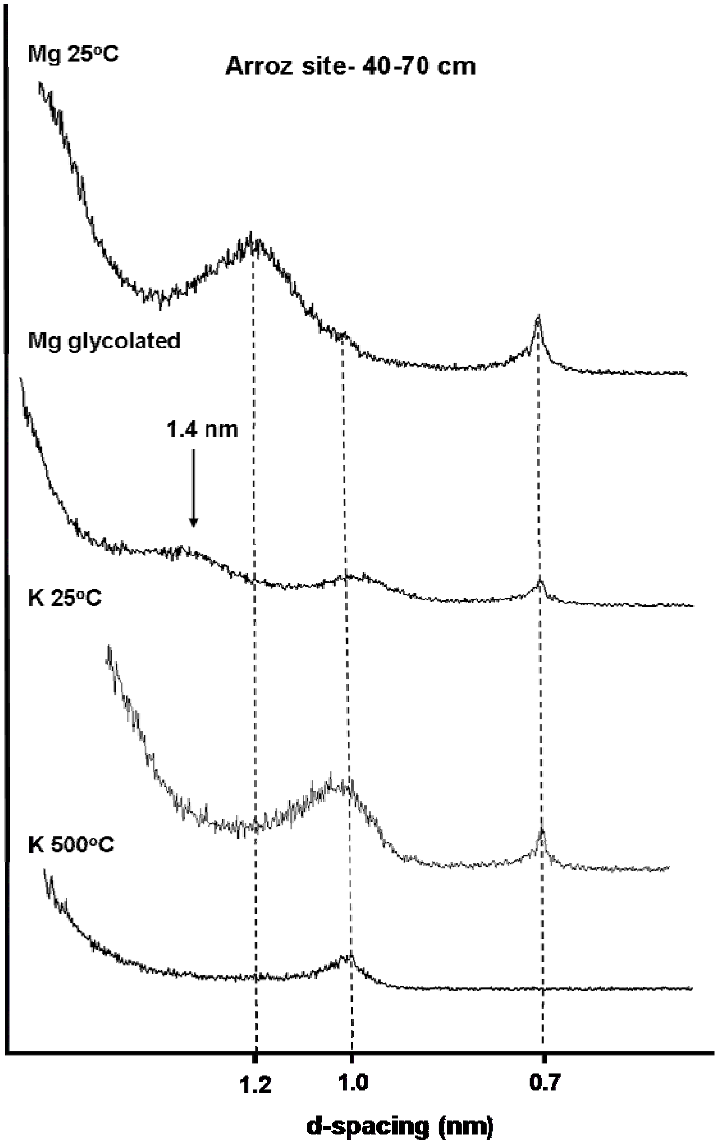

Figure 3.7: X-ray diffractograms of the clay fraction from the Arroz site at 40-70 cm.

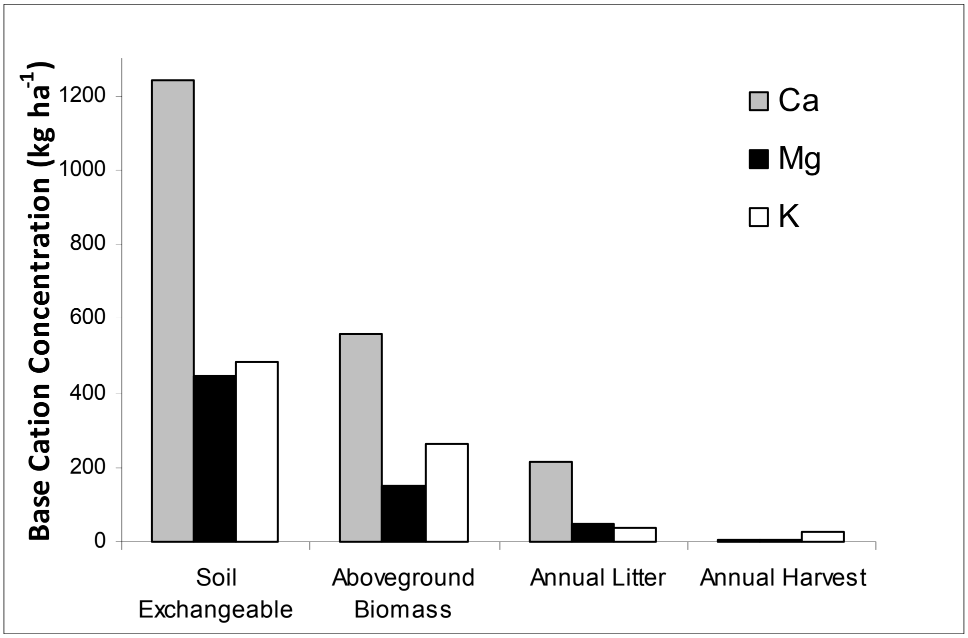

Figure 3.8: Base cation concentrations in soil exchangeable pool, aboveground biomass, litter, and harvested pods at the cacao agroforestry site.

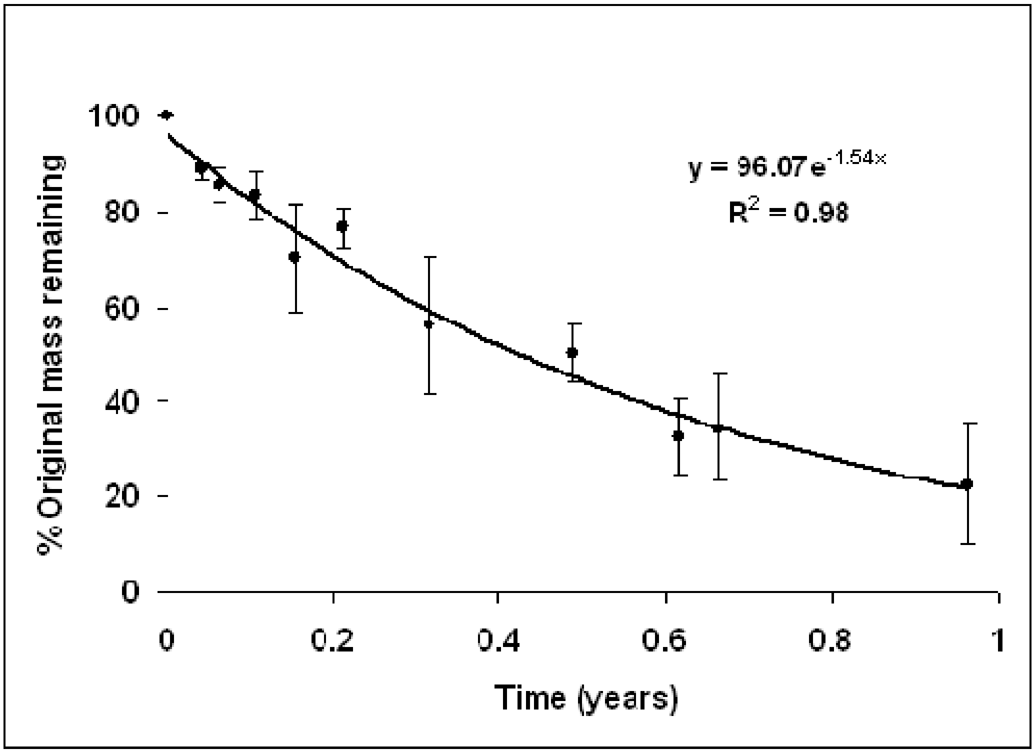

Figure 3.9: Percent of original mass of cacao leaves remaining in litter bags over time with equation of exponential trendline indicating decomposition rate constant of 1.54 yr^{-1}.

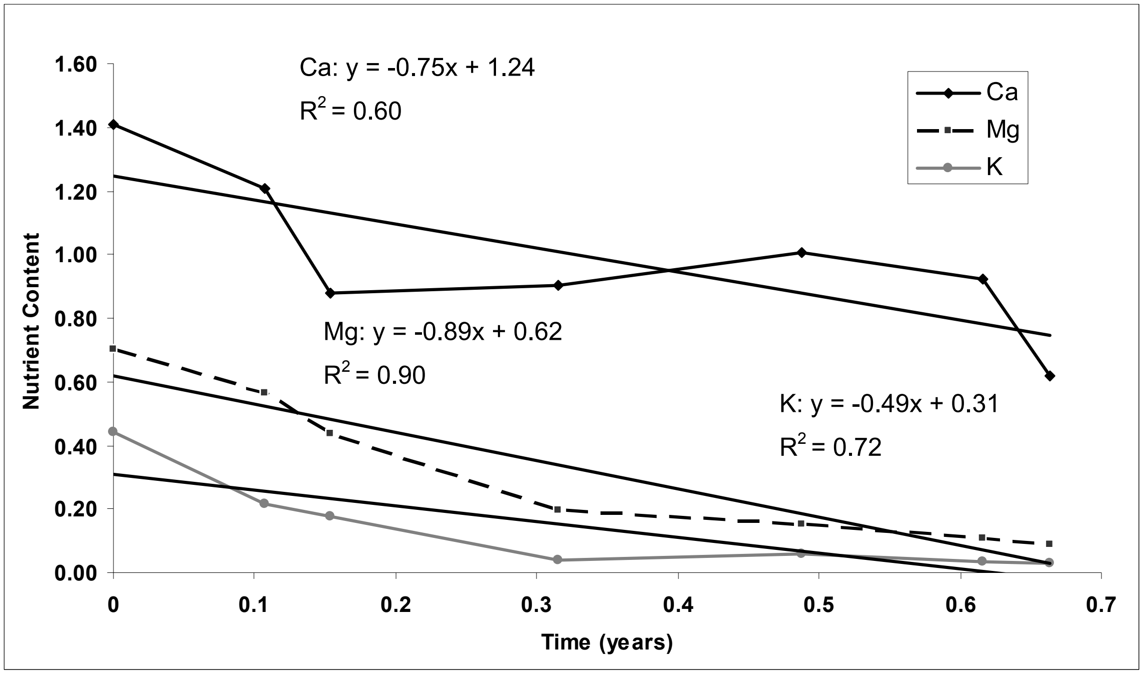

Figure 3.10: Mineralization rates for Ca, Mg, and K in cacao leaves. Data are presented until day 242 when leaves were 68% decomposed. After that, insufficient sample remained to meet minimum weight needed for analysis.

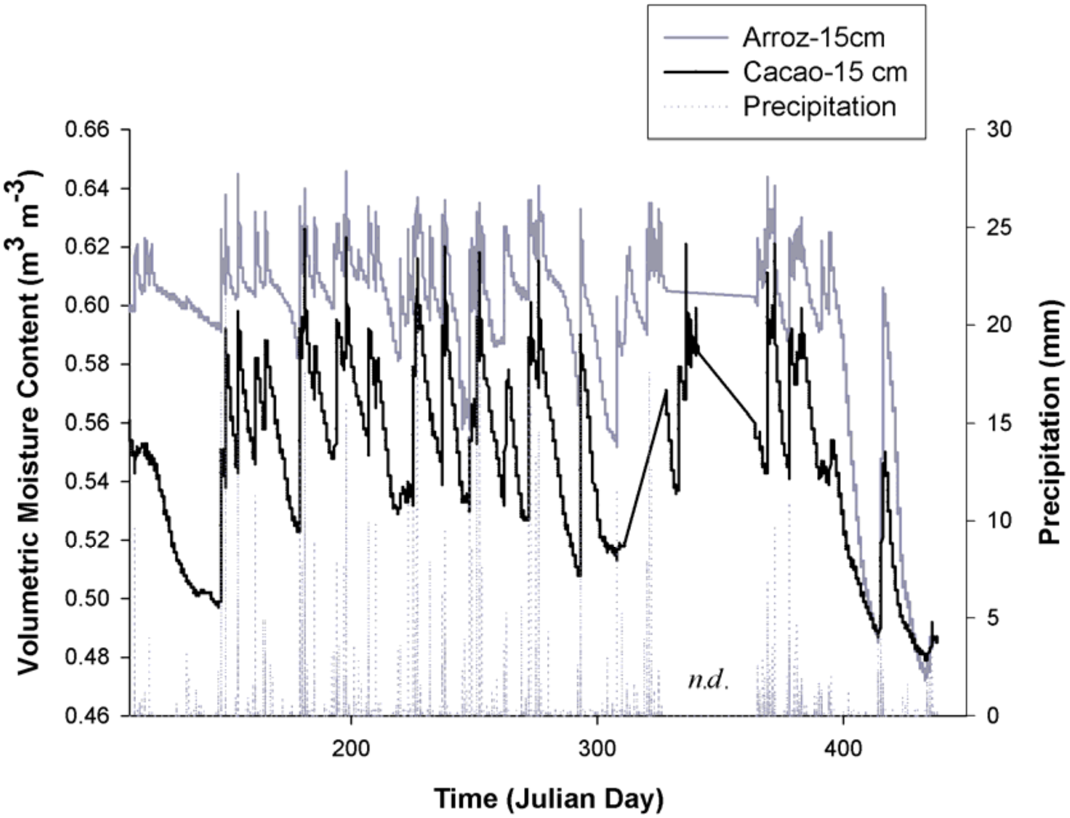

Figure 3.11: Graph of daily precipitation from the arroz site between Julian days 110 to 438 and the volumetric water content at 15 cm at the cacao agroforestry and arroz sites. n.d.= no data.

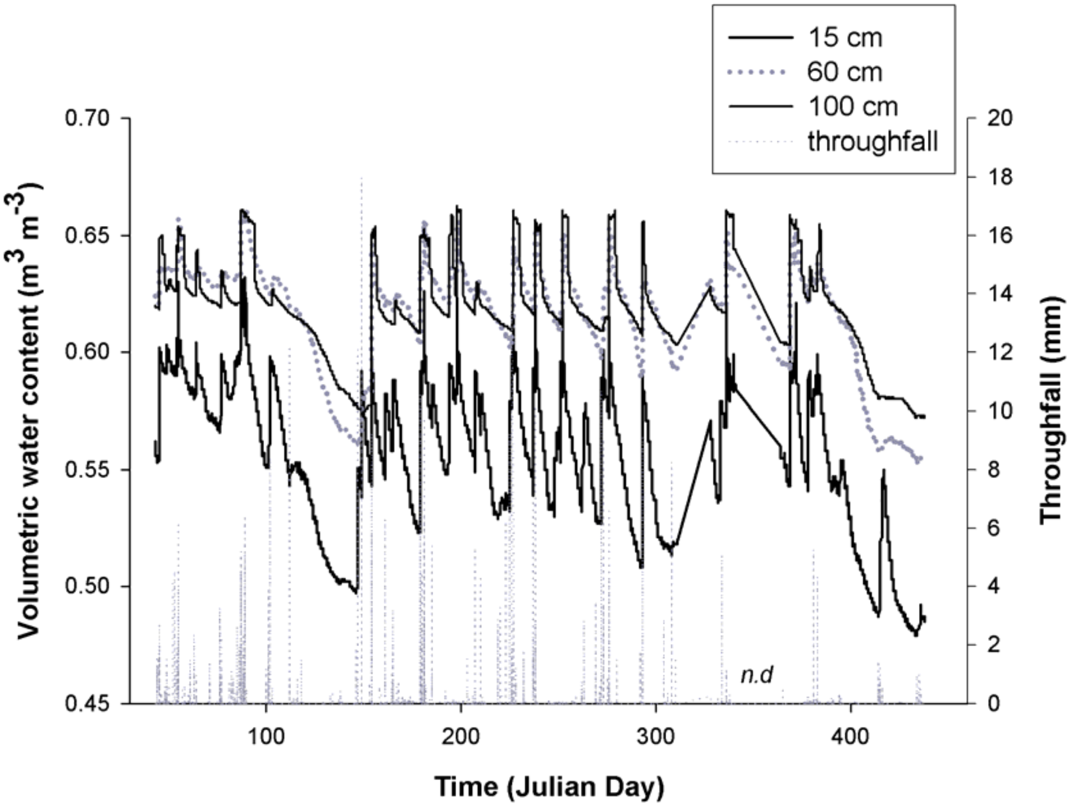

Figure 3.12: Throughfall data (Julian days 43 to 438) at the cacao agroforestry site and volumetric water content at 15, 60, 100-cm depths. n.d.=no data.

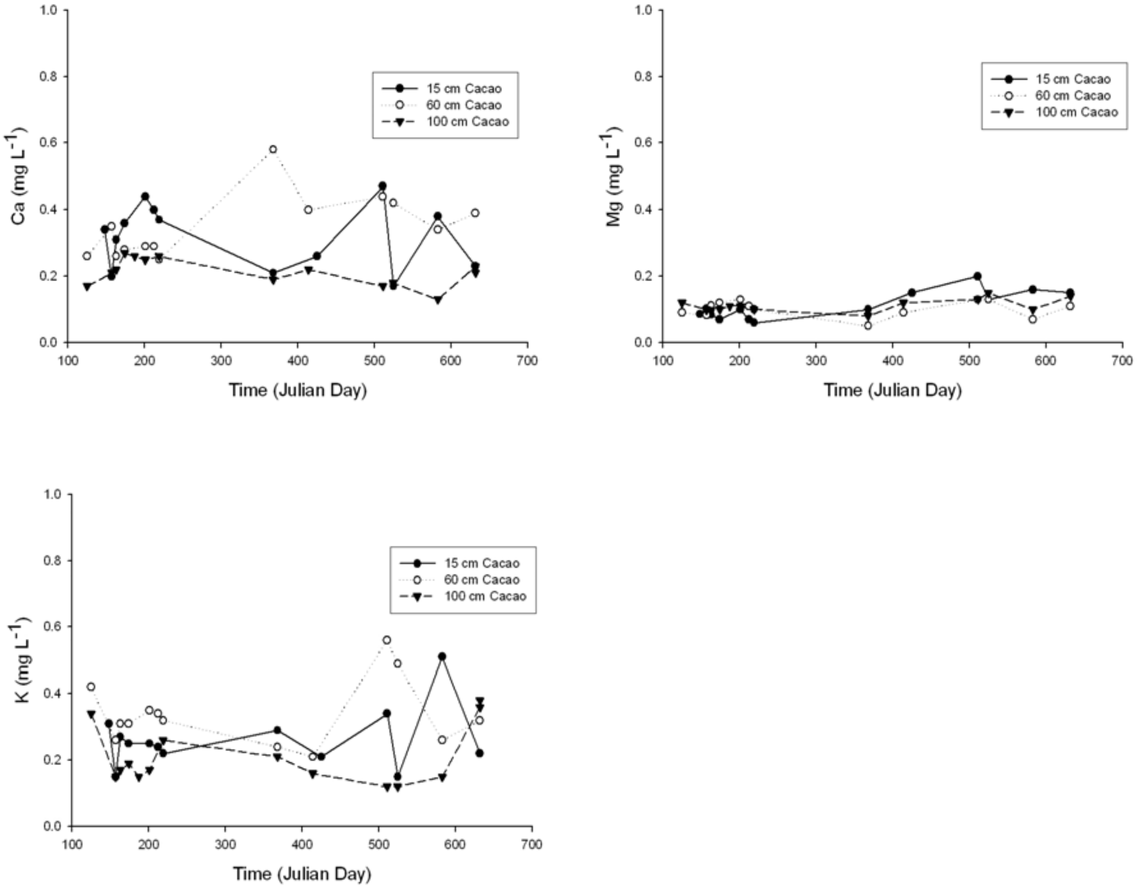

Figure 3.13: Pore water concentrations of calcium (Ca), magnesium (Mg), and potassium (K) at three depths (15, 60, 100 cm) in the cacao site. Note the different scale for porewater concentrations in Figure 3.14.

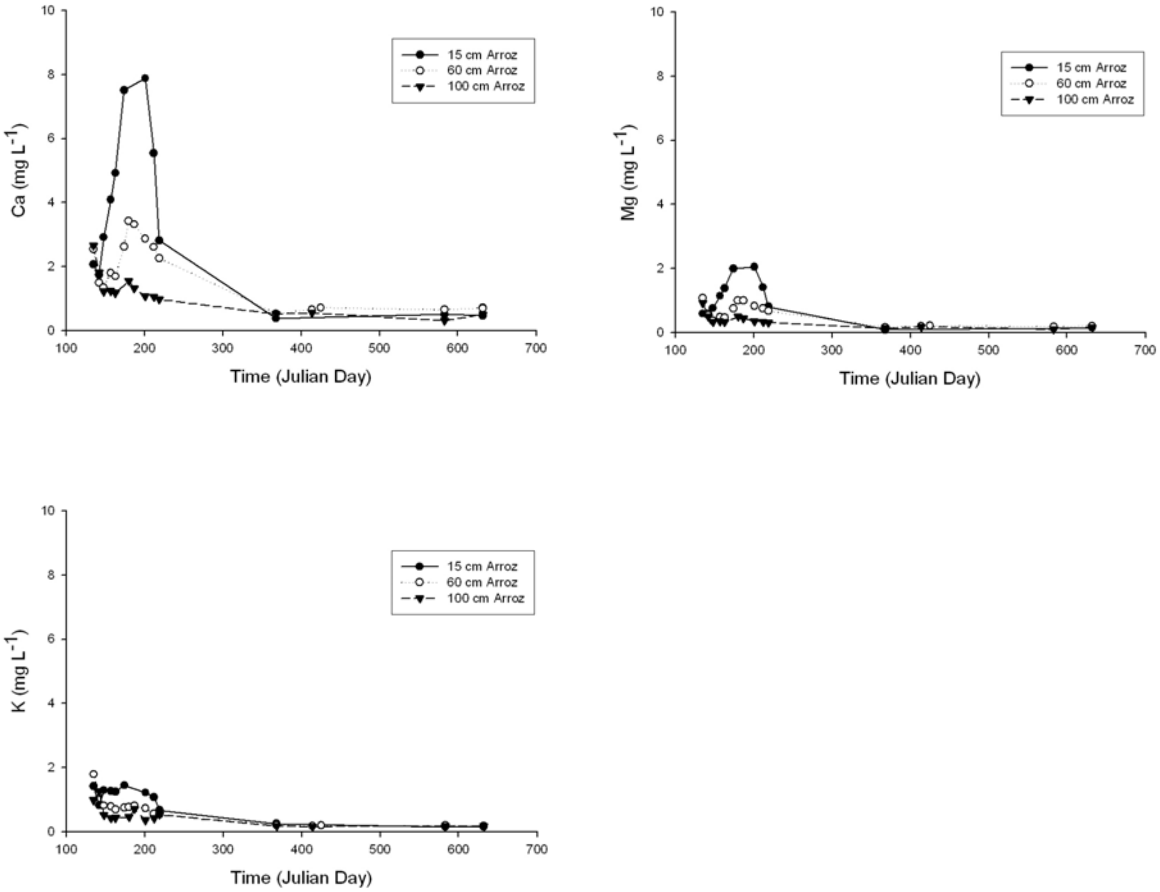

Figure 3.14: Porewater concentrations of calcium (Ca), magnesium (Mg), and potassium (K) at three depths (15, 60, 100 cm) in the arroz site. Note the different scale for porewater concentrations in Figure3.13.

4 CHAPTER FOUR: INTERDISCIPLINARY CHAPTER: INCORPORATING LIVELIHOODS IN BIODIVERSITY CONSERVATION: A CASE STUDY OF CACAO AGROFORESTRY SYSTEMS IN TALAMANCA, COSTA RICA

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4.1 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.

4.2 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).

4.3 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.

4.4 Site Description

4.4.1 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.

4.4.2 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 (Figure 4.1).

4.4.3 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).

4.5 Methods

4.5.1 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.

4.5.2 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 4.1). 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 4.1). 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 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.

4.5.3 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.

4.5.4 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.

4.6 Results

4.6.1 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 4.2). 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 (Figure 4.2). 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%) (Figure 4.3). 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 (Figure 4.4).

4.6.2 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 (Figure 4.2), and total cacao production in Costa Rica declined by 79% (Figure 4.5). 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.

4.6.3 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 (Figures 4.6 and 4.7), 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 (Figure 4.8). 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 4.3), 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 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 (Figure 4.9). Lower income from cacao results in part from low cacao prices, due to both international price trends (Figure 4.6) 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 (Figure 4.9). 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 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.

4.7 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.

4.7.1 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.

4.7.2 Improving Structures and Processes

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.

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.

4.8 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 4.1: 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 (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%

Table 4.2. 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 4.3: 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]	0.14[e]
		\$80-120[a]	0.78 ± 0.80[c]
		\$111 ± 73[b]	1.54[f]
		\$270 ± 88[c]	
Banana	Every 2 weeks	\$160-240[d]	0.97[e]
		\$200 ± 143[e]	1.81 ± 0.66[c]
		1100 ± 339[c]	
Plantain	Every 1-2 weeks	\$600 ± 397[e]	3.42[e]
		\$700-\$3,500[f,g]	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.

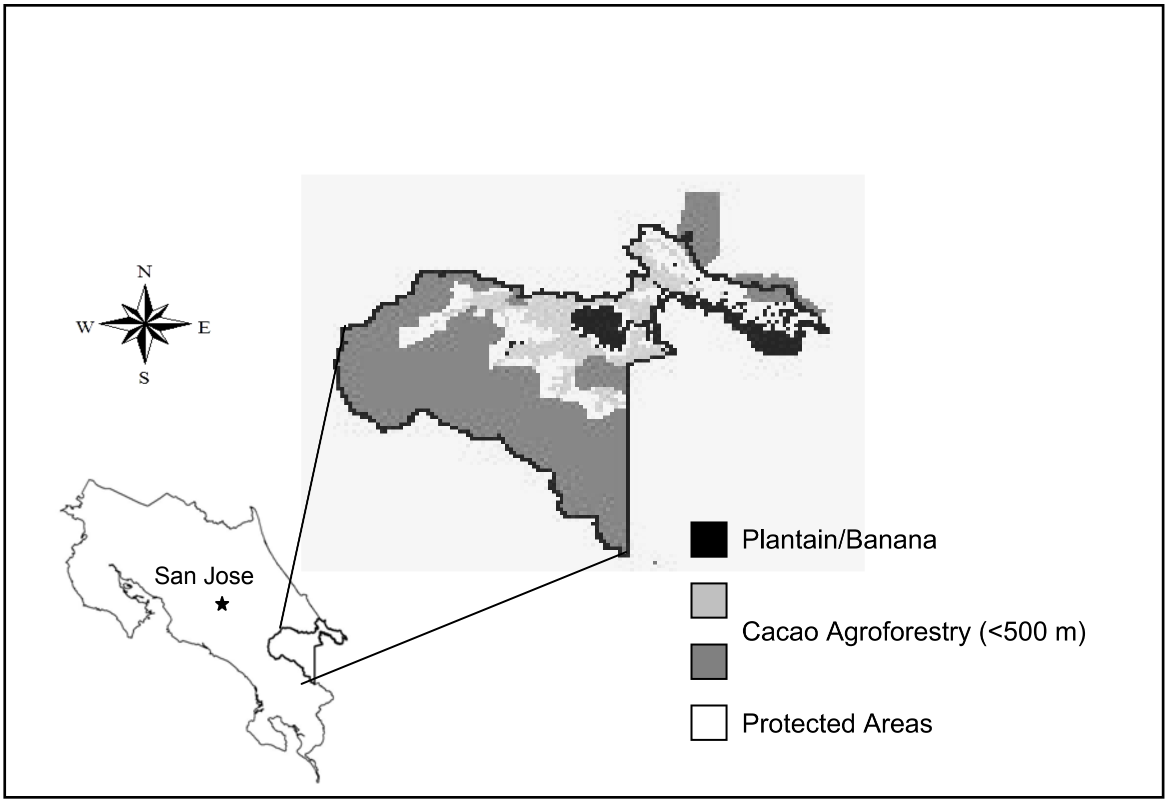

Figure 4.1: Dominant land uses in Talamanca, Costa Rica.

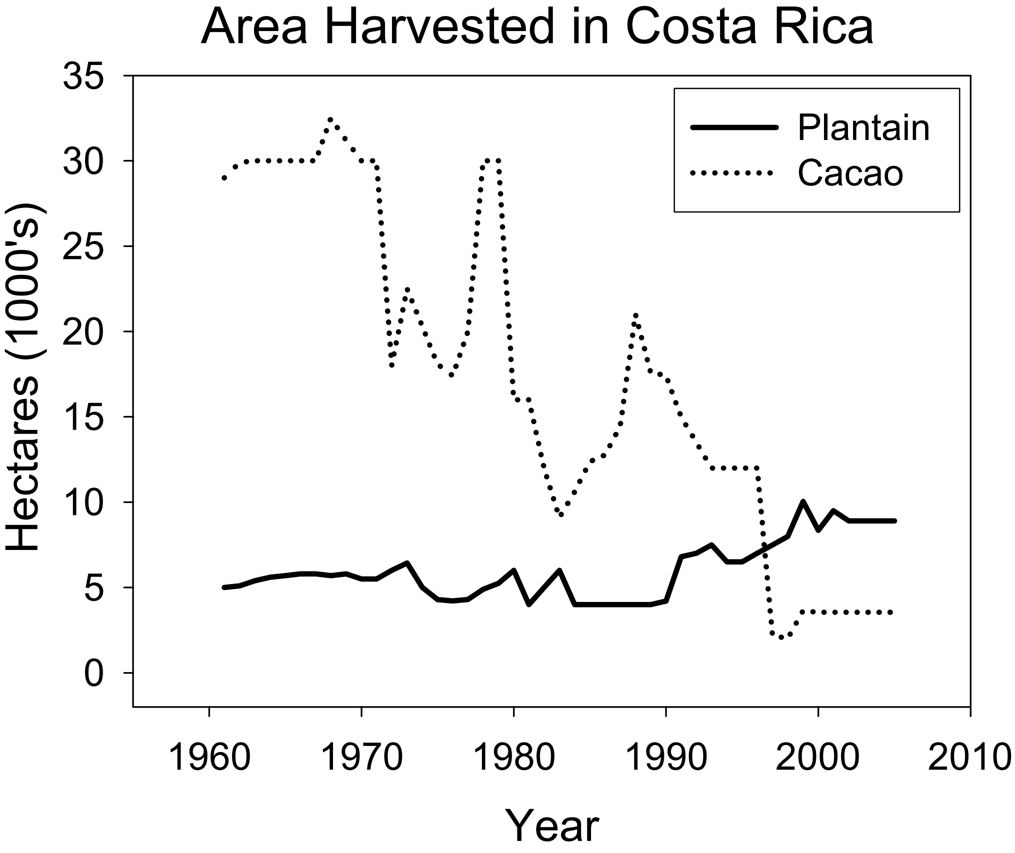

Figure 4.2: Area in Costa Rica harvested for plantain and cacao.

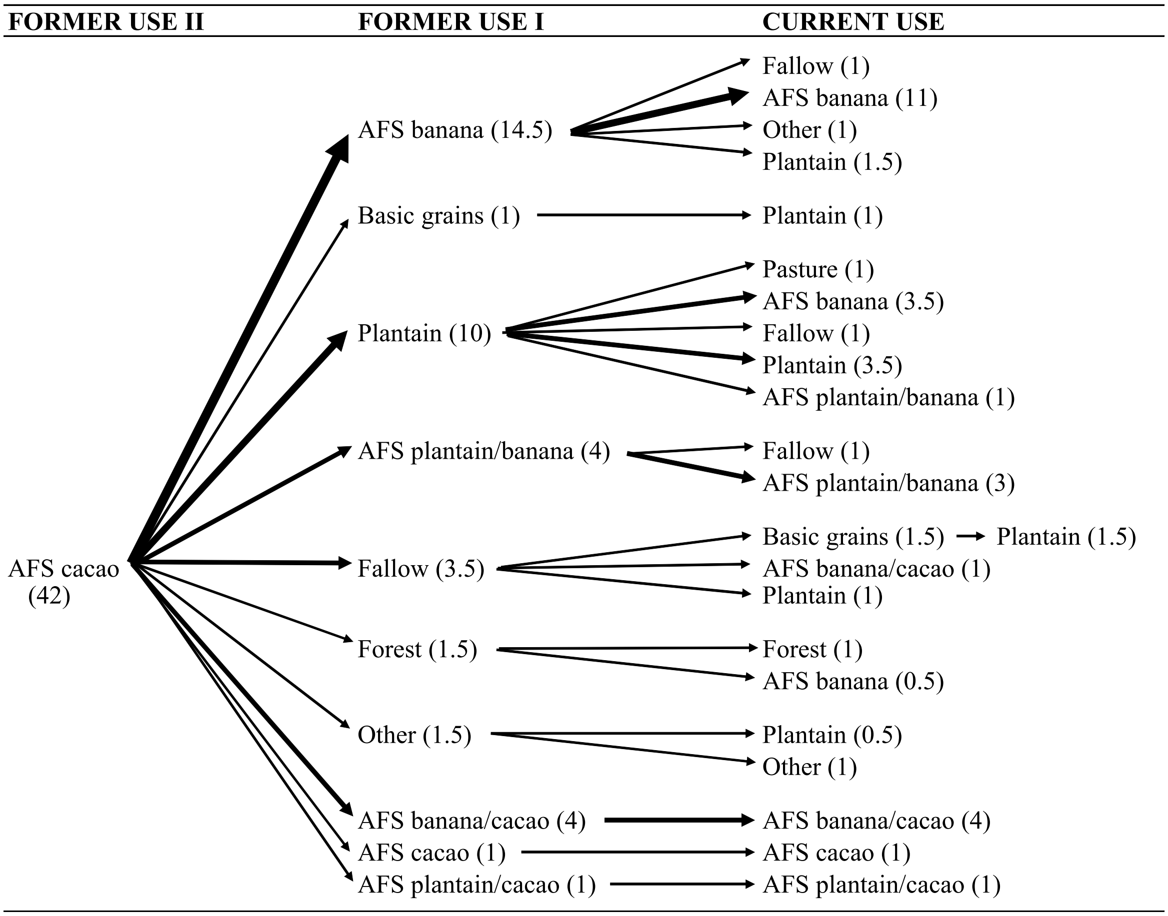

Figure 4.3: Shifts out of cacao agroforestry systems for household parcels whose management began with cacao agroforestry systems in 8 communities in Talamanca. Thicker lines reflect more common land use pathways. Numbers of plots are in parentheses. AFS = agroforestry systems. 'Other' includes tubers, fruit trees, and home gardens. Source: Whelan 2005.

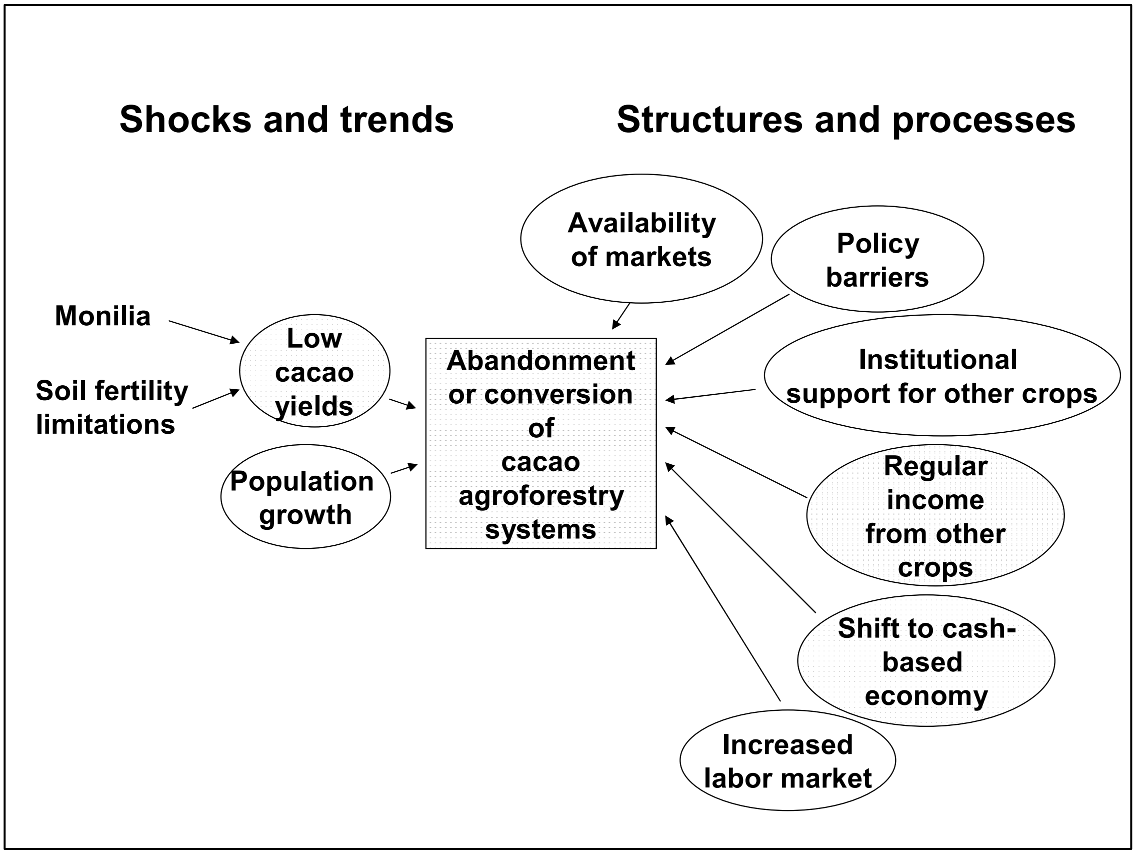

Figure 4.4: Factors influencing abandonment and conversion of cacao agroforestry systems in Talamanca.

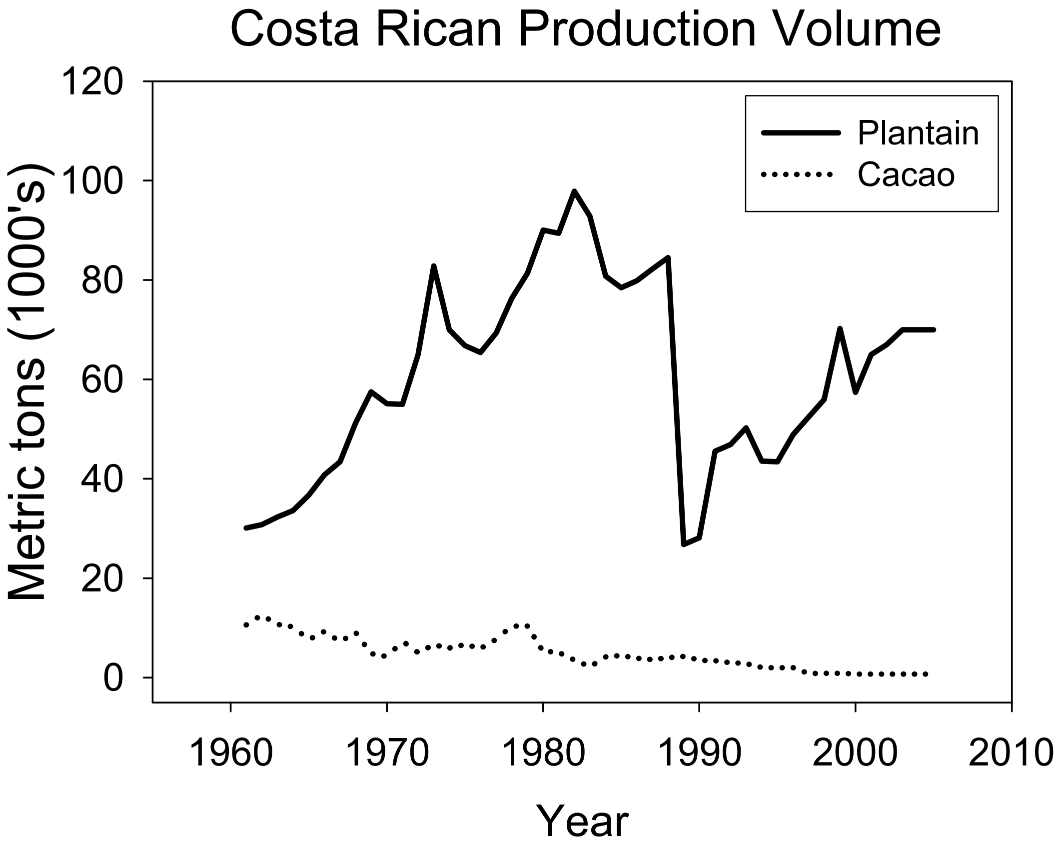

Figure 4.5: Costa Rican production volume of plantain and cacao. (Source: FAO databases, http://faostat.fao.org)

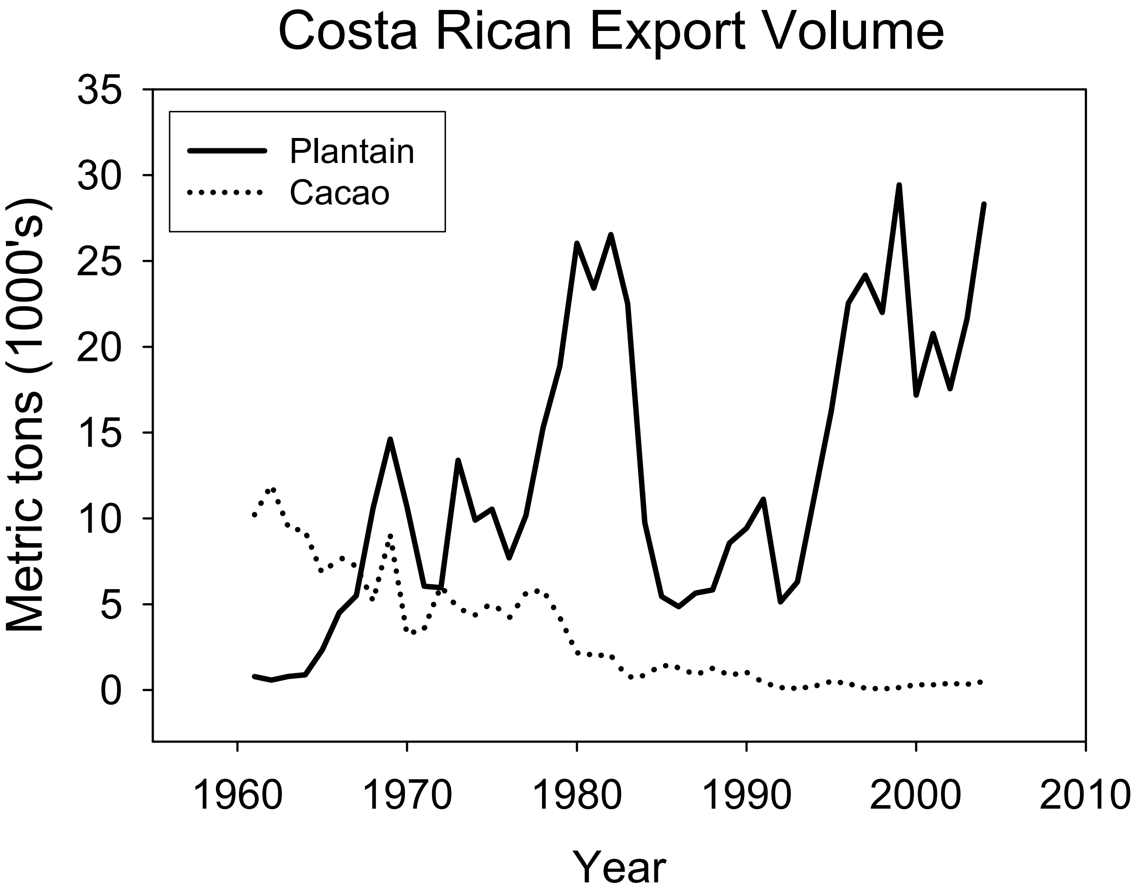

Figure 4.6: Volume of annual Costa Rican exports of plantain and cocoa beans.

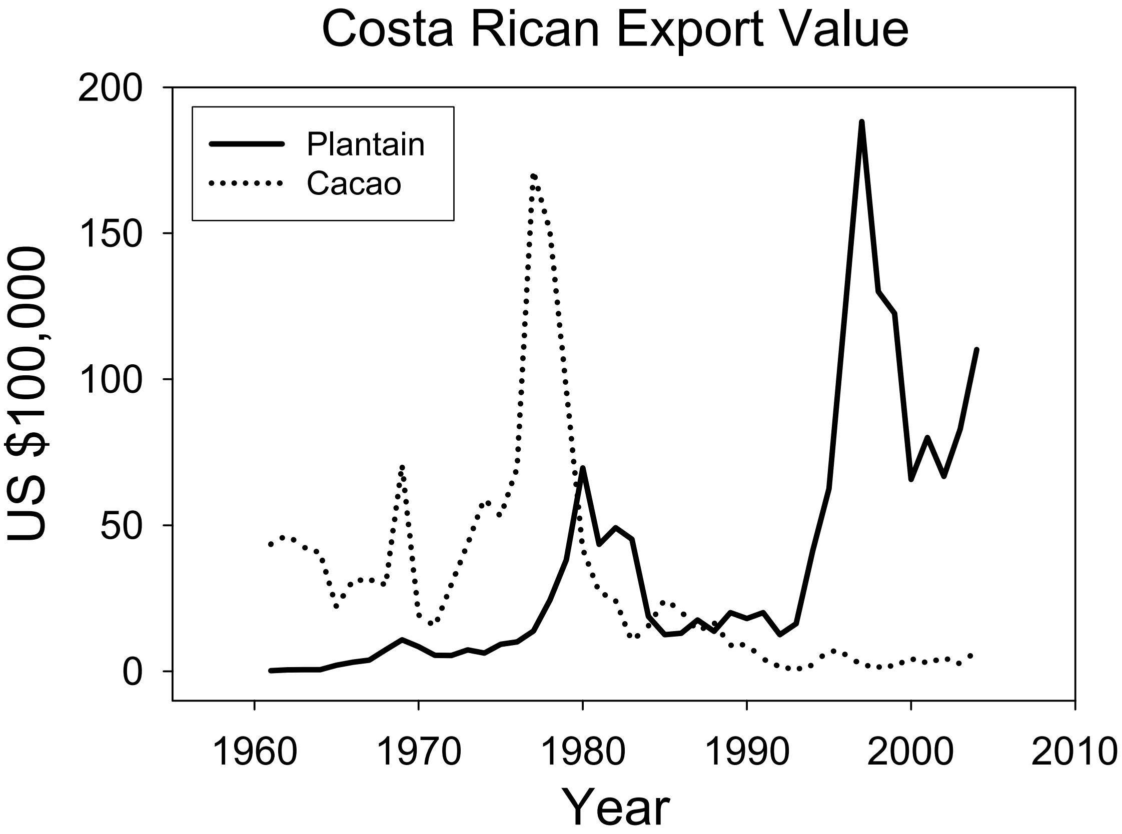

Figure 4.7: Value of annual Costa Rican exports of plantain and cocoa beans. (Source: FAO databases, http://faostat.fao.org

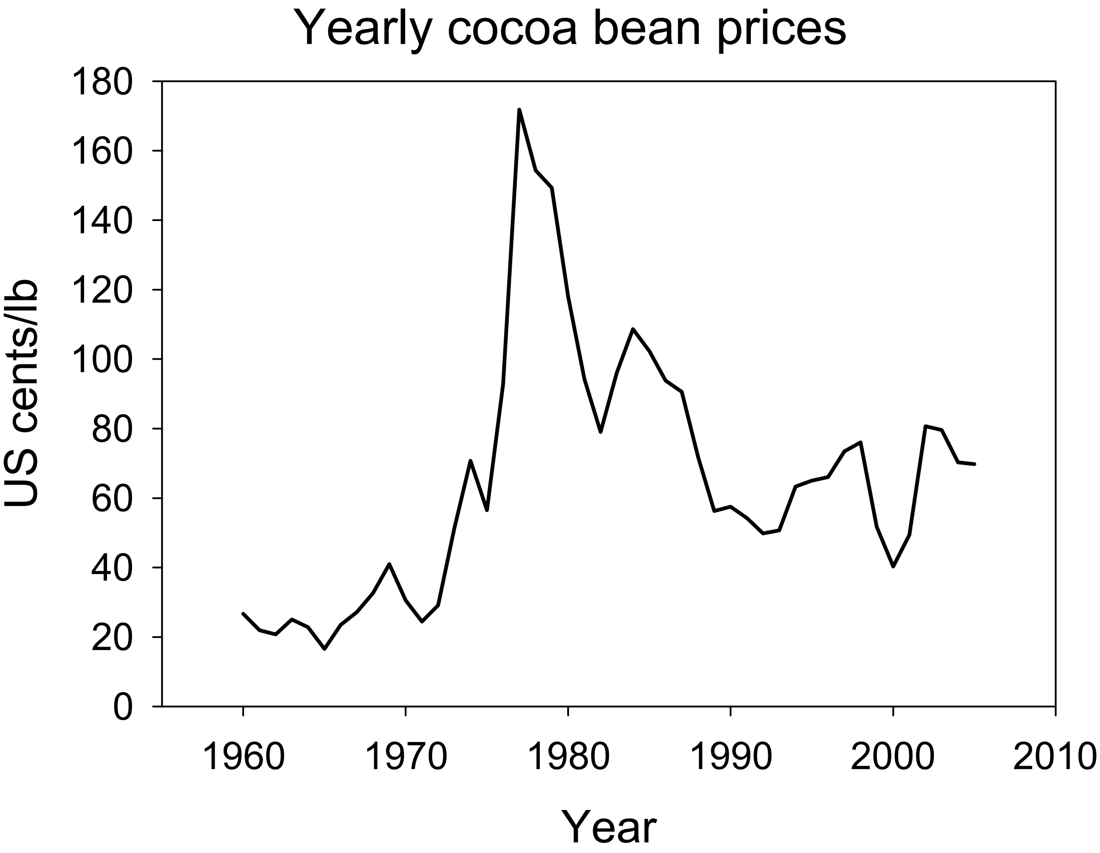

Figure 4.8: International cocoa bean prices (Source: International Cacao Organization, http://www.icco.org/menustats.htm).

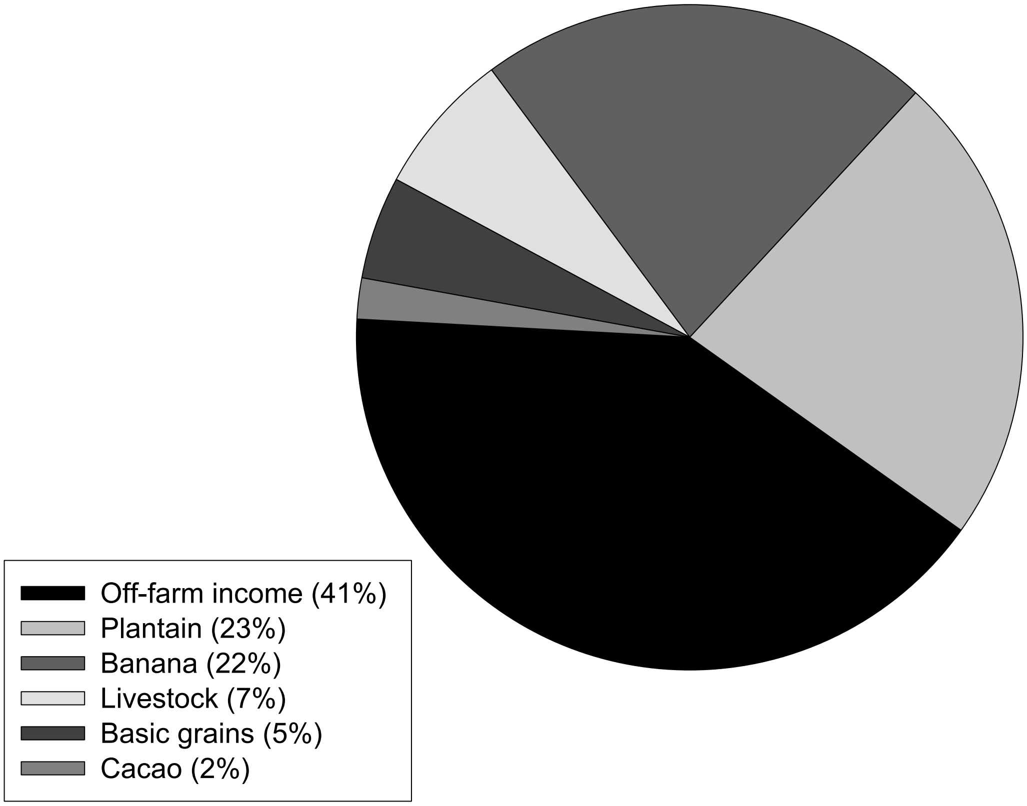

Figure 4.9: Household responses to the question: What are important income sources for your household?

5 APPENDIX A – LIST OF INTERVIEW QUESTIONS FOR CHAPTER ONE (IN SPANISH)

Interview questions in Spanish

I. Información básica del hogar

- ¿Cual es su nombre completo? ¿Su edad? ¿Nombre y edad de pareja?
- ¿Cuales son los nombres y edades de todos los que viven aquí y dependen económicamente de ustedes?
- ¿Cuantos hijos tienen en total?
- ¿Por cuánto tiempo han vivido en Talamanca?
- ¿Dónde nacieron?
- ¿Cuándo vinieron a Talamanca? ¿A esta comunidad?
- ¿Porque vinieron a Talamanca?
- ¿Cuales son los cultivos principales para su familia?
- ¿Cuales son los trabajos principales de los miembros de su familia?
- ¿Cuantas parcelas tienen ustedes? ¿El tamaño de cada parcela?

II. Características del suelo

- ¿Cuales son los diferentes tipos de tierra en su finca? ¿Dónde están?
- ¿Cuáles son los diferentes tipos de tierra en la región? ¿Donde están?
- ¿Cómo son las tierras en la región de donde provienen originalmente?
- ¿Cuales son las características de estos tipos de tierra? ¿Cómo son diferentes?
- ¿Qué tan profundo es cada tipo de tierra?
- ¿Tiene rocas? ¿Vivas o muertas?
- ¿Hay diferencias en la estructura de las raíces de diferentes cultivos? ¿Qué tan profundo son? Describe las raíces de los cultivos (cacao, banana, plátano, arroz, fríjol, maíz)
- ¿Cómo aprendieron de la tierra? ¿Quién les enseño? ¿Hasta que nivel alcanzó en cuanto los estudios?
- ¿Asistieron talleres o charlas relacionados a la tierra o de la agricultura?

II. Cultivos

- ¿Cuáles cultivos crecen mejor en cada tipo de tierra? (cacao, banana, plátano, arroz, fríjol, maíz) ¿Cuáles no crecen bien?
- ¿Cómo saben si un tipo de tierra es bueno o malo para un cultivo?
- ¿Cómo deciden donde sembrara cada cultivo? (cacao, banana, plátano, arroz, fríjol, maíz)

- ¿Cómo maneja su tacotal? ¿Cuánto tiempo lo deja antes de sembrar arroz de nuevo? ¿Fríjol? ¿Maíz?
- ¿Cómo sabe cuando la tierra ya está lista para sembrar de nuevo?
- ¿Usted siembra arroz, fríjol, o maíz en seguida?
- ¿Queman? ¿Con cuales cultivos? ¿Porque? ¿Como afecta la tierra la quema?
- ¿Tiene árboles en la finca? Si tienen, ¿Por qué mantienen árboles?
- ¿Las tierras han cambiado desde que empezaron cultivar aquí? Si han cambiado, ¿Por qué?

III. Uso de la tierra en el presente y en el pasado

- Hagamos un croquis de su finca, indicando todas las parcelas, donde están los siembros ubicados, cuales son los tamaños de las parcelas etc.
- Anotemos si la parcela es pendiente o plano
- Vamos a discutir la historia del uso de la tierra para cada parcela
- Vamos a anotar donde están ubicados los diferentes suelos

IV. Visita a la parcela

- ¿Dónde están los diferentes tipos de suelo en su finca?
- Vamos a escarvar un hueco de 30 centímetros para ver los diferentes suelos.
- Comparamos su designación del color con los colores del libro Munsell.
- ¿Porque sembraron cada cultivo en su presente sitio? ¿Cómo es el suelo en tal sitio?

V. Preguntas finales

- ¿Tienen preguntas para nosotros?
- Están invitado al taller de retroalimentación en abril para discutir los resultados de las entrevistas.
- Pagamos cada hogar c 5000 ($10).

Workshop questions in Spanish

I. Información histórica de la comunidad

- Línea de tiempo. Objetivo: saber cuales han sido los cambios significativos en el pasado de la comunidad, los cuales tienen su influencia en los eventos y actitudes del presente. Material necesario: Para esta actividad necesitamos pizarra y tiza o papelón y plumas. Podemos hacerlo en un solo grupo o con varios grupos (por ejemplo, tres grupos por tres comunidades).

    - ¿Cuándo se fundo la comunidad?
    - ¿Por qué vinieron a Talamanca?
    - ¿Cuáles han sido los eventos significativos en sus comunidades (por ejemplo, inundaciones, terremotos, decaídos en el precio de cacao etc.)?
    - ¿Las tierras han cambiado desde que las primeras personas llegaron aquí?
- Durante las entrevistas, ustedes nos contaron de diferencias entre el clima ahora y el clima antes. ¿Podemos hablar un poco más de eso? ¿Es cierto que el clima ha cambiado? ¿Cómo era cuando vinieron y como es ahora?
- ¿Asistieron talleres o charlas relacionados a la tierra o de la agricultura?

II. Características de la tierra

- Nos contaron de tres tipos principales de tierra en Talamanca: tierra negra de la loma, tierra negra de la isla, y tierra colorada. ¿Eso es correcto? ¿Hay otros tipos de tierra en Talamanca?
- Muchos nos contaron que las tierras de la zona sur son bastante parecidos a los de Talamanca. ¿Eso es cierto? ¿Ustedes han visto otros tipos de tierra en otras partes?
- Si alguien vive en otra planeta y viene a Talamanca y les pregunta de las diferentes tierras, ¿como las describirían? ¿Cuales son las características de estos tipos de tierra? ¿Cómo son diferentes? Hagamos una lista. Colocamos los títulos 'tierra negra de loma', 'tierra negra de isla', 'tierra colorada' y pongamos palabras descriptoras bajo cada titulo.
- Nos contaron de que a veces se encuentra estas tierras en diferentes lugares. Por ejemplo, la tierra negra se encuentra en la bajura y la tierra colorada en la loma. ¿Eso es cierto? ¿Hay excepciones? ¿Si es cierto, porque es así?
- Nos contaron que hay diferencias en la estructura de las raíces de diferentes cultivos. Distribuye a cada individual o cada grupo papel y ellos dibujan las raíces de los diferentes cultivos (cacao, banana, plátano, arroz, fríjol, maíz). ¿La tierra es diferente donde se siembra estos cultivos? ¿Estas raíces tienen efecto en la tierra?

II. Cultivos

- Cuáles cultivos crecen mejor en cada tipo de tierra? (cacao, banana, plátano, arroz, fríjol, maíz) ¿Cuáles no crecen bien?
- ¿Cómo deciden donde sembrara cada cultivo? (cacao, banana, plátano, arroz, fríjol, maíz)
- Nos contaron que hay diferencias en el manejo de tacotal para arroz y para maíz. Muchas nos contaron que el maíz no necesita tacotales tan largas como el arroz. ¿Eso es cierto? ¿Cuánto tiempo necesita el maíz? ¿Arroz?
- Durante las entrevistas, les preguntamos si la quema afecta el suelo. 17 dijeron que no. 6 dijeron que si. ¿Qué piensan ustedes? ¿Afecta la tierra la quema?
- Observamos que las fincas de ustedes tienen muchos árboles de todas clases. ¿Cuáles son los árboles que siembran ustedes? ¿Por qué los siembran?

V. Preguntas finales

- ¿Tienen preguntas para nosotros?

6 APPENDIX B – COPYRIGHT PERMISSION FROM BIODIVERSITY AND CONSERVATION

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7 APPENDIX C – UTM AND CRTM COORDINATES OF SAMPLING SITES

Landscape Position	Community	Farmer	slope	Aspect (degree)	Elevation (m)	Coordinates (UTM (17P) or CRTM)	
depression	Sibuju	Miriam Reyes	5	180	294	17P 0282164	1062399
depression	Sibuji	Cupertino Reyes	5	100	310	17P 0282199	1062905
footslope	San Vicente	Vicente	16	160	270	17P 0278957	1064002
footslope	Los Angeles		10	240	186	17P 0284117	1066312
footslope	San Vicente	Arnolfo	5			17P 0280801	1063720
footslope	San Miguel	Jorge Fernandez	15	320	301	17P 612382	1065435
ridgetop	Los Angeles	Aurelio		280	611	17P 287219	1064282
ridgetop	San Vicente	Carlos Zuniga	8	e	397	17P 280555	1062891
ridgetop	San Vicente		6	250	393	17P 281032	1062943
midslope	Los Angeles	Aurelio	30	w	511	17P 286367	1064782
midslope	Los Angeles		52	200	413	17 P 285437	1063972
midslope	Sibuju	Antonio	7		79	17P 0285301	1060262
midslope	Sibuju		20	40 ne	166	611851	1061417
midslope	Sibuju	don Jose Alberto	35	90	245	611906	1061396
midslope	Sibuju		18	320	395	17P 0281240	1063356
midslope	Los Angeles	Pedro Vargas	20	320	404	17P 286367.973707	1066582
midslope	San Miguel	Fidel	5	270	296	17P 612308	1060909
midslope	Sibuju	Anselmo/Porfirio	16	SE	173	17P 282982	1061313
midslope	Sibuju	Porfirio	12	se	173	17P 283053	1061452
midslope	Sibuju	don Jose Alberto	21	e,ne	166	17P 0282742	1061880
floodplain	Gavilan Canta	Erasmo	0		127	17P 0277780	1061081
floodplain	Gavilan Canta	Hermojenes Morales	0		123	17P 0277281	1060618
floodplain	China Kicha	Colegio S.V.	0		100	17P 280427	1060702

8 APPENDIX D – TREE SPECIES AT THE CACAO AGROFORESTRY SITE

Common Name	**Scientific Name**	**Number on 0.5 ha**
unknown		8
aceituno	*Simarouba spp.*	1
amarion	*Terminalia amazonia*	1
botos		2
cacao	*Theobroma cacao*	237
cedro	*Cedrela odorata*	1
cedro amargo	*Cedrela mexicana* Roem	1
come negro	*Lonchocarpus velutinus*	1
cortez	*Tabebuia guayacan*	9
fino		1
gavilan	*Pentaclethra macroloba*	2
guaba	*Inga* spp.	4
guayaba	*Psidium guajava* L.	3
higueron	*Ficus* spp.	1
jobo	*Spondeas luteae* L.	7
lagartillo	*Zanthoxylum* spp.	1
laurel	*Codia alliodora*	42
mamon chino	*Nephelium lappaceum*	15
mandarina	*Citrus* spp.	1
mango	*Mangifera indica L*	2
manu blano	*Minquartia guianensis*	1
monequillo		1
ojochillo macho		4
oreja burro		3
pejiballe	*Bactris gasipaes* H.B.K	4
pilon, zapatero	*Hieronyma alchorneoides*	1
poro	*Erythrina* spp.	2
sangrillo	*Pterocarpus officinalis*	9
tabacon		2
zapote colombiana	*Quararibea cordata*	1
zapote,cabeza	*Lycania platypus* (Hemsl.)orCalocarpum mamosum L.	1
zorillo		1
TOTAL TREES		370

9 APPENDIX E – HUMAN ASSURANCES APPROVAL

10 APPENDIX F – SAMPLES OF WORKSHEETS DISTRIBUTED TO FARMERS

FARMER WORKSHEET

Suelo debajo de la finca de banano de Cupertino Reyes Reyes

Noviembre 2006

Escarbamos hasta 1 metro de profundidad para mirar los colores del suelo y observar donde llegan las raices. Ahorita, voy a llevar las muestras al laboratorio en Los EE.UU y volver a Talamanca en Junio 2007 para dar todos los datos a Ud.

Leigh Winowiecki y Cupertino

El banano de Cupertino es muy diverso con arboles de laurel, pejivale, cacao, guava, guanabana, burio, waroa, araca.

En la entrevista en Febrero 2006, Cupertino dijo esto suelo es "suelo negro". Photo con Mateo.

¡Su Suelo!

0 cm
La capa negra tiene muchas raices y poros
10 cm
Algunas raices y poros aquí y tambien muchas piedras muertas (pequeñas)
30 cm
El color aquí se cambia, hay pocos racies, mucho arcilla y la roca muerta existe en fragmentas pequeñas.
60 cm
El suelo es un poco de color gris que posible significa que el drenaje aquí no es perfecto.
100 cm

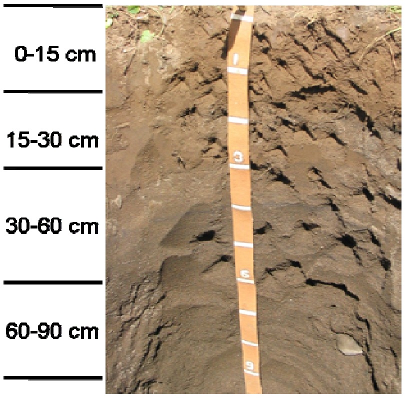
Gracias!

FARMER WORKSHEET B

Finca de Hermogenes Morales Morales, Gavilan Canta

Profundidad (centimetros)	Contenido calcio	Contenido magnesio	Contenido potasio
		cmol (+)/ kg	
0-5	24.5	4.3	0.9
5-15	23.8	3.9	0.5
15-30	21.2	3.7	0.5
30-60	14.8	2.0	0.4
60-90	18.2	1.8	0.3
90-130	17.3	1.6	0.3

Su finca y su suelo!!



Esto suelo tiene 15% de arcilla, 48% de arena y 37% limo en la primera capa y a 60 cm tiene 6% arcilla, 87% arena y 7% limo. Esto es muy poco arcilla y mucho arena. Esto suelo tiene muy poco carbono y nitrogeno por la arena. La hojarasca de arboles de sombra pueda aumentar los nivels de nitrogeno y carbono. Hay niveles suficientes por calcio, magnesio y potasio.

Profundidad (centimetros)	% Nitrogeno	% Carbono
0-5	0.12	1.26
5-15	0.03	0.42
15-30	0.02	0.24
30-60	0.00	0.09
60-90	0.01	0.07
90-130	0.00	0.06

FARMER WORKSHEET

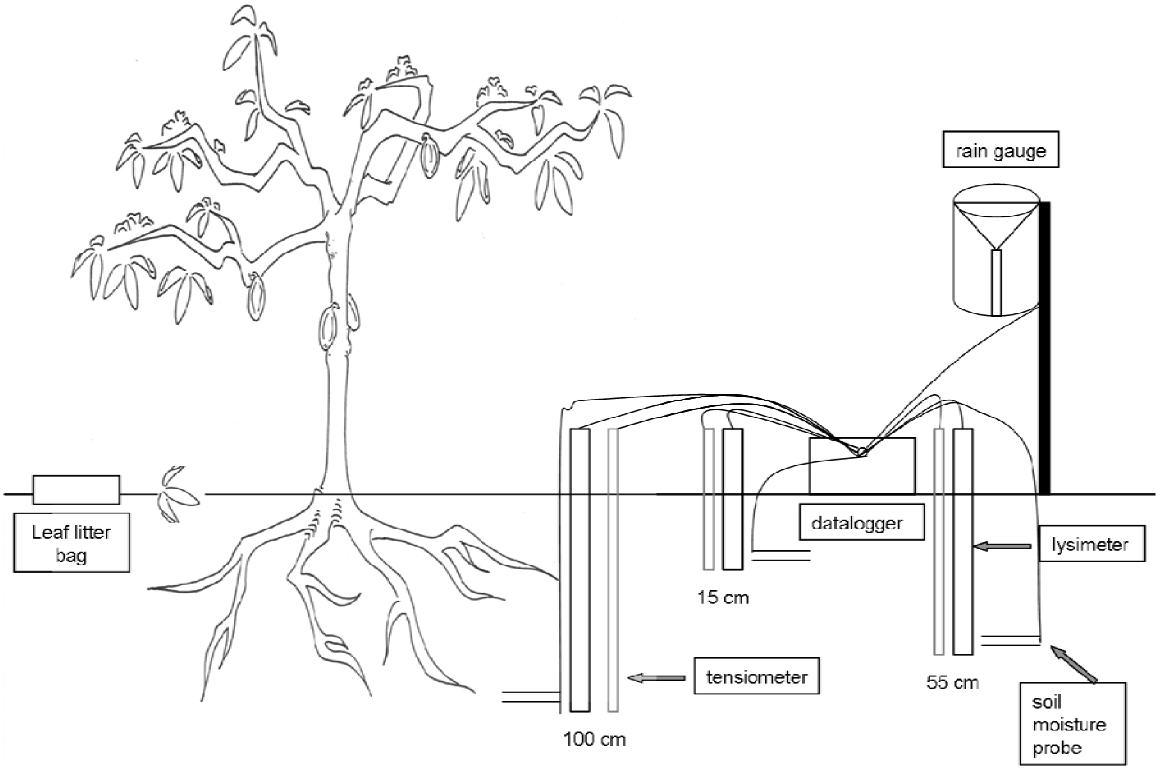
Para estudiar el ciclo de nutrientes en el sitio de cacao de don Porfirio

Cacao: suelo profundidad	% Carbono	% Nitrogeno
0-10 cm	2.5	0.25
10-20 cm	1.5	0.15
20-40 cm	0.98	0.097
40-70 cm	0.67	0.067
70-110 cm	0.42	0.044

Esto suelo es llena con arcilla y es muy bajo en nutrientes, especialmente en potasio y nitrogeno. Tambien el pH es muy bajo; numeros entre 6 y 8 son mejor.

Profundidad	pH	cantidad calcio	cantidad magnesio	cantidad potasio
0-10 cm	3.9	5.68	2.45	0.64
10-20 cm	3.5	2.37	0.94	0.19
20-40 cm	3.6	2.63	1.12	0.22
40-70 cm	3.8	1.53	0.68	0.08
70-110 cm	4.0	0.99	0.47	0.07

11 APPENDIX G – SCHEMATIC OF THE CACAO MONITORING SITE



Cacao tree drawn by Amelia Jurkowska

12 APPENDIX H – PRECIPITATION WORKSHOP WITH THE STUDENTS OF SIBUJU

Cantidad de lluvia que cayó en Sibuju**2 de Marzo a 14 de Marzo 2004**

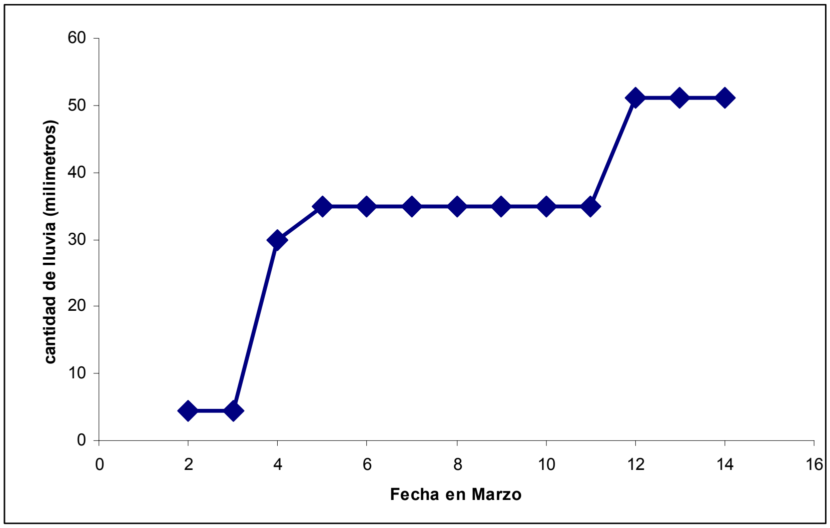
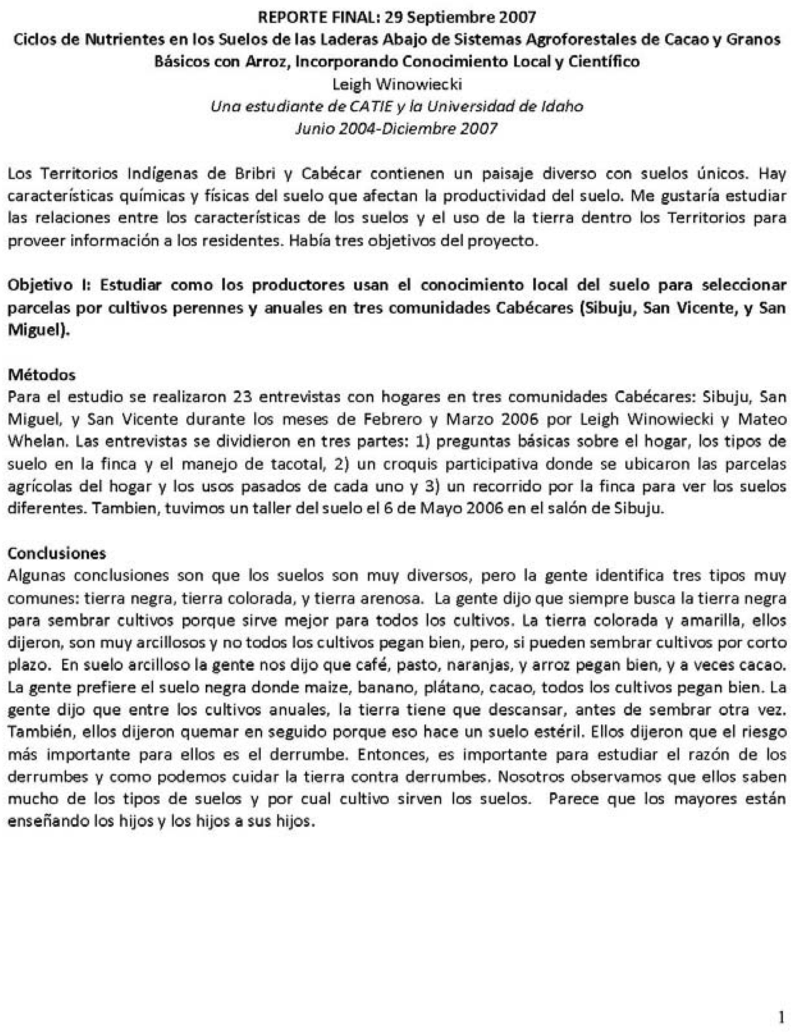


Grafico de la cantidad de lluvia que cayó en Sibuju. Datos midió por Miriam Reyes Fernandez y los estudiantes de de Sibuju con el pluviometer afuera de la escuela.

Los estudiantes aprendieron como medir precipitación.

13 APPENDIX I – FINAL REPORT TO FARMERS, INDIGENOUS COMMUNITIES, AND INDIGENOUS GOVERNMENTS



REPORTE FINAL: 29 Septiembre 2007

Ciclos de Nutrientes en los Suelos de las Laderas Abajo de Sistemas Agroforestales de Cacao y Granos Básicos con Arroz, Incorporando Conocimiento Local y Científico

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Una estudiante de CATIE y la Universidad de Idaho
Junio 2004-Diciembre 2007

Los Territorios Indígenas de Bribri y Cabécar contienen un paisaje diverso con suelos únicos. Hay características químicas y físicas del suelo que afectan la productividad del suelo. Me gustaría estudiar las relaciones entre los características de los suelos y el uso de la tierra dentro los Territorios para proveer información a los residentes. Había tres objetivos del proyecto.

Objetivo I: Estudiar como los productores usan el conocimiento local del suelo para seleccionar parcelas por cultivos perennes y anuales en tres comunidades Cabécares (Sibuju, San Vicente, y San Miguel).

Métodos

Para el estudio se realizaron 23 entrevistas con hogares en tres comunidades Cabécares: Sibuju, San Miguel, y San Vicente durante los meses de Febrero y Marzo 2006 por Leigh Winowiecki y Mateo Whelan. Las entrevistas se dividieron en tres partes: 1) preguntas básicas sobre el hogar, los tipos de suelo en la finca y el manejo de tacotal, 2) un croquis participativa donde se ubicaron las parcelas agrícolas del hogar y los usos pasados de cada uno y 3) un recorrido por la finca para ver los suelos diferentes. Tambien, tuvimos un taller del suelo el 6 de Mayo 2006 en el salón de Sibuju.

Conclusiones

Algunas conclusiones son que los suelos son muy diversos, pero la gente identifica tres tipos muy comunes: tierra negra, tierra colorada, y tierra arenosa. La gente dijo que siempre busca la tierra negra para sembrar cultivos porque sirve mejor para todos los cultivos. La tierra colorada y amarilla, ellos dijeron, son muy arcillosos y no todos los cultivos pegan bien, pero, si pueden sembrar cultivos por corto plazo. En suelo arcilloso la gente nos dijo que café, pasto, naranjas, y arroz pegan bien, y a veces cacao. La gente prefiere el suelo negra donde maize, banano, plátano, cacao, todos los cultivos pegan bien. La gente dijo que entre los cultivos anuales, la tierra tiene que descansar, antes de sembrar otra vez. También, ellos dijeron quemar en seguido porque eso hace un suelo estéril. Ellos dijeron que el riesgo más importante para ellos es el derrumbe. Entonces, es importante para estudiar el razón de los derrumbes y como podemos cuidar la tierra contra derrumbes. Nosotros observamos que ellos saben mucho de los tipos de suelos y por cual cultivo sirven los suelos. Parece que los mayores están enseñando los hijos y los hijos a sus hijos.

Objectivo II. Estudiar los tipos de suelos diferentes en las laderas en Talamanca.

Métodos

Visitamos fincas en cuatro comunidades (Sibuju, San Vicente, San Miguel, Los Angeles) para estudiar los suelos diferentes en las laderas de Talamanca. Escarbamos un hueco (perfile) en las fincas hasta 1 metro de profundidad para mirar los colores de las capas en el suelo, presencia de rocas y raíces, y para llevar muestras al laboratorio para analizar la fertilidad del suelo. Analizamos pH, contenido de calcio, magnesio, y potasio, contenido de arcilla, arena, y limo, y contenido de aluminio. Los cultivos necesitan calcio, magnesio, y potasio para sobrevivir!

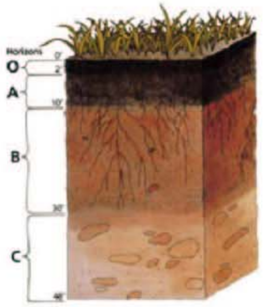

Figure 1:Un ejemplo de perfil del suelo hasta un metro de profundidad

Conclusiones

Los suelos de las laderas son bien diversos. Hay suelos rojos con un contenido de arcilla increíble (más de 60 por ciento del suelo es arcilla). Hay otros suelos arcillosos pero negras. También hay suelos arenosas. Todos estes suelos tienes cosas buenas y limitaciones. Una limitación de los suelos rojos es que los contenidos de calcio, magnesio, y potasio son muy bajos. Pero en los suelos arenosos, los contenidos de nitrógeno y carbono son muy bajos! Entonces tenemos que identificar las limitaciones del suelo y manejar bien los suelos para cultivar bien los cultivos.

Fincas de	**Muestrero**		
	SIBUJU	**TIPO DEL SUELO**	**LIMITACIONES DEL SUELO**
1	Banano de Miriam	negro y arcilloso	bien contenidos de nutrientes pero mucha arcilla
2	Banano de Cupertino	negro y arcilloso	bien contenidos de nutrientes pero mucha arcilla
3	Cacao de Antonio	negro y arcilloso	bien contenidos de nutrientes pero mucha arcilla
4	Bosque de Jose Alberto Reyes	muy arcilloso con mucha roca muerta	muy poco nutrientes importantes
5	Cacao de Jose Alberto Reyes	muy arcilloso con roca muerta	muy poco nutrientes importantes
6	Tacotal de Walter	muchas piedras muertas	bien contenidos de nutrientes pero demasiado piedras
7	Maiz de Adelia	negra y arcilloso	
8	Cacao de Porfirio Hidalgo	muy arcilloso	muy poco nutrientes importantes
9	Cacao-Victor Reyes	muy arcilloso con roca muerta	muy poco nutrientes importantes
10	Arroz de Porfirio y Anselmo	muy arcilloso	muy poco nutrientes importantes
	SAN VICENTE		
11	Potrero don Carlos Zuniga	rojo y arcillosa	muy poco nutrientes importantes
12	Cacao para sembrar Arnolfo	negro con media arcillo	bien contenido de nutrients, mucha arcilla
13	Bosque Footslope Vicente	negro con media arcillo	bien contenido de nutrients, mucha arcilla
	SAN MIGUEL		
14	Cacao de Fidel S.M	negro con medio arcillo	bien contenidos de nutrient, arena y arcilla
15	Jorge	negro con medio arcillo	bien contenidos de nutrient, arena y arcilla
	LOS ANGELES		
16	Restrojo Pedro Vargas	rojo y arcilloso	muy poco nutrientes importantes
17	Potrero don Aurelio	rojo y arcilloso	muy poco nutrientes importantes
18	Bosque Aurelio	negra y arcilloso	bien contenido de nutrients, mucha arcilla
19	Rio Duruy	arenoso	muy poco carbono y nitrogeno
20	Bosque en fila hasta la torre	negro y arcilloso	bien contenido de nutrients, mucha arcilla
	GAVILAN CANTA		
21	Tacotal de Erasmo	arenoso	muy poco carbono y nitrogeno
22	Platano de Hermongenes Morales Morales	arenoso	muy poco carbono y nitrogeno
23	Platano de Colegio de San Vicente	arenoso	muy poco carbono y nitrogeno

Objectivo III. Aprender de los Ciclos de Nutrientes en los Suelos de las Laderas Abajo de Sistemas Agroforestales de Cacao y Granos Básicos con Arroz

Metodos

Midemos la cantidad de lluvia que cae (precipitación), la cantidad de hojarasca, y la tasa de descomposición de las hojas de cacao. Midemos la humedad de los suelos y colectamos agua del suelo a tres profundidades (15-cm, 60-cm, y 100-cm) (Vea Figura 1). Analizamos el agua del suelo para los nutrientes importantes para los cultivos, por ejemplo: calcio (Ca), magnesio (Mg), potasio (K), nitrógeno (N), y fósforo (P). Esta información se usará para comprender el flujo de los nutrientes y agua por la sistema. Estos datos pueden ayudar en las decisiones agrícolas.

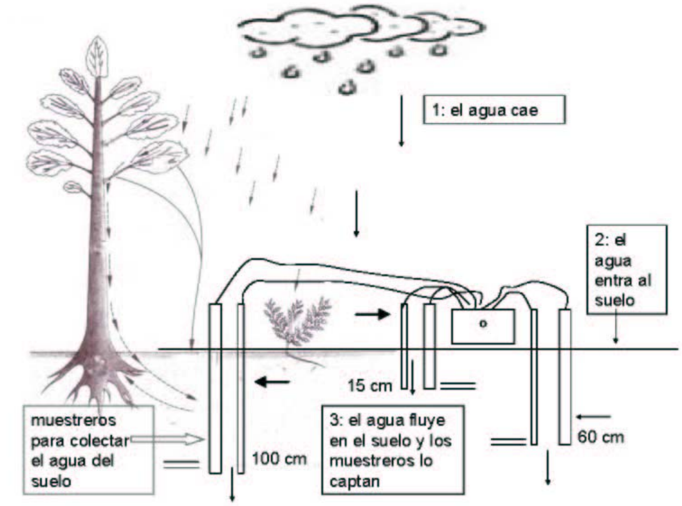

Figura 2: del flujo del agua por el sistema y el equipo necesario para colectar agua del suelo a tres profundidades

Resultados

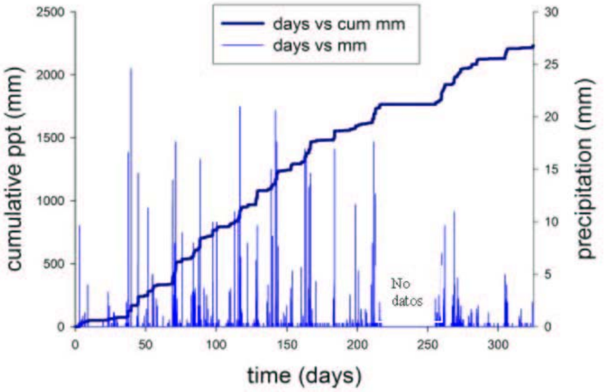

Figura 3: En 325 días, más de 2000 milimetros de lluvia se cayó. No había una época bien seca en Talamanca.

Los datos de hojarasca muestraron que 10.3 toneladas de hojarasca caye en esta finca diversa de cacao. Esta hojarasca es bien importante para apoyar el sistema de cacao. Las hojas proveer nutrientes importantes (vitaminas) al cultivo!

Nuestra estudio mostró que las sistemas de quemar con arroz se pierden más nutrientes importantes que las sistemas diveros de cacao. La razon por eso es porque, cuando una se quema, se pierden muchos nutrients en la ceniza, y estos nutrients se lava con el agua de lluvia. Tambien, arroz falta raices como las raices de arboles absorben agua y los nutrientes. Otra cosa muy importante de los sistemas de cacao es que debemos usar las cascaras de cacao para proveer nutrients al cultivo de cacao. Las cascaras tienen mucho nutrients y debemos volverlos al sistema (no se pone en una colina pero debemos dispersarlas.)

Figura 4: Dos fuentes importantes para apoyar y proveer nutrients importantes (vitaminas) al cultivo!