AN ABSTRACT OF THE THESIS OF

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Title: Exploring Soil-Landscape Relationships on the Pacific Slope of Monteverde, Costa Rica

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Ronald J. Reuter

Landscape positions have been used to determine soil properties. My soil study in Monteverde on the Pacific slope of Costa Rica was designed to examine soil-landscape relationships for sites with various land use histories and management. Soil pits were dug at Nacimiento y Vida, Crandell, Curi-cancha, La Calandria, and Finca Rodriguez. Nacimiento and Curi-cancha are restored pastures, while Crandell, La Calandria, and Finca Rodrigez are restored farms. Soils were point sampled in the surrounding spaces around the pits in order to provide more landscape scale information on soil property variations. I found that each site had significant differences from the next and as a result, analysis should be done individually. There were a few significant relationships that held true for all sites. Percent clay and percent carbon yielded a negative relationship, while percent sand and percent carbon yielded a positive relationship. Percent carbon and depth yielded a negative relationship, as did percent nitrogen and depth and percent sand and depth. Percent sand and percent nitrogen yielded a positive relationship, while percent clay and percent nitrogen yielded a negative relationship. The significant relationship between percent sand and percent carbon is likely the result of the presence of volcanic ash in my soil samples. Volcanic ash can fall into the same particle size class as sand (2 mm) for the purposes of particle size analysis. Volcanic ash particles are very porous and

increase the soil's ability to store carbon. Sandier soils may be a helpful indicator for appropriate planting locations during future tropical forest restoration. Soil color indexes such as PDI (Profile Darkness Index) and RR (Redness Rating) were utilized to provide information on soil carbon content and clay content for the probe points. Statistical analysis revealed a lack of a strong relationship between the indices and slope. PDI and RR were thus not good measures to determine carbon and hematite content based on slope. Future studies that plan to utilize color indices in this region should be weary and maintain a degree of caution.

Exploring Soil-Landscape Relationships on the Pacific Slope of Monteverde, Costa Rica

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Kevin M. Hesson, Author

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Dedicated to the memory of my greatest friend,

favorite person, and younger brother, Tim.

Chapter 1 : Problems in Paradise

Introduction

Disturbed land around the world is currently undergoing reforestation in an effort to undo man-made change that have, in some cases, devastated the natural environment. Places like Monteverde, Costa Rica, are home to a significant number of plant and animal species, some of which are endemic to areas on the mountain. Since the late 20th century, Costa Rica has begun efforts to transform the perception that the public has about their natural resources and attempt to cultivate a movement toward conservation and sustainable use of those resources. An issue with current reforestation efforts in the Monteverde Region of Costa Rica is plant survivorship within restored sites is mixed, with some sites having higher success rates than others.

Soil properties can drastically change from one location to another, altering the level of habitability for plants, which ultimately drives success of reforestation efforts. Soil mapping in Costa Rica as a whole is relatively limited and generalized. There has been no detailed study of soil property distribution in the Monteverde region at the landscape scale as of yet. My study focused on the identification of those properties and their change across the landscape in order to provide information that may assist local efforts in decision making for reforestation projects in the Monteverde region.

In recent decades, studies have been examining the effectiveness of certain strategies for restoration. Some have examined success rates among various tree species (Carpenter et al., 2004, Holl, et al, 2011), while others have investigated the impact of land use on current land conditions (Carter and Ciolkosz, 1991, Thompson et al., 1997, Wang et al., 2017). I was interested in examining soil-landscape relationships; something that has not been done in this study area. The Monteverde Institute has been working toward restoring the tropical forest in specific locations throughout the Monteverde region. In collaborating with them, I was able to visit a variety of sites with different land use histories.

The main focus of the project was to identify soil property distribution across the landscape. Properties that I focused on were the depth to clay at a given site, slope at the site, the thickness of the A horizon present, and percent carbon. I hypothesized that land use change over the past century and into the 21st century heavily influenced the success of restoration efforts in the Monteverde region of Costa Rica. In particular, I hypothesized the conversion of intact tropical forest to farmland or pastureland changed landscape dynamics, leading to losses of soil carbon and soil material at upper slope locations. Studies in the past that have looked at the relationship between slope and soil profile darkness have shown that sites located at lower slope profile positions are associated with darker soil profiles (Thompson et al., 1997). The opposite is true at sites located at up-slope positions in which soil profile darkness is lower. The darkness (specifically the blackness) of a soil is an indicator for the presence of soil carbon. This is important because, as indicated by Thompson, et al. (1997), a site with a high slope will have a lighter soil color, indicating that the soil has less carbon. Soils found at lower slope concave profile positions will have accumulated eroded soil material from up-slope which leads to a thicker A horizon with a greater capacity to store water (Pennock and de Jong, 1990). A horizon material is also associated with a higher level of soil nutrients (Jobbágy and Jackson, 2001).

Areas that accumulate topsoil from erosional processes will therefore receive nutrient inputs as well. I expected this principle to hold true through my study in Costa Rica. In Monteverde, the topography is naturally rugged (Figure 1). This makes for steep slopes that change dramatically over small areas. The topographic environment of Costa Rica contributes to soil development and transportation of soil material across the landscape.

Figure 1. Satellite iamge map of Costa Rica with the study area.

An Overview of Global Deforestation

Deforestation is an issue that mankind has dealt with for centuries. However, with modern technology, the rates of deforestation have become more rapid as developing countries attempt to compete in today's world. In recent world reports spanning 2000 - 2012, the greatest forest losses have occurred in Asia and Africa. There, forest losses in protected areas are measured at 0.16% and 0.15% respectively (Spracklen et al. 2015). In South America, deforestation of tropical rainforests has been spurred by the push to create pasture for cattle, or for the establishment of large monoculture operations like cotton, and coffee (Aide et al. 2000). Deforestation rates will likely continue to increase as the demand for food increases (Aide et al. 2013). This has resulted in the cutting of 4 million hectares annually in South America alone (FAO, 2010).

Deforestation has reached such levels that according to the Food and Agriculture Organization of the United Nations (FAO, 2010) estimates, the world's forests are now a net source of emissions due to the decrease in total forest area. Although deforestation remains a problem, its rates appear to be gradually slowing. This is especially true in Costa Rica, where restoration efforts have been implemented since the 1950's. Costa Rica is a unique example for South and Central America, where deforestation largely continues. A shift occurred in the direction of the Costa Rican economy in the 1950's and the country began protecting and expanding one of its most valuable resources. In the 1950's, the economy in Costa Rica began to focus on small industry and less on agriculture, leaving many agricultural plots abandoned (Aide et al. 2000). The abandonment of pasture and agricultural land gave way to natural regeneration of forest. Despite this shift, traditional agricultural and pastoral practices continued to drive deforestation. By the 1990's, most of the land in Costa Rica was deforested (Aide et al., 2000) and in 2005, the destruction of Costa Rica's tropical forests was almost 90% complete (Leopold, A. C., 2005). During the 1990's, the Costa Rican government began developing a plan to work with its citizenry to protect and reestablish tropical forests, while working to undo the harmful effects of deforestation. Through government programs as well as initiatives like Payment for Ecosystem Services (PES) and Reducing Emissions from Deforestation and Forest Degradation (REDD+), Costa Rica has begun to repair its landscape by offering economic incentive to landowners to become good land stewards (Sanchez-Azofeifa, et al., 2007).

Deforestation heavily impacts the ability of tropical forests sites to intercept and retain water, especially horizontal precipitation, a term which refers to the suspended moisture that lingers over tropical forests for extended periods, accounting for up to 18 to 100% of total precipitation during the wet and dry seasons, respectively (Ray et al., 2006). Horizontal precipitation is a unique feature of the tropical cloud forests of Costa Rica and is a major contributor to the level of biodiversity found there. Deforestation in the cloud forests has decreased cloud cover by 5-13% (Ray et al., 2006). This poses a danger as the Costa Rican cloud forest systems rely on horizontal precipitation as a primary source of freshwater during the dry season (Häger and Dohrenbusch, 2011).

There is spatial variability of precipitation where the Pacific slope of Costa Rica receives less rain than the Atlantic side (Häger and Dohrenbusch, 2011). This is particularly important for my study considering I will be working on the Pacific (drier) slope of Costa Rica, where the ecosystem is more vulnerable to changes in moisture. Established forests allow for the existence of horizontal precipitation (low hanging clouds or mist) to extend to lower altitudes because forests provide canopy cover, and reduce overall temperature within the forests. When deforestation occurs, it is followed by an increase in cloud base height, which leads to drier conditions (Ray et al. 2006). There is no doubt that such a significant loss of moisture in a system that relies heavily on horizontal precipitation will have considerable impacts on the biodiversity and overall health of the region. Restoration may be time sensitive in cloud forest regions where deforestation has occurred and subsequent dry conditions have persisted.

Costa Rican Geography

The geography of the relatively small country of Costa Rica consists of coastal plains separated down the middle by a large mountain range. The coastal plains are generally flat, with smaller slopes that eventually meet the sea. There is also a coastal range on the west side of the country and a smaller range that extends out to the Nicoya Peninsula in the north west. A similar range exists on the Osa peninsula located in the south west as well. The mountains in the center of the country are much more rugged. Because of their elevation they create an orographic effect, which tends to force more precipitation to occur on the northern (Atlantic) slope as opposed to the southern (Pacific) slope. However, both the Pacific and Atlantic slopes of the country receive significant amounts of rainfall. The mountain range is of volcanic origin and scattered throughout it are several active volcanoes. In fact, many are active including the volcano closest to my study sites, Mt. Arenal. To the south west the mountain range continues and the bordering coastal plains narrow slightly until they meet the western boarder of Panama.

Costa Rican Biodiversity

Biodiversity suffers in regions that have been converted to pasture. This is both a short and long-term problem, especially for plant communities. Conversion to pasture eliminates trees, and thus habitat for many species that rely on those forest systems, particularly bird communities. As trees and thus habitat are eliminated, the ability of trees to regenerate is altered. In the long term, seed richness is dampened in pasture as it harbors lower levels of seed diversity than plantation plots or natural regeneration plots (Montagnini, 2008). This makes natural revegetation increasingly difficult as tree seed levels are low and saplings that manage to germinate and establish themselves must then compete with grasses and other competitive shrub species. In some cases, remnant trees are left in pasture. These trees play a critical role in the regeneration of the former forest. They shed litter, which suppresses grass growth, and encourages the development of other woody species (Montagnini, 2008). In these cases, the loss of a seed bank is lessened, but in many cases, remnant trees are not present and future biodiversity suffers.

In a region that exhibits some of the highest levels of biodiversity on the planet, many species are affected by deforestation in Costa Rica. Forests serve as habitat for charismatic species like the quetzal, bats, and other frugivorous species which increase seed dispersal; a process upon which natural tree regeneration relies (Nadkarni and Haber, 2009). The continued presence of the quetzal is important for numerous reasons. It contributes to the eco-tourism of the region and has charisma that attracts tourists from other parts of the world (Wheelwright, 1983). It is mostly frugivorous, and annually feeds on fruits from a total of 41 different tree species (Wheelwright, 1983). They mainly depend on trees from the Lauracaea (avocado) family. The distribution of this family of tree also influences the quetzal's seasonal movements. Their nesting distribution is also interesting to note since it has implications for management and reforestation efforts. In Monteverde, 74% of nests occur in forest, 12% occur on the edges of pasture, and snags or remnant trees make up the remaining 14% (Wheelwright, 1983). This indicates that forest habitat is the best way to encourage quetzals to nest, but forest edge and remnant trees are also utilized. From this, we understand that completely open pasture will likely not attract birds to nest.

Birds aside from the quetzal also make use of remnant trees in open pasture. Bird visitation to remnant trees can be explained by examining tree isolation, size, and epiphytic biomass (Sheldon and Nadkarni, 2013). Larger trees that are more isolated, and have larger amounts of epiphytic biomass attract more birds (Sheldon and Nadkarni, 2013). In addition, larger trees provide more canopy cover, as well as a greater degree of protection from predators (Sheldon and Nadkarni, 2013). However, this information is not to be misinterpreted; Isolated trees do provide a critical service to bird species, but a complete forest will provide much greater levels of habitat and food sources for all bird species, according to Wheelwright (1983).

The Effort to Combat Deforestation

Many countries that heavily utilize forest resources have developed "Protected Areas" (PA) to prevent the total deforestation of large swaths of land. The establishment of PA's often represent the maximum effort exerted by developing countries, particularly in Asia, West Africa, and Central America (Spracklen et al. 2015). In Ethiopia, the effectiveness of PAs has been evaluated by investigating their ability to preserve organic carbon stocks and soil quality (Girmay and Signh, 2012). The effectiveness of PA's is mixed and depends on geography. PA's located on steep slopes and at high elevations tend to be more effective (Spracklen et al. 2015). Currently, 13% of the world's forests are protected areas (FAO, 2010). Humans have struggled to balance resource consumption with replenishment, and this is especially true in areas that are particularly gifted with natural resources. South and Central America contains some of the largest rainforest ecosystems on the planet. These ecosystems have been estimated to contain a significant portion of biodiversity that is deemed worth preserving by Costa Rica and the global community as well (De Camino et al., 2000).

Aside from a Protected Area program in Costa Rica, there have been numerous government projects directed toward reestablishing tropical forests and their respective ecological services. The government created a program called the Certificate of Forestry Payment (CAF) which was more effective than previous programs at engaging less wealthy citizens to participate in restoration efforts (De Camino et al., 2000). After the implementation of these programs, the Costa Rican government decided to further change the target for the programs, shifting toward local communities in order to facilitate restoration.

Potential Benefits of Combating Deforestation

As a country begins reforestation efforts, the benefits can be seen rather quickly. In tropical regions that initiate reforestation efforts, increases in above ground biomass, species richness, forest density, and basal area are similar to old growth forest sites (80 years old or older) (Aide et al., 2000). More rapid restoration might be achieved with larger scale and more comprehensive planting schemes. We must recognize that in some circumstances, restoration efforts must be modified in order to achieve the goals of a plan, even if that means a slower, or possibly less successful, recovery. Organizations interested in restoration will always be limited by the resources they have at their disposal.

It is also becoming increasingly important to develop effective ways of sequestering and storing carbon as a method to help mitigate the rate at which the climate is changing. In a study conducted in Monteverde that examined the rate at which soils change during restoration, they found that in pasture sites, 12.5% of lost carbon was restored after only three decades of secondary forest growth (Tanner et al., 2014). The same study also estimated that it will take about two centuries to restore soil carbon to a level comparable to mature forest. Regardless of the timescale for carbon levels to approach primary forest levels, restoration of forest has a positive impact on sequestration of carbon in the topsoil (Nave et al., 2018).

A Beacon of Light

For countries like Costa Rica, reforestation presents benefits beyond ecological services. For instance, in 2001, ecotourism in Costa Rica accounted for roughly 13% of its GDP (Honey, 2008). This number is only expected to grow as the country continues to attract international attention for its biodiversity and leadership in ecological restoration. The number of tourists visiting the Monteverde Ecological Biological Cloud Forest Reserve has increased dramatically since the 70's. Tourist growth has changed from less than 5,000 annually in 1974, to over 40,000 annually in 1991 at the Monteverde reserve alone (Menkhaus, 1995). Since Costa Rica began passing its landmark environmental protection policies in the latter half of the 20th century, it has reaped both the economic and ecological benefits. As developing nations consider restoring some of their forests, particularly in South America and Asia, places like Costa Rica provide examples of the potential economic benefits that can be seen from restoration efforts.

Factors in Restoration Success

In the past decades, as forest restoration plans have been executed in different regions across the world, various strategies for restoring forests have been used with varying rates of success. Success rates depend on the quality of the site and its level of fertility which depends on multiple site and soil characteristics. Those include : elevation (Dieleman et al., 2013), aspect, slope, profile curvature, and plan curvature which have an impact on the direction of soil movement and development (Hugget, 1975), pH, soil organic carbon, which often determines other nutrient levels (Girmay and Signh, 2012) , soil texture and soil structure, which influence organic carbon levels (Willis et al., 2007; Konen et al. 2003), bulk density, water holding capacity, and effective rooting depth.

Elevation

It has been shown that variations in soil organic carbon (SOC) stocks in the tropics can be predicted based on altitude (Dieleman et al., 2013; Andriamananjara et al. 2017; Sierra and Causeret, 2018). In a study conducted in 2013 by Dieleman et al. they determined that when SOC is corrected for the difference in bulk density between tropical forests and grasslands, forest soils are shown to contain more carbon. The disparity between SOC stocks found in forests and grasslands increases with elevation (Dieleman et al., 2013). This is important because soil organic matter is a contributor to increased nutrient availability, and overall soil fertility (Sierra and Causeret, 2018). The data provided by Dieleman et al. is particularly important considering tropical forests are more underrepresented as a biome in global datasets when compared to grasslands (Dieleman et al., 2013). Andriamanan et al. (2017) also discovered that soil organic matter in the topsoil of the tropics increases with altitude. A study by Sierra and Causeret (2018) on soil carbon in agricultural tropical volcanic soils also found that the relationship between SOC and altitude was significant. With more available nutrients and overall fertility at higher elevations, we can expect that higher elevations will provide more accommodating locations for restoration and increase success rates.

Epiphytic biomass is also greater at higher elevations, partially due to the increase in horizontal precipitation (Häger and Dohrenbusch, 2011). Epiphytes exist in arboreal Histosols which are made exclusively from plant debris originating from the canopy. In order to support epiphytes, there must be a canopy capable of providing enough debris inputs to generate an arboreal Histosol.

Species selection

In plantation and patch plantings, various species are selected for restoration. Species are selected for multiple reasons that depend on the goals of the restoration effort. According to a study conducted in Puerto Rico by Aide et al., (2000), it takes approximately 40 years for a forest system to naturally regenerate to a point at which it is comparable in structure to old growth. When the main goal is to reestablish a forest system quickly, promote biodiversity, and limit the extent of erosion, fast growing tree species are often preferred (Aide et al., 2000). In this case, they are not always native species. However, they can establish themselves at a pace quick enough to compete with and shade out grass species that prevent other species from germinating (Aide et al., 1995), (Aide et al., 2000).

In Costa Rica, *Pinus tecunumanii* has been used with success in more degraded pasture sites and is native to Central America, but not Costa Rica (Carpenter et al., 2004). The species can establish quickly, and has a high success (survivorship) rate as well. The other effective native pioneer species that is used is *Vochysia guatemalensis* which has an overall success rate slightly higher than *Pinus tecunumanii*, but is more effected by erosion than *Pinus tecunumanii* (Carpenter et al., 2004). In fact, *Pinus tecunumanii* is so effective at growing in degraded areas, it succeeds in locations where grasses cannot (Carpenter et al., 2004). *Terminalia Amazonia* (a native high value timber species) has been utilized in the past as climax hardwood species (Carpenter et al., 2004).

Pouteria reticulata is a species that has been used in restoration projects in Monteverde. It is a late successional species and is more often found in mature forests (Lozada et al., 2012). Since it is a late successional species, it may be better suited for sites that are further along in the restoration process. Another species used in restoration projects conducted by the Monteverde Institute is critically endangered. *Ocotea monteverdensis* which is endemic to the Costa Rica's Pacific slope exists only in the Montane tropical forests of Costa Rica (IUCN Red List of Threatened Species). Its current population numbers are not well known, although estimates suggest it is below 2,000 individuals (IUCN Red List of Threatened Species).

Microbial Communities

The soil system is home to numerous microorganisms, including fungi and bacteria species. These organisms have an impact on various soil properties and as a result, can have influence over the success rates of plants. In examining the difference in microbial communities between tropical pasture and forest soils in Costa Rica, it has been found that bacteria dominate pasture soil and fungal communities dominate forest soils (Eaton et al., 2010). This suggests that as soils become forested, the balance of microorganisms shifts to a fungi-dominated system. Another study conducted by Eaton et al. (2012) found that moister soils were dominated by fungi, and also possessed greater fungal diversity. This is explained by the relationship between moisture levels and organic matter decomposition. As moisture levels increase, organic matter stimulates microbial activity, microbial biomass development, and changes nutrient consumption (Eaton et al., 2012). Conversely, lower soil moisture will lead to detrimental impacts to the microbial community, decreasing organic matter accumulation, and leading to a soil more vulnerable to desiccation and erosional processes. Soils more exposed to sunlight and increased temperatures like in deforested areas will increase in temperature and exacerbate this process. Other, more recent studies contradict this premise, stating that warmer, moister soils are more dominated by bacterial communities (Zhou et al., 2017).

Erosion

Erosion is a primary factor controlling growth success of species, and subsequent overall restoration success. In Monteverde, there appears to be erosional transport of topsoil material from up-slope positions down to foot slope positions (Reuter, 2017). This is especially true at our site, Nacimiento. This loss of material from up-slope positions leaves a shallower depth to clay at those positions. This lessens the soil's effective rooting depth, soil organic carbon levels, and water holding capacity by removing organic rich tropical topsoil. Conversely, down-slope positions receive eroded material which generates the formation of root accommodating, soil carbon rich soils that can better retain water. Therefore, it is important to select species that will do well in areas that have been historically degraded through agricultural or pastoral practices. In addition, abandoned pasture is typically populated with early successional and highly competitive grass and shrub species.

Slope

There was no relationship between slope and SOC in a study examining this relationship in in-tact tropical forest and anthropogenic grasslands conducted by Dieleman et al., (2013). The development of individual trees has been shown to be independent of slope angle (Clark and Clark, 2000). Other studies have shown that there is a correlation between organic matter and landscape position. In areas that are downslope, there tends to be a greater accumulation of organic material due to transportation through runoff, or other erosional processes (Pennock and de Jong, 1990). Regarding surface runoff, slopes of less than 10% typically do not cause an issue (Birkel et al., 2012). While there may be conflicting studies about the direct relation between slope and soil organic matter accumulation, it is important to consider landscape position, as it relates to erosional processes and accumulation of organic material. Slope is likely a contributing factor to differences in soil properties.

The Catena

A catena refers to a sequence of soils along a slope gradient (Brady and Weil, 2010). Considering that topography is one of the soil forming factors, this concept is important to the study of soil property and landscape mapping. The catena theory holds that at different points along a slope, the soil will predictably change and those variations are the direct cause of slope driven factors such as erosion, drainage, and movement of chemical constituents (Seibert et al., 2007, Rosemary et al., 2017). They are useful when attempting to define the dynamic losses experienced by a soil system along a gradient (Huggett, 1975). Examining soils along a catena can also help identify the degree to which water has modified soil development and properties. In some soils, where a restrictive layer is present, water may be unable to infiltrate. In this case, water will move laterally in the form of "throughflow," (Huggett, 1975). Through soil development along a slope gradient, the catena explains that well drained soils will occur in up-slope locations, while more poorly drained soils will occur in down-slope locations or depressions. The catena concept will also be helpful for the project purposes because it also has potential to explain carbon levels based on topographic position, (Hook and Burke, 1999) with lower slope locations containing higher levels of carbon than adjacent locations with higher slopes. Catenas have long been used in pedology to investigate landscape trends and attempt to understand their relationships with different soil properties. I used the catena theory to structure my sampling methods in a way that captures these slope driven landscape trends.

Soil and Landscape Type

Forest structure in old growth rainforest systems change with landscape and soil type. A study conducted by Clark and Clark, (2000) examined forest structure variations in La Selva, Costa Rica. The study found that the largest trees were located in the flattest locations within the study areas. They also found that above-ground biomass (AGBM) is relatively unaffected by soil type and topography in upland locations (Clark and Clark, 2000). A Puerto Rico study by Johnson et al. (2011) found that SOC was higher at sites located on ridges when compared to sites located in valleys, which runs counter to what is typically envisioned when examining a catena. In that case, the soil depths were also deeper at the ridge sites due to their less disturbed state in comparison to the valley sites, many of which were long used for agriculture. Sites with alluvially-influenced soils have also been shown to harbor fewer and smaller trees, with lower basal area than sites at hill-tops, and on slopes (Clark and Clark, 2000). Clark and Clark (2000) were also able to show that Ultisols on steep slopes have higher stand density than on less steep slopes. The study acknowledges that soils composed of recent alluvium are more fertile than the Ultisols of old alluvium at their sites. They explain that a potential reason for the lower stand density at sites with recent alluvium may be effects of frequent flooding, which often results in low stem counts, basal area, and AGBM (Clark and Clark, 2000). Another study in the tropics of Indonesia examined the variability of biochemical soil properties across converted lowland landscapes (Allen et al. 2016). They found that inherent spatial variability of biochemical soil properties was a better indicator for nutrient stocks than land-use change. A study in Jamaica by McDonald et al. (2002) addressed the effects of clearing tropical forest on soil properties. They found the role of steep mountain hillslopes significant in instigating erosion of soil material within areas that were cleared of forest. They also found that agricultural cultivation did not have a significant relationship with erosion rates, but that the data were influenced by a high degree of spatial variability (McDonald et al., 2002). Studies investigating the relationship between landscape type and soil properties in the tropics indicate there is a degree of uncertainty in attempts to make linkages between these two factors.

Forested Soils vs. Pasture Soils

Establishment of pastureland in tropical rainforests in Costa Rica has led to changes in soil properties that can affect the soil's ability to support effective restoration. In pasture, saturated hydraulic conductivity was considerably lower compared to forested soils (Tobón et al., 2010). In general, forested soils have higher moisture, recharge capability, and infiltration rates than more compacted soils (Birkel et al., 2012). Conversion to pasture also lowers the soil's infiltration capability, lowers porosity, and increases density due to compaction (Tobón et al., 2010). These are all properties that affect the success rates of tropical forest restoration. For many tree species, high bulk density, low porosity, and poorly drained soils are properties that negatively impact their ability to establish and grow. High levels of compaction either from grazing cattle or agricultural machinery can also lead to increased overland flow and runoff potential. Soils in these agricultural fields or pasture clearings have higher potential for erosion than the forested soils. It should be noted however, that the creation of high bulk density in these soils from agricultural practices often only extends to about 25 cm below the soils surface.

Horizonation between forested and pasture soils differs as well. In pasture there is typically a thin O and B horizon, and distinct A and C horizons (Tanner et al., 2014). However, in secondary forest, O horizons are often thin, with distinct A and B horizons, followed by indistinct C horizons (Tanner et al., 2014). As for primary forest soils, an O horizon is mostly absent, with a distinct A and B horizon (Tanner et al., 2014). There are limitations to these results as the study only sampled to 30 cm and many of the soils in my sites are much deeper. The sites explored by Tanner et al. (2014) also dealt with sandy and gravelly soils which is not the case for all my sites.

Primary Forest vs. Secondary Forest

While secondary forests can establish themselves relatively quickly in the tropical regions of Costa Rica, biomass takes longer to reach levels comparable with primary forests. According to Nadkarni et al., (2004) aboveground terrestrially rooted biomass is higher in primary forests compared to secondary forests. A reason for this gap can be explained by the lack of development of epiphytic biomass in secondary forests. Older canopies often house epiphytes which, over time, produce their own canopy organic matter, sometimes referred to as “crown humus,” (Nadkarni et al., 2004). Within crown humus, dead organic matter (crown humus and dead leaves) makes up 60% of canopy organic matter in primary forests, compared to only trace amounts in secondary forests (Nadkarni et al., 2004). This is important because dead organic matter plays a critical role in providing habitat for invertebrates, birds, and other wildlife, as well as retention of atmospheric nutrients (Nadkarni et al., 2004). Tree diameters also vary between primary and secondary forest. In secondary forests, smaller diameter class trees dominate, whereas in primary forests, larger diameter class trees dominate (Nadkarni et al., 2004).

There is a disparity in carbon dioxide (CO_2) flux between primary and secondary forests. Secondary forest soils contain noticeably less soil carbon than mature forest soils, but still more than pasture soils (Tanner et al., 2014). In the study by Tanner et al., (2014) higher CO2 flux values were found in mature forests, but the mean flux for primary and secondary forests were not distinguishable. Evaluating carbon dynamics, deforestation makes up 23% of anthropogenic CO_2 inputs to the atmosphere (Melillo et al., 1996). Of that 23%, 75% comes from aboveground biomass loss and soil carbon loss accounts for the remaining 25% (Melillo et al., 1996). Soil carbon storage is most variable in secondary forest systems, whereas the upper soils of mature forest and pasture are more spatially consistent (Tanner et al., 2014). The upper portion of soils is most affected by carbon inputs over time, and increasingly stores more carbon as land surface age increases (Tanner et al., 2014). Secondary forest establishment can also be rapid and has potential to store significant amounts of carbon within as little as a decade (Schedlbauer and Kavanagh, 2008) and potentially up to two petagrams within a century (Nave et al., 2018). Secondary forests are still seen as a valuable resource for accumulating and storing carbon in a rapid manner (Hughes et al., 1999). The main issue with maintaining their effectiveness comes from their typical lack of continuity (Hughes et al., 1999).

Planting Strategies

Planting Styles : Patch Planting

There are multiple methods to facilitate forest recovery depending on prior land-use and the state of the area in question at the start of the restoration project. One method is patch planting. This involves planting tree seedlings in small patches throughout an area. These patches are expected to mature, and then expand over time as they begin to connect with other patches. Success rates of this method are similar to plantation style planting in studies that compare the two methods (Holl et al. 2011). However, success is also dependent on-site characteristics like the prevalence of soil nutrients.

Planting Styles : Plantation Planting

Plantation style planting involves large scale planting of trees in order to facilitate system restoration, and stimulate forest regrowth. It is not as widely implemented than some other planting styles largely due to its cost. Plantation style planting requires more resources than other planting methods because it is larger in scale and thus needs more manpower to implement. Furthermore, plots must be maintained, and monitored in addition to the initial cost of the plants themselves. Plantation style planting has its benefits however. In plantations, seedling height and canopy area are greater than in areas that utilize patch style planting methods (Holl et al., 2011). Efficient use of phosphorus is also higher within plantation systems compared to patch forest systems (Holl et al., 2011).

Planting Styles : Tree Seed Method / Remnant trees

Areas that have been cut for pasture are not always clear cut. In some circumstances, remnant trees are present, which can serve multiple important functions involved in the recovery of tropical forests. Remnant trees maintain immediate area soil stability, foraging cover, and nesting habitat for birds and can improve nutrient availability as compared to pastures that lack remnant trees (Rhoades et al., 1998). Their contribution to canopy cover is critical for the shading out of grasses which can facilitate germination and growth of tree saplings, and also lowers soil temperature, protecting from desiccation (Belsky et al., 1989). Remnant trees also disperse seeds, and subsequently have an impact on the composition of future forests following regeneration within its area of influence (Schlawin and Zahawi, 2008).

Canopy Epiphyte Seed Method

Seed banks in Costa Rica can hold seeds from thousands of different species. In Monteverde specifically, there are over 5,500 remnant trees from 190 different species present on 24 farms and pastures (Harvey and Haber, 1999). Seed banks can exist outside of a traditional soil system. In Costa Rica, canopy seed banks are found within arboreal Histosols, or soils that develop under epiphytic vegetation (Bohlrnan et al., 1995). As a result of the extremely wet conditions found in the tropical cloud forests of Costa Rica, epiphytic mats of vegetation in tree canopies are not uncommon. Those mats of vegetation play an important role in storing and distributing seeds. Epiphytic mats fall from the canopy, and decompose, which provides favorable conditions for stored seeds to germinate on the forest floor (Nadkarni and Haber, 2009).

Remnant trees that harbor arboreal Histosols are a critical component to the success of the tree seed method. Those same epiphytic mats contribute nutrients from litterfall, which enhance the survivorship of germinating trees (Nadkarni and Haber, 2009). The macronutrient concentrations found in canopy organic matter are similar to the macronutrient concentrations found in forest floor organic matter (Bohlrnan et al., 1995).

Natural Revegetation of Abandoned Pasture

Abandoned pastures in Costa Rica are common once an area's productivity begins to slow. Areas that used to be agricultural land but are now abandoned present a unique opportunity for scientists and those wishing to study succession in these communities. An added benefit to allowing natural reforestation is vegetation will be representative of an original component of the system.

Natural revegetation of abandoned pasture typically begins with the colonization and establishment of early successional shrubs. These plants are very effective at dispersing seeds, as well as shading out grasses in pasture communities (Holl et al., 2000). This is important to consider since a large proportion of Costa Rica's land has been converted to pasture (46% as of 2000) (Holl et al., 2000). That number has likely changed since then, but an understanding of scale is necessary when considering the most economically and functionally effective restoration methods. The shading out of grasses by shrubs is critical to make room in the system for tree seedlings. In fact, some consider pasture grasses to be the primary reason for low seedling survival rates (Holl et al. 2000).

Pasture sites attract a different community of organisms than a forest community. Rabbit herbivory is a primary contributor to low rates of seedling survival (Holl et al., 2000). Rabbits often feed on tree seedlings before they have a chance to establish, creating a difficult and competitive environment for tree regeneration that favors fast growing, and in some instances, less valuable tree species. In pastures without any remnant trees, the seed bank is continuously depleted as a result of germination and failed establishment of tree seedlings. Seed rain from neighboring forests and frugivore dispersal are the main natural methods by which seed banks can be replenished (Schlawin and Zahawi, 2008). Tree seed density is also much lower in pasture (21/m^2) than in neighboring secondary forests (402/m^2) according to a study by Wijdeven and Kuzee (2000). In that same study, they determined that 42% of woody species seedlings were consumed by predators.

Natural revegetation is further complicated by the fact that some sites have more degraded seed sources than others due to erosion and can also have poor seed dispersal. This process presents its own challenges, but time will eventually allow for the establishment of secondary forest communities.

The Relationship Between Soil and Landscape Properties

Attempting to test for correlation between landscape properties and soil properties is inherently tricky. No two sites are the same and every system is different. In a study in Pennsylvania that examined the relationship between slope and soil thickness of O, A, and E horizons in secondary forests, they found there was no correlation. They posited that the rate of soil development at their sites outpaced the rate of erosion (Carter and Ciolkosz, 1991). They also made the case that tree-throws, which were common in their study sites, might have contributed to the offsetting of gradient effects and their impacts on soil development and movement (Carter and Ciolkosz, 1991). Other studies have found that there are correlations between slope and soil erosion. Pennock and de Jong (1990) suggest that erosional processes have the greatest influence at shoulder positions, and the least amount of influence at footslope positions, contributing to the formation of thick A horizons in concave landscapes. A recent study examined the historic agriculturally driven changes to the carbon cycle, specifically looking at SOC. Wang et al., (2017) determined carbon burial rates have increased as a result of agricultural disturbance and erosion. Furthermore, SOC has not simply been transported, but has also formed protective complexes with minerals and stored long term. Therefore, historic erosion of SOC has led to a terrestrial C uptake (Wang et al., 2017).

Studies have examined the relationships between landscape properties like slope, and profile and plan curvature. Thompson et al. examined these relationships using a profile darkness index (PDI) as a method to measure the level of organic matter accumulation at specific locations along transects. The accumulation of organic matter in sloped landscapes is typically related to the profile curvature and water flow. As water flows downslope, material is carried from shoulder and upslope positions to the downslope positions in the landscape. The movement of water in catchment areas leads to different levels of wetness throughout a profile curvature. Wetness index has been used to measure the value of wetness at a specific location. Wetness index is typically found to be highest on hill-crests and in valleys, and lowest on steep slopes or in areas where water can drain freely (Moore et.al., 1993). Thompson et al. (1997)

found that PDI was greatest at downslope positions, in areas that had accumulated organic matter due to erosional processes and where moist conditions slowed decomposition. This supports the notion that erosion, coupled with slope and landscape position, will lead to the thickening of organic and A horizons at more concave landscape positions (Thompson et. al, 1997).

Considering my study location and the importance of data collection specific to my sites, scale was an important factor in conducting soil landscape analysis. In analyzing data and attempting to extrapolate information across landscapes using 100 m x 100 m grid sizes or larger change the information content for parameters like wetness index (Moore et al. 1993). Furthermore, scales of that size may smooth out surfaces, and subsequent data may not represent slopes, profile, and plan curvatures accurately.

Volcanic Influence on Soils

In the tropics, volcanic influence can have a profound impact on the characteristics of the soil and the landscape. Volcanically influenced soils have high porosity, small particle size, high water holding capacity, and low bulk density. In Costa Rica has experienced the effects of volcanic activity recently. An eruption has occurred as recently as 2010, however the last major eruption was in 1968, which blanketed the surrounding area and the Monteverde region (Volcano World, 2017). Therefore, it is important to consider the presence of andic properties at my sites.

Hypothesis and Objectives

Considering my understanding of the region and the complexity of landscapes in Costa Rica, I developed several research questions.

- "What are the relationships between soil properties and landscape factors on the Pacific Slope of Monteverde, Costa Rica?"
- "Can landscape attributes be used to explain variations in soil properties?"

We know based on accepted scientific theory that specific soil properties change with changes in slope. We also know that the tropics are a complex landscape which often yield different results for studies with similar objectives, leading to a degree of uncertainty when attempting to make conclusions. My main objective is to describe soil characteristics across multiple landscapes in the Monteverde region and attempt to explain variation in soil characteristics using landscape attributes. I believe that despite natural variation, soil properties such as carbon, depth to clay, and A horizon depth can vary predictably based on landscape position and slope. PDI will also be well correlated with slope and will be useful in understanding carbon dynamics at the landscape scale. Knowledge of the region coupled with preliminary research and communications with the Monteverde Institute helped us formulate my objectives for the project. Properties of importance for us are the depth to clay, slope, the thickness of the A horizon present, land use history, and percent carbon.

References

Aide, T. M. et al. 2013. Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). Biotropica 45 : 262 – 271.

Aide, T. M., J.K. Zimmerman, J.B. Pascarella, L. Rivera, H. Marcano-Vega. 2000. Forest Regeneration in a Chronosequence of Tropical Abandoned Pastures : Implications for Restoration Ecology. Restoration Ecology 8 : 328 – 338.

Aide, T.M., J.K. Zimmerman, L. Herrera, M. Rosario, M. Serrano. 1995. Forest recovery in abandoned tropical pastures in Puerto Rico. Forest Ecology and Management 77: 77 – 86.

Allen, K. M.D. Corre, S. Kurniawan, S.R. Utami, E. Veldkamp. 2016. Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia. Geoderma 284 : 42 - 50.

Andriamananjara, A. N Ranaivosonm T. Razafimbelo, J. Hewson, N. Ramifehiarivo, A. Rasolohery, R. H. Andrisoa, M.A. Razafindrakoto, M. P. Razafimanantsoa, N. Rabetokotany, and R.H. Razakamanarivo. 2017. Towards a better understanding of soil organic carbon variation in Madagascar. European Jmynal of Soil Science 68 : 930 – 940.

Belsky, A.J., R.G. Amundson, J.M. Duxbury, S.J. Riha, A.R. Ali, and S.M. Mwonga. 1989. The Effects of Trees on Their Physical, Chemical and Biological Environments in a Semi-Arid Savanna in Kenya. Jmynal of Applied Ecology 26 : 1005 – 1024.

Birkel, C., C. Soulsby, D. Tetzlaff. 2012. Modelling the impacts of land-cover change on streamflow dynamics of a tropical rainforest headwater catchment. Hydrological Sciences 57: 1543 – 1561.

Bohlrnan S.A., T. J. Matelson, N.M. Nadkarni. 1995. Moisture and Temperature Patterns of Canopy Humus and Forest Floor Soil of a Montane Cloud Forest, Costa Rica. Biotropica 27 : 13 – 19.

Brady N.C. and R.R. Weil. 2010. Elements of the Nature and Properties of Soils, 3rd Edition. Prentice Hall, San Fransisco, CA.

De Camino, R, O Segura, LG Arias, and I Pérez. 2000. Costa Rica: Forest Strategy and the Evolution of Land Use. Evaluation Country Case Study Series. The World Bank, Washington, D.C.

Carpenter, F.L., J.D. Nichols, and E. Sandi. 2004. Early growth of native and exotic trees planted on degraded tropical pasture. Forest Ecology and Management 196: 367-378.

Carter, J.B., and E.J. Ciolkosz. 1991. Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. Geoderma 49: 199-213.

Clark, D.B. D.A. Clark. 2000. Landscape – scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137 : 185 – 198.

Dieleman, W.I.J., M. Venter, A. Ramachandra, A.K. Krockenberger, M.I. Bird. 2013. Soil carbon stocks vary predictably with altitude in tropical forests : Implications for soil carbon storage. Geoderma 204 – 205 : 59 – 67.

Eaton, W.D., M. Roed, O. Chassot & D. Barry. 2012. Differences in soil moisture, nutrients and the microbial community between forests on the upper Pacific and Caribbean slopes at Monteverde, Cordillera de Tilaran: implications for responses to climate change. Tropical Ecology 53(2): 235-240.

Eaton, W.D. 2010. Microbial Community Indicators of Soil Development in Tropical Secondary Forests (Costa Rica). Ecological Restoration 23 : 236 – 238.

Food And Agriculture Organization of the United Nations. 2010. Global Forest Resources Assessment 2010: Main report. FAO Forestry Paper 163. United Nations.

Girmay, G., B.R. Singh. 2012. Changes in soil organic carbon stocks and soil quality : land-use system effects in northern Ethiopia. 62 : 519 – 530.

Häger, A., A. Dohrenbusch. 2011. Hydrometeorology and structure of tropical montane cloud forests under contrasting biophysical conditions in north-western Costa Rica. Hydrological Processes 25 : 392 – 410.

Harvey, C., and W. Haber. 1999. Remnant trees and the Conservation of Biodiversity in Costa Rican pastures. Agroforestry Systems 44 : 37 – 68.

Holl, K. D., Zahawi, R. A., Cole, R. J., Ostertag, R., & Cordell, S. 2011. Planting Seedlings in Tree Islands Versus Plantations as a Large-Scale Tropical Forest Restoration Strategy. Restoration Ecology, 19(4), 470-479.

Hook P.B. and I.G. Burke. 1999. Biogeochemistry in a Shortgrass Landscape: Control by Topography, Soil Texture, and Microclimate. Ecology 81(10) : 2686 – 2703.

Honey, M. 2008. Ecotourism and Sustainable Development : Who Owns Paradise? Second edition. Island Press. Washington D.C.

Huggett, R.J. 1976. Soil Landscape Systems : A Model of Soil Genesis. Geoderma 13 : 1 – 22.

Hughes R. F. J. B. Kauffman, V.J. Jaramillo. 1999. Biomass, Carbon, and Nutrient Dynamics of Secondary Forests in a Humid Tropical Region of Mexico. Ecology 80 : 1892 – 1907.

IUCN Red List of Threatened Species. Ocotea monteverdensis. http://www.iucnredlist.org/details/full/48724260/0, accessed 5/2/18.

Jobbágy E.G., and R.B. Jackson. 2001. The Distribution of Soil Nutrients with Depth: Global Patterns and the Imprint of Plants. Biogeochemistry 53: 51-77.

Johnson K.D., F.N Scatena, W.L. Silver. 2011. Atypical soil carbon distribution across a tropical steepland forest catena. Catena 87 : 391 – 397.

Konen, M.E., C.L. Burras, J.A. Sandor. 2003. Organic Carbon, Texture, and Quantitative Color Measurement Relationships for Cultivated Soils in North Central Iowa. Soil Science Society of America 67 : 1823-1830.

Leopold, A.C. 2005. Toward Restoration of a Wet Tropical Forest in Costa Rica : A Ten-Year Report. Ecological Restoration. 23 : 230 – 234.

Lozada, J.R., E. Arends, D. Sanchez, A. Villarreal, P. Soriano, M. Costa. 2012. Vegetation Succession of Logged Forest in the Western Alluvial Plains of Venezuela. Journal of Tropical Forest Science 24 (3) : 300 – 311.

Melillo, J.M, R.A. Houghten, D.W. Kicklighter, A.D. McGuire. 1996. Tropical Deforestation and the Global Carbon Budget. Annual Review of Energy and the Environment 21 (1) : 293 – 310.

Menkhaus, S. D.J. Lober. 1995. International Ecotourism and the Valuation of Tropical Rainforests in Costa Rica. Jmynal of Environmental Management. 47: 1-10.

McDonald, M.A., J.R. Healey, P.A. Stevens. 2002. The effects of secondary forest clearance and subsequent land-use on erosion losses and soil properties in the Blue Mountains of Jamaica. Agriculture, Ecosystems and Environment 92 : 1 – 19.

Montagnini, F. 2008. Management for Sustainability and Restoration of Degraded Pastures in the Neotropics. In: RW Myster (ed) Post Agricultural Succession in the Neotropics. Springer. New York.

Moore, I.D., A. Lewis, J.C. Gallant. 1993. Terrain Attributes : Estimation Methods and Scale Effects. In : Modelling Change in Environmental Systems. John Wiley & Sons Ltd. 1 – 26.

Nadkarni, N.M., W.A. Haber. 2009. Canopy Seed Banks as Time Capsules of Biodiversity in Pasture-Remnant Tree Crowns. Conservation Biology. 23 : 1117 – 1126.

Nadkarni, N.M., D. Schaefer, T.J. Matelson, R. Solano. 2004. Biomass and nutrient pools of canopy and terrestrial components in a primary and a secondary montane cloud forest, Costa Rica. Forest Ecology and Management 198 : 223 – 236.

Nave, L.E., G.M. Domke, K.L. Hofmeister, U. Mishra, C.H. Perry, B.F. Walters, C.W. Swanston. Reforestation can sequester two petagrams of carbon in US topsoils in a century. Proceedings of the National Academy of Sciences 115(11): 2776-2781.

Pennock, D.J and E. De Jong. 1990. Regional and Catenary Variations in Properties of Borolls of Southern Saskatchewan, Canada. Soil Science Society of America 54: 1697 – 1701.

Ray, D. K., S. N. Udaysankar, R.O. Lawton, R. M. Welch, R. A. Pielke Sr. 2006. Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of orographic cloud formation to deforestation in the plains. Jmynal of Geophysical Research 111: 1 – 16.

Reuter, R. 2017. Soil and tropical forest restoration, Costa Rica: project proposal. Oregon State University. 1-5.

Rhoades, C.C., G.E. Eckert, D.C. Coleman. 1998. Effect of Pasture Trees on Soil Nitrogen and Organic Matter: Implications for Tropical Montane Forest Restoration. Restoration Ecology 6 : 262 – 270.

Rosemary F., U.W.A. Vitharana. S.P. Indraratne, R. Weerasooriya., U. Mishra. 2017. Exploring the spatial variability of soil properties in an Alfisol soil catena. Catena 150 : 53 – 61.

Sanchez-Azofeifa, G.A., Pfaff, A., Robalino, J.A., Boomhower, J.P. 2007. Costa Rica's Payment for Environmental Services Program: Intention, Implementation, and Impact. Conservation Biology. 21 (5): 1165 – 1173.

Schedlbauer, J.L., K.L. Kavanagh. 2008. Soil carbon dynamics in a chronosequence of secondary forests in northeastern Costa Rica. Forest Ecology and Management 255 : 1326 – 1335.

Schlawin, J. R.A. Zahawi. 2008. "Nucleating" succession in recovering neotropical wet forests: The legacy of remnant trees. Jmynal of Vegetation Science 19 : 485 – 492.

Seibert J., J. Stendahl, R. Sorensen. 2007. Topographical influences on soil properties in boreal forests. Geoderma 141 : 139 – 148.

Sheldon, K.S. and N.M. Nadkarni. 2013. The use of pasture trees by birds in a tropical montane landscape in Monteverde, Costa Rica. Jmynal of Tropical Ecology 29: 459 – 462.

Sierra, J. and F. Causeret. 2018. Changes in soil carbon inputs and outputs along a tropical altitudinal gradient of volcanic soils under intensive agriculture. Goederma 320 : 95 – 104.

Spracklen, B.D., M. Kalamandeen, D. Galbraith, E. Gloor, D.V. Spracklen. 2015. A Global Analysis of Deforestation in Moist Tropical Forest Protected Areas. Plos One : 1 – 16.

Tanner, L.H., D.L. Smith, J. Curry, J. Twist. 2014. Effect of Land Use Change on Carbon Content and CO_2 Flux of Cloud Forest Soils, Santa Elena, Costa Rica. Open Jmynal of Soil Science 4 : 64 – 71.

Tobón, C., L.A. Bruinjnzeel, K.F.A. Frumau, J.C. Calvo-Alvarado. 2010. Changes in soil physical properties after conversion of tropical montane cloud forest to pasture in northern Costa Rica. Tropical Montane Cloud Forests : Science for Conservation and Management. Cambridge University Press : 502 – 515.

Thompson, J. A., J.C. Bell, C.A. Butler. 1997. Quantitative Soil-Landscape Modeling for Estimating the Areal Extent of Hydromorphic Soils. Soil Science Society of America 61 : 971 – 980.

Volcano World. 2017. Arenal. Oregon State University. http://volcano.oregonstate.edu/arenal. Accessed 12/28/17.

Wang, Z., T. Hoffman, J. Six, J.O. Kaplan, G. Grovers, S. Doetteri, & K.V. Oost. 2017. Human-induced erosion has offset one-third of carbon emissions from land cover change. Nature Climate Change 7 : 345-349.

Wheelwright, N.T. 1983. Fruits and the Ecology of Resplendent Quetzals. American Ornithological Society 100: 286 - 301.

Willis, S.A., C.L. Burras, J.A. Sandor. 2007. Prediction of Soil Organic Carbon Content Using Field and Laboratory Measurements of Soil Color. Soil Science Society of America 71 : 380-388.

Wijdeven, S.J. and M.E. Kuzee. 2000. Seed availability as a limiting factor in forest recovery processes in Costa Rica. Restoration Ecology 8 : 414-424.

Zhou, W.P., W.J. Shen, Y.E. Li, D.F. Hui. 2017. Interactive Effects of Temperature and Moisture on Composition of the Soil Microbial Community. European Journal of Soil Science 68: 909-918.

Chapter 2 : Project Planning and Execution

Introduction

Deforestation continues at an alarming rate across the world. Costa Rica has instituted programs to reverse the impacts of deforestation by regenerating tropical forest. In recent years, Costa Rica has been a leader in tropical forest restoration. In the 1990's government programs like Payment for Ecosystem Services (PES) and Reducing Emissions from Deforestation and Forest Degradation (REDD+) were created in Costa Rica. These programs have led to an increase in localized restoration efforts through economic incentive to landowners (Sanchez-Azofeifa, et al., 2007).

Tropical forest restoration in Costa Rica has seen mixed success. On the Pacific slope of Monteverde, there have been efforts to restore tropical forest on pasture and agricultural land. The Monteverde Institute has been involved with these projects in recent years and has begun record keeping for their various sites in order to better document tree survivorship and overall restoration success rates. Success rates for tropical forest restoration in Monteverde, Costa Rica range from 0% to 94% tree survivorship (Debra Hamilton, personal communication, February 11, 2018). This is an issue for the region as Costa Rica relies heavily on eco-tourism for income, especially the Monteverde region. Restoration of the tropical forest in other parts of the country has been able to not only restore the forest, but also encourage the return of charismatic wildlife such as the quetzal and bell bird. Restoration of these forests also helps to prevent and mitigate future erosional events that can devastate these communities that live on such steep slopes, causing the destruction of infrastructure and threats to the wellbeing of the local environment.

Soil-landscape relationships may explain reasons for high and low tree survivorship. Landscape position can be used as a predictor of certain soil properties including soil thickness, soil carbon, and plant available water (Moore et al., 1993; Pennock and de Jong 1990; Thompson et. al, 1997). Factors like thickness of soil, soil carbon content, and plant available water will determine the ability of plants to establish roots and grow and maintain nutrient needs. The catena concept suggests that down-slope positions (lower backslope, footslope) will have thicker topsoil and a deeper depth to clay because of erosional movements and soil development (Hugget, 1975). Conversely, positions that are up-slope (upper backslope, shoulder) will have generally thinner soils and a shallower depth to clay, with less water available for plants, with summit positions exhibiting more stable soils.

My study objectives were to describe soil characteristics across multiple landscapes in the Monteverde region and attempt to explain variation in soil characteristics using landscape attributes. My hypotheses are soil properties which are important for plant growth such as carbon, depth to clay, and A horizon thickness can vary predictably based on landscape position and slope. Higher landscape positions will yield lower levels of carbon, shallower depths to clay, and thinner A horizons, while lower landscape positions will yield higher levels of carbon, deeper depths to clay, and thicker A horizons. PDI will also be well correlated with slope and will be useful in understanding carbon dynamics at the landscape scale.

Materials and Methods

Site Description

The Monteverde Region of Costa Rica is located in the northern section of the Cordillera de Talamanca (Talamanca Mountains) and straddles the provinces of Guanacaste and Punta Arenas. The principal towns of the region are Santa Elena, Monteverde, and San Luis. The overall study area ranges from elevations of ~1500 m to 1100 m, largely in the Premontane Wet Forest life zone (Tropical Scientific Center, "Ecological Map of Costa Rican Life Zones”). The region receives 240.3 cm of rainfall annually and mean annual high and low temperatures of 20.4 and 13.6 °C, respectively (Johnson et al., 2005).

The higher elevations and Caribbean slope of the region contain protected forest areas.

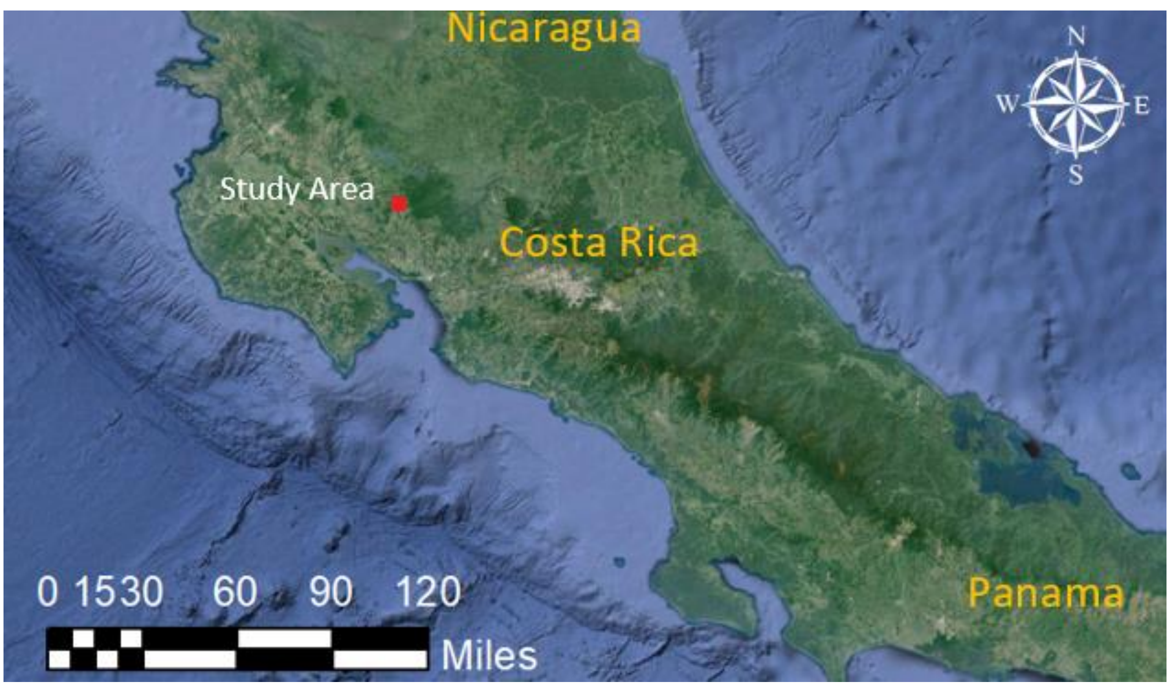


Figure 2. Satellite iamge map of Costa Rica with the study area.

The Pacific Slope, where this study is located, was historically forested, but post

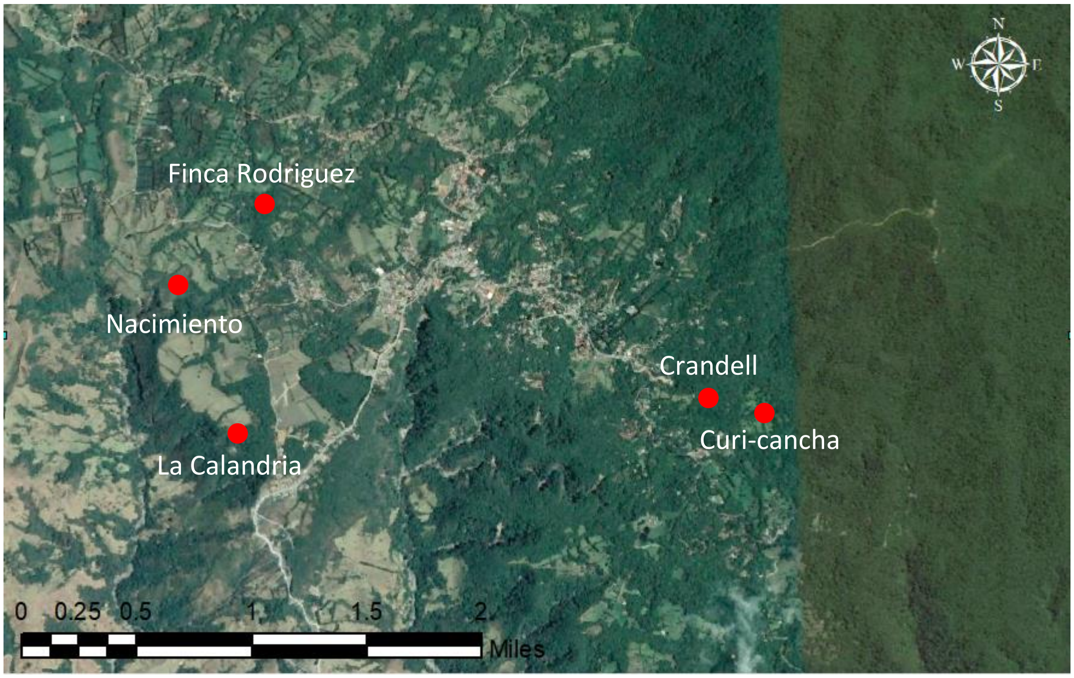


Figure 3. Satellite image map of the region in which we sampled, indicating study sites.

European settlement, land was cleared for timber and developed for agriculture, including coffee and grazing land. For this study, five sites were investigated (Figure 2, 3) for soil and landscape attributes. These sites were chosen for their variation in land use and slope characteristics. The sites are: Nacimiento y Vida, Crandell, Curi-cancha, La Calandria, and Finca Rodriguez.

Nacimiento y Vida (referred to as Nacimiento):

Nacimiento is a large site which consists of active and restored pasture and is located on the western side of Santa Elena at an elevation of about 1200 m. The active pasture is virtually void of trees and is dominated by grasses. The restored pasture is a space comparable in size to the active pasture and is dominated by trees and shrubs. Restoration has been conducted here during the past decade by the Monteverde Institute. Vegetation in the restored pasture is much more varied and the canopy, while not full, provides shade and lower temperatures compared to the active pasture area. Slopes on the site range from 1.7 to 27.9 slope degrees. The overall aspect is south west and pits were excavated at the footslope, backslope, and shoulder positions. Point sampling was concentrated along the slope profile as well as in close proximity to the soil pits.

Finca Rodriguez:

Finca Rodriguez at an average elevation of 1260 m is located north of Nacimiento, on the west side of Santa Elena and is also still used for agriculture in certain areas. The site has undergone forest restoration efforts for several years and vegetation there is the most dense of any of the restored sites we visited. The vegetation is predominantly composed of older trees, with younger trees and shrubs also present. The canopy provides cover from the sun and keeps temperatures here cooler. Slopes range from 1 to 20 degrees. The pit was sampled at a footslope location along a central slope transect that extended though the property. Point sampling was also concentrated along this slope profile as well as in the area around the soil pit.

Curi Cancha:

Curi Cancha is an ecological reserve that was purchased in 1970 by the Lowther family and allowed to mostly regrow without any cutting or manipulation (Reserva Curi-cancha, 2017). In 1997, the reserve was designated as a reserve and has been undergoing restoration from pasture to forest (Reserva Curi-cancha, 2017). It is located east of Crandell on the eastern side of Monteverde at an elevation of 1460 m. The reserve is a large area, but our permitted sampling area was limited to the restored pasture and part of the in-tact forest that remains in the southern portion of that area. The restored pasture is dominated by tall grasses and shrubs, with older trees also dispersed throughout. The in-tact forest is dominated by older, mature trees. The site is characterized by an undulating uneven surface extending across sloped surfaces. Slopes on the site range from 6 to 17 slope degrees. The pit first was chosen based on its location at the footslope of a central slope profile in the restored pasture. The second pit was selected based on its location in the in-tact forest south of the pasture. Point sampling was conducted by concentrating on capturing soil variability across the slope profile. This was made difficult by the sites undulating nature as well as thick masses of vegetation which prevented sampling.

Crandell:

Crandell is a smaller site located on the eastern side of Monteverde on the property of the Monteverde Institute with an elevation of 1460 m. It is formally pasture and has also undergone restoration for several years, with windbreak trees still present at the site. Vegetation at the site is more dense than other sites like Nacimiento and Curi-cancha's pasture, with larger trees and a fuller canopy which keeps the temperature in the area cooler. It is dominated by older trees, with some younger saplings and shrubs as well. The site is generally low-sloping ranging from 2 to 16 slope degrees. The landscape here is less complex than sites like Nacimiento and Curi-cancha. The pit was chosen based on its location at a footslope. Point sampling was conducted by sampling the area in close proximity to the pit the site's gentle slope profile.

La Calandria:

La Calandria is a site that has also undergone restoration in the recent past and is currently used as a private biological reserve. It was purchased by Research and Preservation for Costa Rica in 1999 and is managed by the Costa Rican Conservation Foundation (Debra Hamilton, personal communication, January 30, 2018) and derives its name from the Spanish word for the three-wattled bellbird (*Procnias tricarunculatus)*. It is located south west of Santa Elena at an elevation of 1230 m. The site is a fairly large in comparaison to Nacimiento and can essentially be divided into two sections, east and west. The west side has undergone restoration for a longer period than the east side. These differences have led to a disparity in overall success and aesthetics of each section. Unfortunately, exact details on the restoration history of the two portions of the site are unavailable. La Calandria is dominated by younger trees, with some older trees and shrubs present. The site is generally low sloping with slopes ranging from 2 to 34 slope degrees, although most slope measurements were below 10 slope degrees. Pit sampling was conducted by sampling the shoulder and point sampling was concentrated around the pits as well as further downslope to capture soil property changes at the foot-slope position.

Soils:

Pit Location and Point sampling

For each site, the overall landscape was evaluated to identify key attributes that might be associated with distinct soil variations, such as slope profile (e.g. shoulder, backslope, footslope) and exploratory soil auger holes were conducted to assess this. Representative positions that captured soil variation were then selected for full soil pit excavation. Landscape complexity at each site, as well as accessibility, dictated the number of pits excavated and the subsequent landscape auger sampling (Table 1).

Site	Number of Pits	Slope Position(s)	# of Auger Samples	Landuse(s)
Nacimiento	3	Footslope, backslope, and shoulder	70	Reforested pasture and active pasture
Crandell	1	Footslope	32	Reforested pasture
Curicancha	2	Footslope	33	Reforested pasture and in-tact forest
La Calandria	2	Shoulder	35	Reforested farmland and pasture
Finca Rodriguez	1	Footslope	30	Resforested farmland

Table 1. Sites sampled with their respective numbers of pits and auger samples, as well as the pit slope positions and site land-use.

The original ideal sampling design included soil profiles at the shoulder, backslope, and footslope positions. Each site presented unique constrains and landforms, resulting in adjustments to soil pit locations and quantity. Time in country also limited an exhaustive sampling regime.

Soil Profile Descriptions

Horizons were broken down based on physical differences like structure, texture, and color. Horizon depths, boundaries, moist color, resistivity, percent clay, and roots were also recorded following NRCS methodology (Schoeneberger et al. 2012). Slope and elevation information were recorded along with GPS coordinates. The sites I visited were all located in Guanacaste Province (Figure 2). Samples were collected from the horizon groups by sampling across the width and depth of the pit to select a representative sample from each group. Samples were bagged and stored in a refrigerator at the Monteverde Institute's lab until shipment to the analysis lab. My main concern in my investigations was the depth of the A horizon (normally found at the surface of the profile) and the depth to root restrictive clay (present throughout the region). At some pit locations, there were more than a single A (A1 and A2 or an AB). Therefore, I sampled on a lumpers scale and grouped horizons as necessary to capture the entirety of the A horizon and the respective underlying horizons as well as the root restrictive clay itself.

Soil Point Samples

Probing locations were selected to capture expected soil-landscape variations (e.g. concave-concave or convex-linear profile-plan landscape positions). Point sampling allows for more rapid sampling than a soil pit and can provide more broad scale landscape information. Using soil push probes with a 1.75 cm diameter and a 6.4 cm open faced soil auger, soil color was measured at about 20 cm using the Munsell color system. Soils were sampled to contact with the characteristic red clay-rich B horizon or to a restriction, typically saprolite or more intact rock. A and B horizon depths and Munsell colors, slope, and GPS location were recorded. Two separate point sampling crews worked on collecting samples to provide soil-landscape information throughout the site.

Soil Pit Properties

Soil Color and Texture

Color was measured in the field using a Munsell color book. I decided to only measure moist color because the field conditions were wet which made it difficult to measure dry color. Blacker colors (lower value and chroma) indicate greater concentrations of organic material. In my study region, more red colors indicate higher concentrations of clay material.

Texture was measured in the field following the guidelines set by USDA-NRCS for the texture by hand method (Schoeneberger et al., 2012).

Structure and Roots

Structure was measured in the field following the guidelines set by USDA-NRCS for identifying the type, grade, and size of soil structure (Schoeneberger et al., 2012). Abundance and size of roots were recorded.

Resistivity

Resistivity was measured using a model H-4195 pocket penetrometer (Humboldt Manufacturing). Resistivity measurements were taken in sets of 3 for each horizon. The average was then taken and recorded. Holes and areas that were visually structurally compromised were avoided as to help prevent an inaccurate measurement form being recorded. The penetrometer was pressed until the line on the probe end met with the soil pit face. The resistivity was then read (measurements were taken in .025 kg/cm^2). The penetrometer can measure up to 4.5 kg/cm^2. There is no calibration needed and the device measurement errors can range from 0 – 0.121 kg/cm^2. High measurements indicate more dense material, while lower measurements indicate a less dense material.

Lab analysis

Soil samples were sent to the CATIE lab for nutrient analysis, pH, and particle size analysis. Lab analysis by CATIE provided a more detailed and accurate analysis of texture using the hydrometer method for particle size analysis (Gee and Bauder, 1986) as well as nutrient levels for pit samples.

Carbon and Nitrogen

Total percent carbon measurements were conducted using the total combustion method. A ThermoFinigan FlashEA 1112 carbon and nitrogen autoanalyzer was used. One hundred grams of homogenized and soil sample was dried at 40° C and sieved with a 2mm sieve. A subsample of 30 to 40 mg was taken and sieved with a 0.250 mm sieve for analysis in the autoanalyzer.

pH

pH was measured by using the 1:1 soil and water method using a calibrated electrode following the procedure outlined in the USDA Soil Survey Laboratory Methods Manual (2004). Measurements were recorded to the nearest .01 pH unit.

Copper, Zinc, Manganese, Iron, and Potassium

These elements were measured using the Olsen modified pH 8.5 method (Olsen et al., 1954). Samples were dried at 40° C and sieved with a 2 mm sieve. Subsamples of 2.5 g were taken and stirred into the modified Olsen reagent for 10 minutes in a shaker at 400 rpm. The sample was subsequently filtered through Whatman #2 paper. Measurements for Cu, Zn, Mn, Fe, and K were made on the filtrate using an atomic absorption spectrometer.

Phosphorus

Measurement of P was conducted using the colorimetric method. After measurements for Cu, Zn, Mn, Fe, and K, 2 ml of the sample was diluted with 10 ml of Ammonium molybdate and 8 ml of diluted stannous chloride. A calibration curve was made with concentrations of P at 0.25, 0.5, 1.00, 2.00, and 4.00 mg/L in Olsen reagent from 100 mg / L of P. Once the sample color changed to the same color as the previous samples, absorbance was read in a colorimeter at 660 nm. Between 7 and 20 minutes were given for the chemical reactions in the sample come into equilibrium. Samples were subsequently analyzed in a colorimeter.

Calcium and Magnesium

Potassium Chloride extraction was used to measure Ca and Mg. Soil samples of 2.5 g were air dried at 40° C and sieved with a 2 mm sieve. Samples were administered 25 ml of 1 N KCI and stirred for 10 minutes in a shaker at 440 rpm. The sample was subsequently filtered through Whattman # 2 filter paper and filtrate was saved. Then 9 ml of distilled water and 15 ml of Lantano Oxide were added to 1 ml of filtrate. A calibration curve for Ca with concentrations of 1.00, 2.00, 4.00 mg/L. was prepared in 1 N KCI. Another calibration curve for

Mg was made with concentrations of 0.1, 0.25, and 0.5 mg/L. Subsequently, 10 ml of 1 N KCI was diluted with distilled water and 2 drops of phenolphthalein were added. Titration was used until the color changed from colorless to pale pink and held color for 15 seconds.

Soil-Landscape Analysis

Redness Rating and Profile Darkness Index

Carbon dynamics at the landscape scale are particularly important to the project and as a result it became clear that a method to measure soil carbon for my probe data was needed. PDI or "Profile Darkness Index" was developed by Thompson and Bell (1996) to measure the darkness of soil samples. It is measured using the following formula :

$$PDI = \sum_{i=1}^{n} \frac{(A\ horizon\ thickness)}{(V_i * C_i) + 1}$$

where V is Munsell value, moist, and C is Munsell chroma, moist.

The primary purpose of the index is to act as a proxy for soil carbon and thus allow for rapid, large-scale, and inexpensive analysis of soil carbon dynamics. PDI was calculated for my probe sample data and mapped to assist in expanding my understanding of soil carbon dynamics at my sites.

PDI was developed and used in a glacial till landscape in the northern Midwestern U.S. Parent mineralogy is decidedly mafic and degree of soil development is low due to a cold climate and short time window of 12,000 years post glaciation. PDI was developed for this landscape because other color indices were not effective in describing landscape soil distributions. The Redness Rating (RR), which served as a base to develop PDI, was developed for soils in a more developed landscape, where iron oxides are more prevalent in soil profiles (Torrent et al., 1980, 1983). RR is calculated as:

$$RR = (H) * (\frac{C}{V})$$

Where H is Munsell hue (in the red spectrum), moist, C is Munsell chroma, moist, and V is Munsell value, moist. Thompson and Bell (1996) altered the RR to account for a wider range of hues. I used this modified version because we observed subsoil colors outside of the red spectrum (e.g. 7.5 YR). The modified RR is:

$$RR = (45 - H) * (\frac{C}{V})$$

Statistical Analysis

Statistical analysis was conducted using R and Microsoft Excel. the objectives of the data analysis was to explore the soils and landscape relationships using linear regression and descriptive statistics.

Due to the sampling scheme, which was purposeful rather than random, and the distinctly different site histories and soil geomorphologies, I made the decision to focus on linear regression and descriptive statistics. This makes sense for the project because it allowed us to analyze sites individually. It was important for us to recognize the limitations of the data and to adapt my statistical methods to match the nature of my data as well as the goals of the overall project.

Results and Discussion

Sites

Field work took place over the course of seven days. Nacimiento was the first site visited and was the original impetus for this study. Pre-study visits to the site suggested soil-landscape relationships that fit the classic toposequence concept, especially for a landscape that has been deforested, converted to pasture, and had significant slopewash erosion. Reforestation efforts had strong success in the overthickened footslopes and were weak in the degraded backslope and shoulder slopes. For the study, it was expected that all five sites would have similar stories. Analysis showed that our study sites were all different.

<u>Nacimiento</u>

At Nacimiento, a total of 70 point samples were recorded and three pits described. Nacimiento had the most evident relationship between A horizon thickness and slope degrees (Figure 4). At Nacimiento, as slope degrees increases, A horizon thickness decreases. Also evident is that as slope increases, the depth to root restrictive clay decreases (Figure 5). This likely has much to do with land use history. After the native forest was removed, Nacimiento was over-grazed pasture (Debra Hamilton, personal communication, January, 2018). This

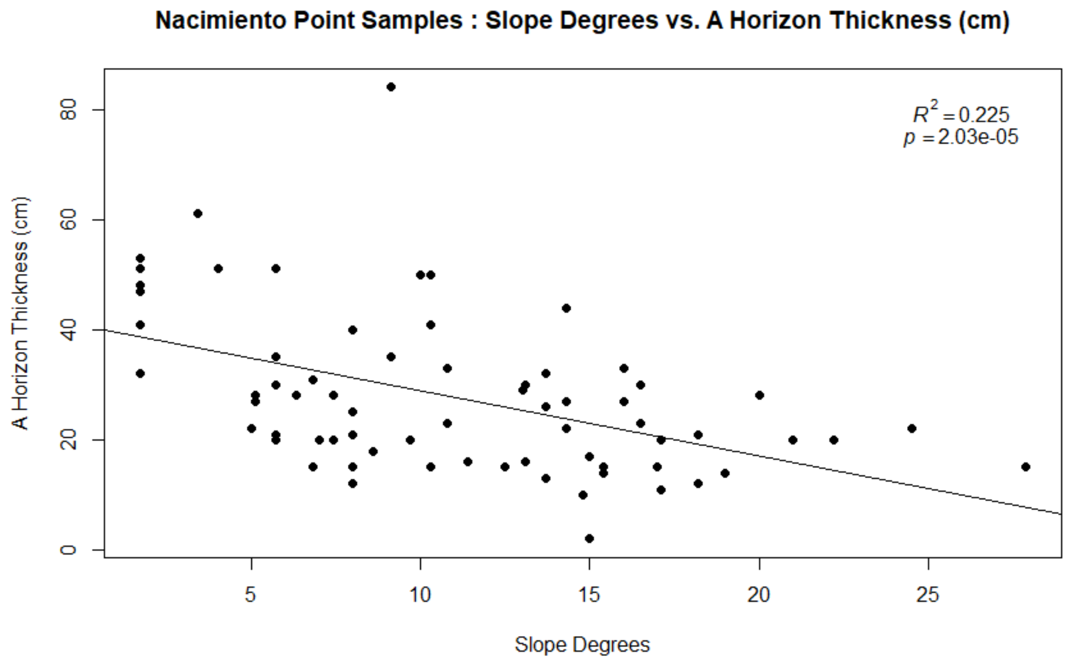


Figure 4. Point samples from Nacimiento with a simple linear regression line displaying the relationship between Slope Degrees and A Horizon Depth (cm).

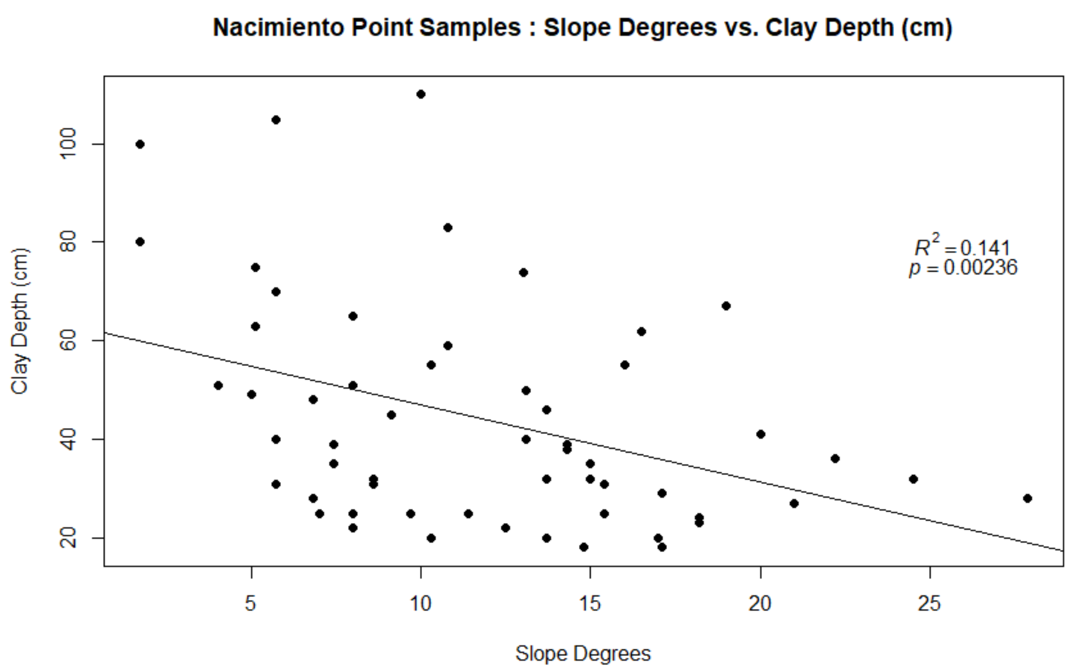


Figure 5. Point samples from Nacimiento with a simple linear regression line displaying the relationship between Slope Degrees and depth to clay (cm).

intensive land use change caused erosional issues as there was no root system to hold the soil intact. In addition, the upper soil parent material is derived from volcanic ash and tuff which is low in weight and density and is susceptible to wind and water erosion. Because of these past management practices one can see that there has been movement of material to the footslope (with a slope of 4 degrees) by comparing with the locations of the second and third pits at the back slope (with a slope of 17 degrees) and shoulder (with a slope of 11 degrees) respectively (Figure 6). Because of the soil-landscape variations present at Nacimeinto, it follows classic soil geomorphological theory and represents a catena well.

Figure 6. Displaying Nacimiento's footslope (left), backslope (center), and shoulder (right).

Nacimiento's Pits

The pits dug at Nacimiento show an obvious contrast between three different slope positions: footslope, backslope, and shoulder. At the shoulder, clay content increased markedly between the upper two horizons and the third Bt horizon. The percent carbon in each horizon decreased with depth as did percent sand. Resistivity and pH also increased with depth.

The 109 cm pit dug at the footslope position at Nacimiento revealed the culmination of years of soil erosion downslope (Table 2). The horizonation in this pit was more complicated than the other two due to the land use history of the site. Contact with the root restrictive clay layer was not made until 120+ cm. The percent carbon remained similar to 98 cm, where it then began to decrease. Clay content was also low in the first 3 groups and increased sharply in groups 4 and 5. This pit presents an example of the accumulation of material from up-slope positions, thickening the upper portions of the soil and influencing clay content and percent carbon.

Table 2. Pit data for the footslope pit at Nacimiento. pH, % Organic Carbon (OC) and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A1	0-24	N20	SL	1.5	6.3	6.94	69.3, 3.4
A2	24-45	N20	SL	1.75			
BC	45-65	10YR2/1	SL	4.5	6.4	6.12	69.3, 6.1
C	65-89	10YR3/1	SL	4.5+			
Ab	89-98	N20	L	2.5	6.3	6.13	56.8, 5.9
Bwb	98-109	7.5YR5/3	L	3.25	6.4	2.94	51.8, 37.2
2Bt	109-120+		CL		6.4	1.42	31.8, 41.2

At the backslope, clay content increased with depth, with the Bt horizon reaching the highest percent clay of any of the pits at Nacimiento (Table 3). Similar to the soil from the shoulder position (Table 4), percent carbon decreased with depth with overall lower levels of carbon in its respective horizons. The pit also had a thinner A horizon than the shoulder, again suggesting erosional movement of material to down-slope positions.

Table 3. Pit data for the backslope pit at Nacimiento. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-18	N20	SL	1	5.8	4.32	71.7, 11.2
BA	18-28	7.5YR2.5/2	SCL	2.5	6.1	2.26	49.2, 26.2
Bt	28-99+	7.5YR2.5/3	C	4.5+	6.3	0.83	21.6, 53.7

Table 4. Pit data for the shoulder pit at Nacimiento. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-23	N20	SL	1.75	5.8	6.69	74.2, 6.3
AB	23-31	7.5YR3/2	SL	2	6.0	4.27	64.2, 8.9
Bt	31-72+	7.5YR3/3	SICL	4.5	6.0	1.81	39.2, 36.4

Nacimiento: Active vs. Restored Pasture

A section of Nacimiento is still currently used for pasture, which presented us with the opportunity to sample modern pasture and compare it to the restored pasture at Nacimiento. The pasture is only vegetated by grasses used as food for grazing livestock. The amount of data collected for the modern pasture at Nacimiento was not enough to warrant an independent analysis due to the low sample size for the probe samples and a partial pit description. Here, six points samples were taken and one pit was dug. The partial pit was dug on a slope of 16 degrees at the backslope position, however my time was cut short due to a thunderstorm, although I still managed to collect pit samples in time. The clay content in the pit increased with depth and carbon decreased with depth (Table 5). Point sampling showed a trend similar to the A horizon depth variation in the restored pasture at the backslope and shoulder locations.

Table 5. Pit data for the pasture pit at Nacimiento. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	pH	% OC	% Sand, Clay (lab based)
A	0-38	6.2	6.06	74.2, 6.3
AB	38-55	6.3	5.38	64.2, 8.9
Bt	55-69+	6.3	2.30	39.2, 36.4

Nacimiento In Context

Considering Nacimiento's land use history, I have determined that erosion induced slope-wash has contributed to the thickening of the soil profile located at the footslope position, while at the same time thinning much of the upper portion of the landscape, especially at the backslope position. There is an 81 cm difference between the depth to the root restrictive clay of the backslope pit and the footslope pit which indicates the degree to which soil erosion has occurred at this site.

Finca Rodriguez

The data collected from Finca Rodriguez consisted of 30 point samples and a soil pit. As a former farm, one would expect there to be erosion similar to other sites. This expectation is furthered by the presence of steep slopes found on the site (as high as 20 degrees). However, at Finca Rodriguez there is significant vegetation present, including the areas in which coffee is grown. I would expect this to slow erosion as the land management in the agricultural portions of the site seem to minimize exposed soil surfaces. The forest structure had a noticeable portion of trees in older age classes. The number of older trees present at this site were greater than most of the other sites which indicate that cutting has either not occurred in a long period of time, or the cutting was not as comprehensive as at other sites. This also could indicate better site conditions as it may be possible that the vegetation is able to grow more readily at Finca Rodriguez than at other sites due to less eroded landscape conditions.

In point sampling, the A horizon at Finca Rodriguez exhibited an opposite, but weaker

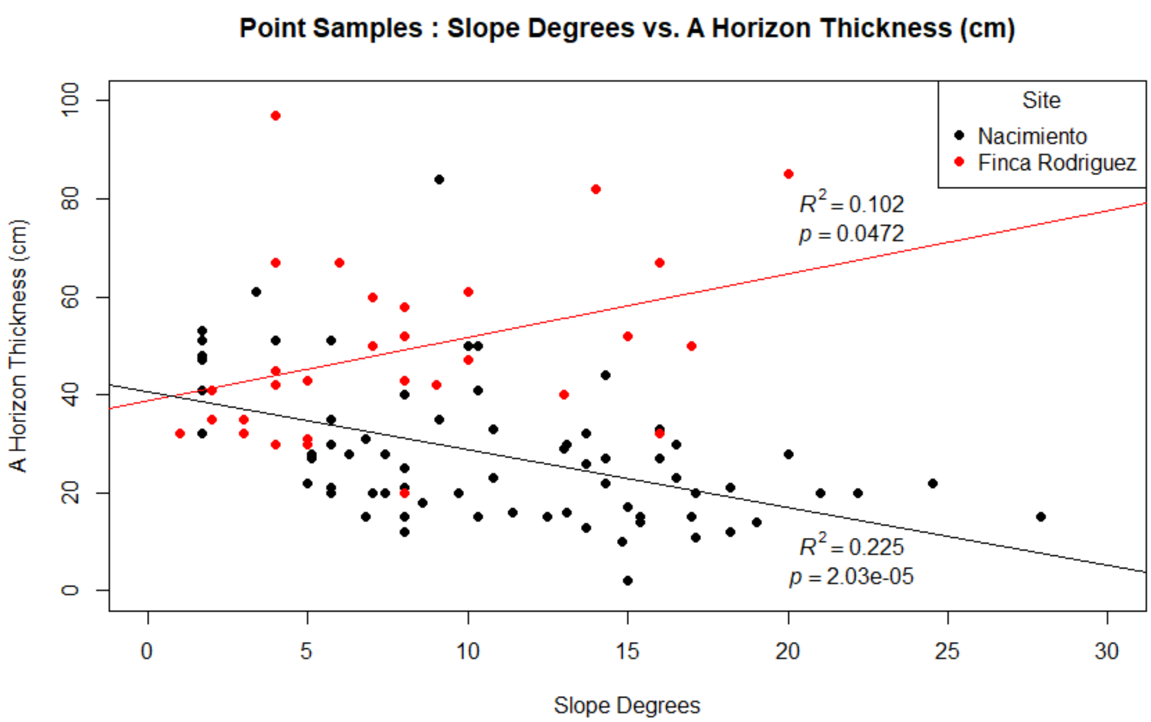


Figure 7. Comparison of point samples from Nacimiento and Finca Rodriguez with simple linear regression lines displaying

trend compared to Nacimiento showing that as slope degrees increase, A horizon thickness increases. It may be that some of the larger trees, tree throws, and root systems in the established forest at Finca Rodriguez are able to trap soil carbon as it erodes from upslope positions to downslope positions. Daniels et al. (1987) reported similar condition in undisturbed montane sites in North Carolina, United States with regard to tree throws, comparing their soils to tropical forest soils. Finca Rodriguez may reveal trapping of soil carbon by larger trees with more developed root structures that are able to both prevent movement of soil downslope, as well as catch soil during erosional events or creep. Also important to consider are the range of slope values sampled for Finca Rodriguez. The range of slopes is more narrow than for Nacimiento, which may explain the positive trend. Analysis of depth to clay and slope was inconclusive due to low sample size.

The site exhibited a thick dark A horizon at the pit location which included course volcanic ash from 16 to 20 cm. The ash is likely remnants of the 1968 eruption of the proximate volcano, Arenal (Smithsonian Institution, 2013) which deposited significant ash over 15 sq. km (Volcano World, 2017), including the Monteverde region (Debra Hamilton, personal communication, July, 2017). If that holds true, then the soil below the A horizon is older than the material deposited from the erruption. Considering the lighter densities and textures at Finca Rodriguez, this soil may be an Andisol. However, it is difficult to say definitively due to a

Figure 8. Pit dug in the restored farm of Finca Rodriguez. The total depth of the pit was 108 cm. Contact was not made with the root restrictive clay later

lack of specific lab work to identify it as such. The total depth of the pit at Finca Rodriguez was 120 cm (with a slope of 6 degrees located at a local footslope) and the root restrictive clay layer was not reached (Figure 8). The clay content was relatively low throughout the pit and percent carbon decreased with depth (Table 6).

Table 6. Pit data for Finca Rodriguez. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-21	N20	SL	1	6.0	7.45	76.8, 3.3
AB	21-54	10YR2/2	SL	2	6.4	4.75	71.8, 3.2
Bw	54-61	10YR3/3	SL	3			
ABb	61-108	10YR2/2	L	2	6.6	2.97	59.3, 8.2
Bwb	108-120	7.5YR3/3	L	1.5			

The history of the site is partially illustrated in the pit. There is an ABb horizon present from 61-108 cm, below the Bw, indicating a buried profile. It would also suggest that there has been moderate soil development since deposition events. Enough time has passed, or enough soil development has occurred to allow for the Ab to transition to an AB. Historic volcanic deposition may contribute to the site's ability to maintain vegetation despite its land use history as a farm. This may indicate that either practices have been implemented at Finca Rodriguez which have resulted in effective erosion control and soil remediation, or the site has been able to retain characteristics of good soil due to its fertile components.

Curi-cancha

Curi-cancha was formerly a pasture with portions of intact Forest. The regrowth of vegetation there has been ongoing since the 90s (Reserva Curi-cancha, 2017). In total, two pits were dug, along with 33 point samples. The site was largely vegetated by tall grasses and the landscape exhibited a unique undulating quality. While erosion has been part of this site's history, revegetation appears to have eliminated surface indicators of erosional problems and has worked to stabilize the landscape.

Point sampling at Curi-cancha did not reveal a significant trend between A horizon thickness and slope degrees nor depth to clay and slope degrees. This may indicate that the restoration efforts conducted at Curi-cancha have been relatively successful since landscape level evidence of slope driven A horizon transport is not evident. However, the site's landscape is highly variable and this also had an impact on the lack of significant relationship between the two variables.

Figure 9. Pit dug in the restored pasture of Curi-cancha. The total depth of the pit was 108 cm. Contact with the root restrictive clay was made from 99-108 cm.

The pit dug in the former pasture at Curi-cancha was 108 cm deep with a slope of 15 degrees (Figure 9). Clay content did not increase consistently with depth due to the buried A horizons (Table 7).

Table 7. Pit data for the restored pasture pit at Curicancha. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-28	10YR2/2	CL	1.25	5.8	6.32	64.1, 11.1
Ab	28-43	N20	CL	1.25	6.0	9.72	71.5, 6.2
C	43-80	10YR2/2	COSL	1.5	6.5	3.45	81.6, 6.2
Ab2	80-99	10YR2/1	L	2.75	6.6	3.67	64.0, 8.8
2Bt	99-108+	7.5YR3/3	C	2.25	6.5	1.51	26.4, 46.5

This also led to an inconsistent decrease of carbon with depth, with the highest level of carbon found in the Ab horizon. The second pit was dug in intact forest at Curi-cancha. This pit had a depth of 58 cm and a slope of 6.27 degrees (Figure 10).

Figure 10a. Pit dug in the in-tact forest of Curi-cancha. The total pit depth was 58 cm and the root restrictive clay layer was not reached.

Figure 10b. Bottom half of the pit dug in the in-tact forest at Curi-cancha.

Table 8. Pit data for the in-tact forest pit at Curi-cancha. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	pH	% OC	% Sand, Clay (lab based)
A	0-12	6.1	14.85	81.5, 4.0
AB	12-26	6.4	4.02	76.5, 4.0
Bw	26-58+	6.5	1.57	86.5, 3.9

The A horizon here had the highest level of carbon of any pit (Table 8). This is likely due to its location in the in-tact forest, representing preservation of high levels of organic material in the soil. Clay did not vary much between horizons and was relatively low throughout. The pasture pit at Curi-cancha compares well to the sample taken by Tanner et al. (2014) in a study located several km north of Santa Elena. The pasture pit in their study is comparable in texture as both are described as sandy and coarse. This suggests that Curi-cancha is geomorphologically different from the other sites.

Crandell

The Crandell site is located just north and up-slope of the Monteverde Institute. The site was formerly a farm and has relatively low slope. Windbreaks planted decades ago are still distinguishable from the surrounding vegetation in part because they are non-native. I dug a single pit here and point sampling suggested relative uniformity in profile composition. A total of 32 point samples were taken at the site.

There was no significant relationship between A horizon thickness and slope nor depth to clay and slope at Crandell. Site history has complicated the soil property distribution across the landscape. Low slopes in combination with terracing from former agricultural practices and windbreaks have made interpretation difficult.

The total pit depth was 110 cm deep with a slope of 3 degrees (Figure 11). The origin for the buried A horizon could be agriculturally related. The site has been left to grow in the recent past and this may be part of the reason behind the dark color and high percent carbon that is persistent to a depth of 96 cm (Table 9). Clay content remained low until contact with the root restrictive clay layer. This pit in particular was dug fairly easily, suggesting much of the upper portion of the pit had a low bulk density. Being located in a forest ecosystem would contribute to high levels of organic matter input in the form of woody debris, and leaf litter, the accumulation and decomposition of which would lower bulk density over time (Sollins and Gregg, 2017).

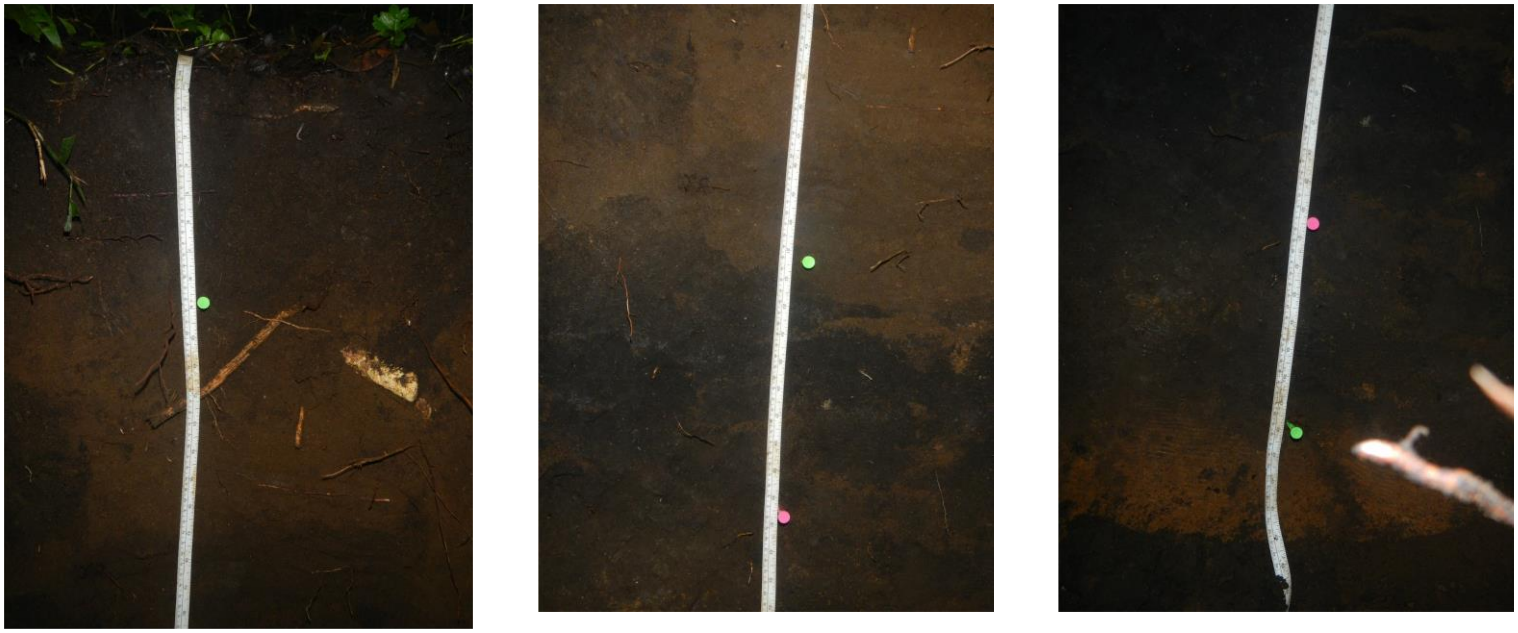


Figure 11. Pit dug at Crandell. Top of pit (left), center of pit (center), and bottom of pit (right). The total depth of the pit was 110 cm.

Table 9. Pit data for Crandell. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm³)	pH	% OC	% Sand, Clay (lab based)
A	0-22	N20	L	0.5	6.2	7.13	79.1, 4.0
Bw1	22-54	7.5YR5/2	SL	1			
Ab	54-77	N20	L	2	6.1	7.81	71.6, 4.0
Bwb	77-96	7.5YR2.5/1	SL	2.5			
Bt	96-110+	7.5YR3/4	CL	3	6.4	3.21	54.1, 21.0

<u>La Calandria</u>

The private ecological preserve is located on 27 hectares and was privately purchased in 2000 in order to protect tropical habitat (Calandria Lodge, 2012) The site was formally a farm and most recently was used for pasture before being purchased. Geographically, it lies on a broad interfluve, so slopes are generally low.

Analysis of the relationship between A horizon thickness and slope and depth to clay and slope at La Calandria yielded insignificant results. A difference in site history between the western portion of the site, located down-slope and the eastern portion of the site, located up-slope may explain this. The western side of the site has undergone restoration for a longer period of time than the eastern side (Debra Hamilton, personal communication, July, 2017).

Two pits were dug and 35 point samples were taken. The first pit was dug near the center of the preserve to a total depth of 72 cm with a slope of 10 degrees (Figure 12). Upon reaching the 72 cm, there were virtually no roots present. There was evidence of a change in horizons at the bottom of the pit and due to the difficulty of continued digging, I augered to a depth of 105 cm. The near-surface clay content in this pit was noticeably higher in comparison

Figure 12. The first pit dug at La Calandria. The total depth of the pit was 72 cm. Contact with the root restrictive clay layer was made from 72-105 cm.

to soils at the other sites and remained high to the bottom of the pit and the percent carbon decreased with depth (Table 10).

Table 10. Pit data for the first pit dug at La Calandria. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-22	10YR 2/2	CL	1	6.2	5.85	73.8, 11.7
Bt	22-72	7.5YR 3/4	C	4	6.3	1.42	21.8, 47.9
Bt2	72-105+	5YR3/4	C	4	6.4	0.44	14.3, 60.6

The second pit located closer to the entrance of the preserve was dug to a depth of 62 cm with a slope of 8 degrees (Figure 13). Clay content here was lower than the other pit and the BA horizon exhibited a decrease in percent clay before contact with the root restrictive clay layer was made (Table 11). The percent carbon in this pit decreased with depth. Most of the trees on-site were younger as evidenced by the smaller tree diameters and lower tree canopy. This may contribute to the level of growth present at this site. Trees are noticeably smaller and may experience difficulty reaching deeper depths within the soil due to the presence of the root restrictive clay beginning at 72 cm and 42 cm for the first and second pits respectively.

Figure 13. The second pit dug at La Calandria. The total depth of the pit was 62 cm. Contact with the root restrictive clay layer was made at 62 cm.

Table 11. Pit data for the second pit dug at La Calandria. (*) indicates saprolite. pH, % OC and % Sand and Clay are grouped.

Horizon	Depth (cm)	Color	Texture (field based)	Resistance (kg/cm^3)	pH	% OC	% Sand, Clay (lab based)
A	0-17	10YR 2/2	SL	1	5.9	6.19	69.3, 8.1
BA	17-42	7.5YR 3/3	SCL	1.25	6.1	3.53	64.3, 5.7
Bt	42-62	7.5YR 3/4	SICL	2	6.1	1.28	41.8, 35.7
	62+			2.5 (*4.5)			

Land use history suggests mass movement of soil material. This is supported by the lack of the common dark (N20) color present at the surface indicating long term organic matter accumulation. Furthermore, the shallow nature of both pits with their high percent clay suggest that material has been lost due to erosion, creating a shallower depth to the root restrictive clay that persists across the area.

Analysis in GIS

<u>Nacimiento</u>

An examination of PDI at Nacimiento helps to illustrate the variation in storage of darker, more organic soil material across the site. Probe samples from the upper portion of the site, near the shoulder, are less dark than the probes taken from the footslope and backslope positions. At the shoulder position, the probe points were dominated by lighter PDI values. PDI values at Nacimiento were as low as 1.1 (with 17 degrees slope) and 1.2 (with 18 degrees slope) at the backslope and shoulder position respectively and were as high as 84 (with a slope of 9.1 degrees) at the backslope. There were two probe points that yielded PDI values of 30 and 35. These probes points were located at slopes as steep as other probe points with much lower PDI values. The reason for these anomalies most likely lies with the variation found in the vegetation on the landscape. This may be the same phenomena that I observed at Finca Rodriguez. The vegetation present in these areas may be trapping soil material near the surface, which is generally rich in carbon. In effect, these pockets of erosional protection in the form of roots and branches may be creating islands of darker, more organically rich soils.

RR tells a similar story. This gives insight on the depth to clay at a given location since my probe colors were sampled at 20 cm. The more red values (higher values) are located at the backslope and shoulder. The footslope is dominated by 0 values due to the N 2/0 colors of the samples. The reddest samples of all the probes are also located at the shoulder and backslope positions.

Finca Rodriguez

In examining PDI on an elevation map for Finca Rodriguez, we see a similar trend to the one found when plotting A horizon depth against slope degrees. The PDI map for Finca

Rodriguez shows that some higher slopes result in darker soil color (higher PDI). This helps to support the idea that the older forest present at Finca Rodriguez is assisting in trapping carbon rich soil material during erosional events. As soil material moves down slope, the larger area covered by the older trees at Finca Rodriguez allows for carbon rich soil to be caught and trapped in place, where it might otherwise continue its decent down-slope. The highest PDI value is 50, found on a slope of 7 degrees. The lowest PDI value at 6 was found toward the center of the site on a 5 degree slope. It appears the carbon dynamics at Finca Rodriguez appear not to be driven only by slope.

In examining Finca Rodriguez using RR, there is a lack of a clear trend. The highest RR value measured at Finca Rodriguez was 35, of which there were 7. Of those 7 probe locations, the lowest slope recorded was 3 degrees and the highest was 15 degrees.

Curi-cancha

Analysis of probe samples in Curi-cancha is complicated due to a its varied landscape. The site itself is undulating and exhibits multiple stages of restoration and environment types. The intact forest at Curi-cancha exhibited the highest (darkest) PDI values. The highest PDI value at Curi-cancha was found there, at 47 (with a slope of 10 degrees), found at the south-east section of the site in the intact forest. Curi-cancha's lowest PDI value was measured at 1.4 (with a slope of 10 degrees) which was located at the backslope at the center of the site. We also see a concentration of low (light) PDI values towards the north portion of the site, which is upslope. Considering Curi-cancha's complex history and undulating landscape, the process of piecing together it's history of soil movement is difficult.

RR is largely a reflection of the mapped PDI values. The highest RR value found at Curi-cancha was 37.5 (with a slope of 9 degrees) which was located in the north-west section of the site, while the lowest RR value was 0, of which there were eight. The 0's were located in the areas where N 2/0 color measurements were taken, which are concentrated in the area dominated by intact forest. This indicates the forest has a more stabilized landscape than the pasture as it has been able to develop darker more organic rich soil.

Crandell

The highest PDI recorded was 47 and was found in the south-east section of the site, with a slope of 11. The lowest PDI measured was 2.1 and was found in two locations. The first was located in the central-northern portion of the site with a slope of 7 degrees, while the second was located nearby, to the east, with a slope of 11 degrees. Crandell is relatively low sloping, with the highest slope recorded at 16 degrees. It also is completely forested, although none of it is in-tact primary forest. Considering the generally low sloping nature of Crandell, it is difficult to believe that slope is the only factor playing a strong role in erosion and landscape changes. This site may be an example of the natural variations in soil characteristics and carbon dynamics that occur in a forest system in the tropics. Tree throws can expose soil located in deeper horizons and other naturally created ditches can fill with litter material and influence the carbon levels of that particular area.

The highest RR value at Crandell was 37.5, of which there were two measured. These probe locations are the same two as those that represent the lowest PDI values. This is evidence that slope has played some role in influencing changes at Crandell. The areas that have become the most eroded are also the ones that may be the most influenced by the root restrictive clay layer.

La Calandria

From the observations made at the site, as well as the history of the property, La Calandria exhibits two sections, each slightly different. The western portion of the site has undergone restoration for several more years than the eastern portion of the site. This is evidenced by the larger trees, more comprehensive forest canopy, as well as a darker overall A horizon color found there. The western portion of La Calandria is also downslope from the Eastern portion of the site. The eastern portion of La Calandria has undergone restoration for a shorter period than the western portion.

The highest PDI value measured at La Calandria was 39 and was located within the western portion of the site with a slope of 15 degrees. This location is likely an example of soil material in the process of descending down slope. The highest PDI value measured in the eastern portion of the site was 30 and was located on a slope of 9 degrees. This probe had a noticeably higher PDI than any of the other probes in taken on the eastern side of the site. The next highest PDI measured within the eastern portion of La Calandria was 7 with a slope of 3 degrees. The majority of PDI values measured in the eastern portion of the site were below 6. The lowest PDI value measured at La Calandria was 2.1 with a slope of 6 degrees and was located in the south-east section of the site.

The distribution of high RR values at La Calandria was related to the distribution of low PDI values. The lowest RR value measured at the site was 0 (the result of an N 2/0 color). Two

0's were measured, both of which were the same probe points which yielded the highest PDI values (39 within the western portion, and 30 within the eastern portion of the site). The reddest RR value was 37.5 and was located on the eastern side of the site towards the lower section, on a slope of 5 degrees.

Analysis of Indices

Nacimiento had a significant relationship between PDI and slope (adjusted R^2 0.333, p-value = 1.02 x e^{-7}). However, none of the other sites had a significant relationship between the two variables. Examining the relationship between PDI and slope degrees for all sites indicates a significant, but weak relationship (Figure 14). Their different site histories and landscapes at

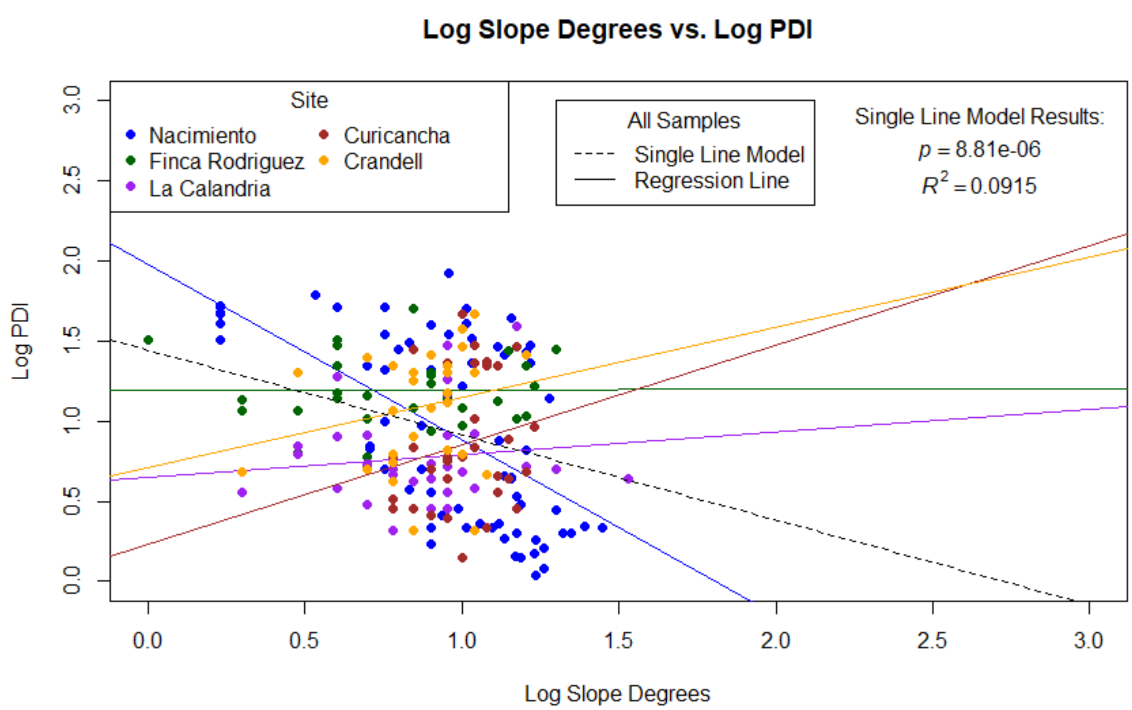


Figure 14. Log PDI from all probe points plotted against log slope degrees.

those sites complicate the relationship between the two variables. When probing data is separated by site, there is no consistent trend. There are positive, negative, and almost neutral relationships between PDI and slope degrees. This may serve as a warning against relying on using slope to predict levels of carbon using PDI. If PDI is to be measured, it should be for the purposes of investigating carbon levels during mapping activities, but not for predictive modelling in my study region.

Linear regression analysis was not able to adequately explain the relationship between RR and slope. Nacimiento was the only site that yielded a significant relationship between the two variables (adjusted R^2 0.2938, p-value = 7.542 x e^{-7}). The analysis of this index is made difficult by the lack of variation in measurements. RR is limited to soil color and produces a more limited spectrum of numbers due to relying strictly on color measurements for calculation. It is still useful for generalized mapping purposes in identifying areas that may have higher clay content or shallower depth to a root restrictive clay layer.

Relationship Between A Horizon Thickness and Elevation

Statistical analysis showed there was no significant relationship between A horizon thickness and elevation (ft.). This may be attributed to multiple factors. The first of which was the inaccuracy of the GPS units in their ability to measure elevation. This difficulty was made worse when attempting to take measurements in partially or fully forested areas.

Volcanic Influence on Soils in Monteverde

Of all my study sites, Finca Rodriguez appeared to be most affected by volcanic activity as indicated by the thickness and darkness of the upper horizons in the profile, as well as the presence of a coarse ash layer. All the sites in the project are historically influenced by volcanic activity by their proximity to Arenal. However, it is more difficult to determine the degree to which they are influenced by volcanic material.

<u>Particle Size Influence on Carbon Dynamics</u>

Studies have examined the influence of particle size on carbon (Willis et al., 2007, Konen et al. 2003, Franzmeier 1988, and Nichols 1984). For my data, these same relationships were explored in order to identify any links between particle size and soil carbon as well their distribution among my various sites.

The relationship between percent carbon and percent clay is usually a positive relationship. Konnen et al. (2003) yielded results that show as percent clay increases, percent carbon also increases. The relationship between percent carbon and percent clay that was identified in my data did not match that of Konen et al., (2003) (Figure 15). As percent clay increases in my samples, percent carbon decreases. The pit from the in-tact forest at Curi-cancha differs from the rest, but I believe this is due to low sample size as well as the sample location itself. As the only in-tact forest sample, it contains much less clay overall due to organic matter inputs and soil development over the root restrictive clay layer. In trying to determine why my results differed from Konen et al. (2003) and other similar papers (Steinwand, 1992, Burras and Scholtes, 1987), it is important to remember the great variety that differences in

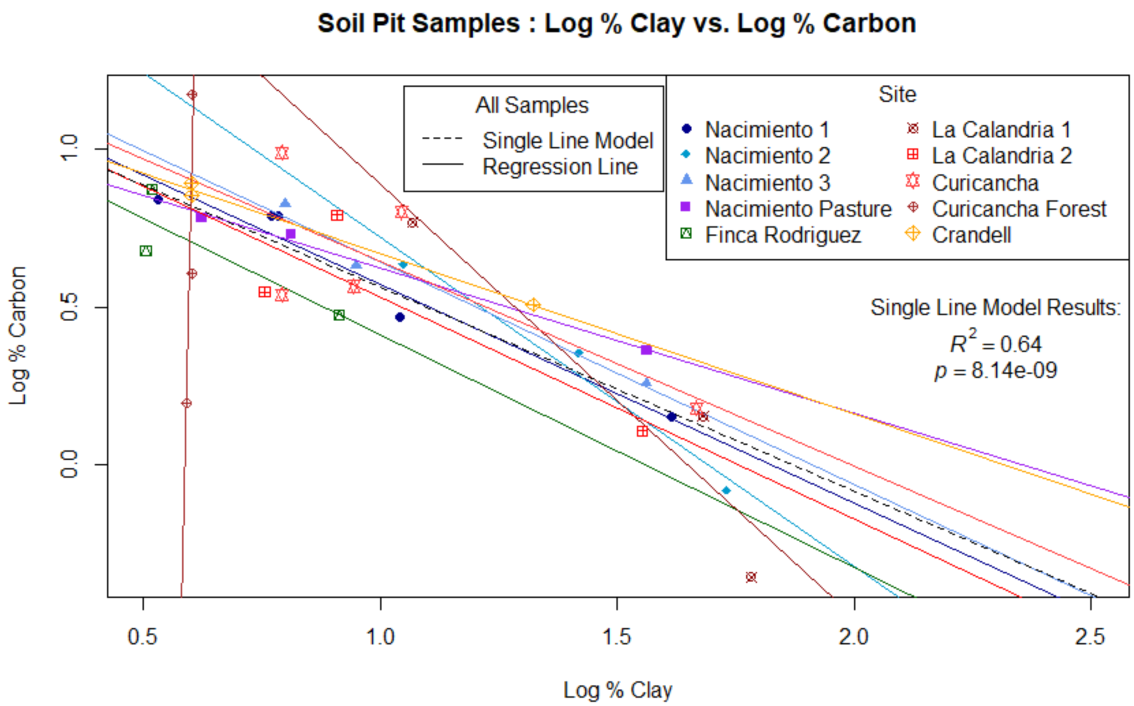


Figure 15. Pit data plotting log % clay and log % carbon.

climate can produce in a soil. Many of the studies that discuss this relationship were conducted in Iowa. The soil in Iowa is vastly different from the soil found on the Pacific slope of Monterverde Costa Rica compared to the Mollisols of Iowa. In their paper, Konen et al. (2003) admit that the variations found between studies examining these relationships indicate that there is no universal equation that can be used to measure this phenomenon.

The relationship between percent carbon and percent sand is also different from what other studies like those conducted by Konen et al. (2003) found in their analysis. It is normal to expect an increase in percent sand to relate to a decrease in percent carbon. Sand has a neutral charge, high pore space, and lower surface area compared to clay and making it difficult for carbon to build up in a sand heavy soil. This is not the case in my data, which show a positive relationship between percent carbon and percent sand (Figure 16). In order to make more

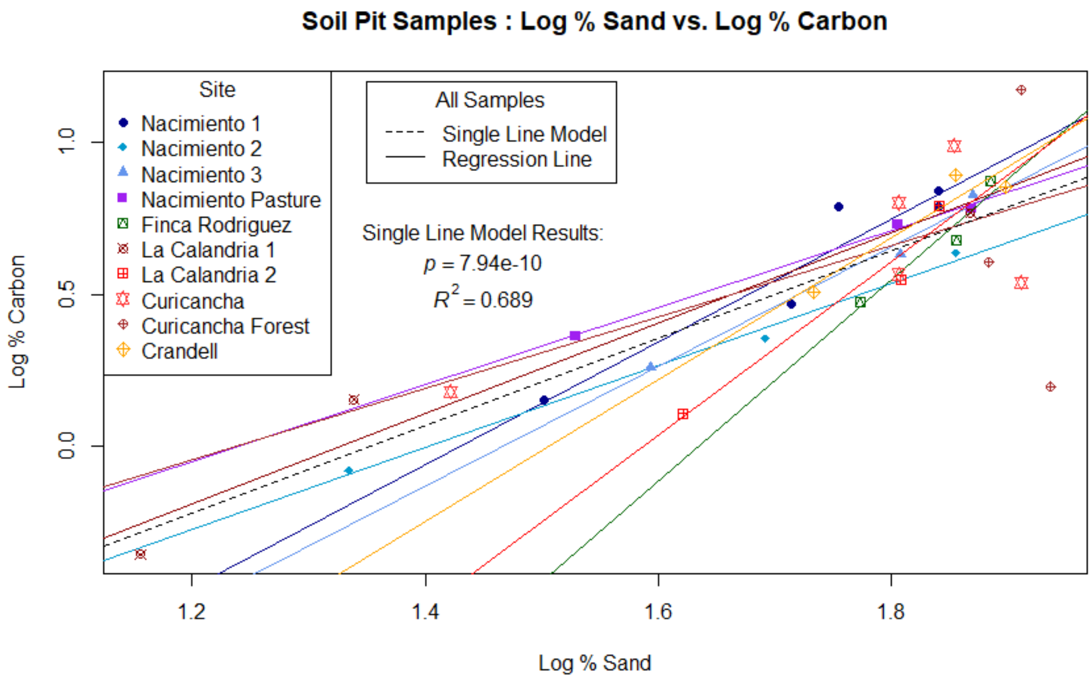


Figure 16. Pit data plotting log % sand and log % carbon.

sense of this relationship, it must be broken down further. The common assumption is that as depth increases, soil carbon and percent sand decrease. To see if the trend persisted, I split the data to include only surface horizons since percent carbon is normally higher in the topsoil.

After splitting the data to examine only the surface horizons, the positive trend between percent carbon and percent sand can still be seen visually, but the relationship becomes statistically insignificant (Figure 17). My sample size is reduced to ten as a result, which impacts the validity of the model results and may explain the insignificant p-value. The sub sample analysis of surface horizons is also unable to completely isolate A horizons due to the nature of

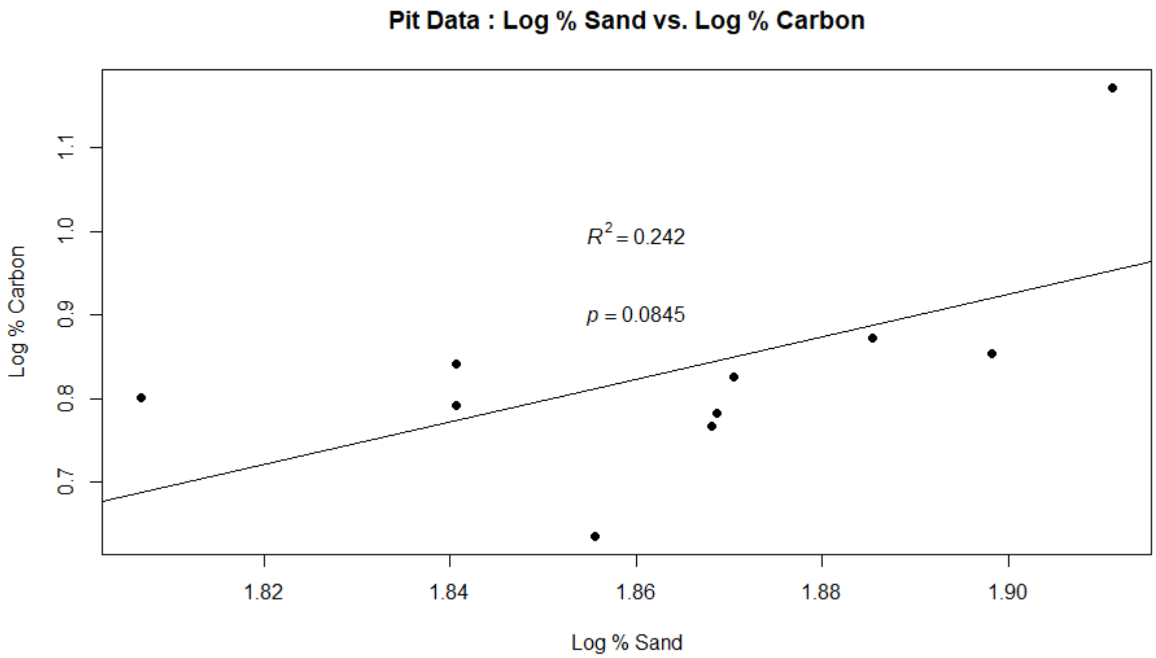


Figure 17. Pit data plotting log % sand and log % carbon, isolated for Group 1 samples (most of which include A Horizons, but also include a Bw1 horizon from the Crandell pit due to grouping methods).

my grouping method. In addition, each horizon was sampled in the center of the group, which takes place at a different depth for each of the pits. My pit data also shows a decrease in percent sand with depth (Figure 18), indicating that generally, sand particles are concentrated nearer to the surface, which is what we see from the percent sand and percent carbon plot. We should be weary to discount the influence of percent sand on percent carbon, despite its insignificant p-value.

This poses another question : to what degree is the soil influenced by local volcanic activity? A coarse ash layer was visually identified in my pit at Finca Rodriguez, and it is likely in

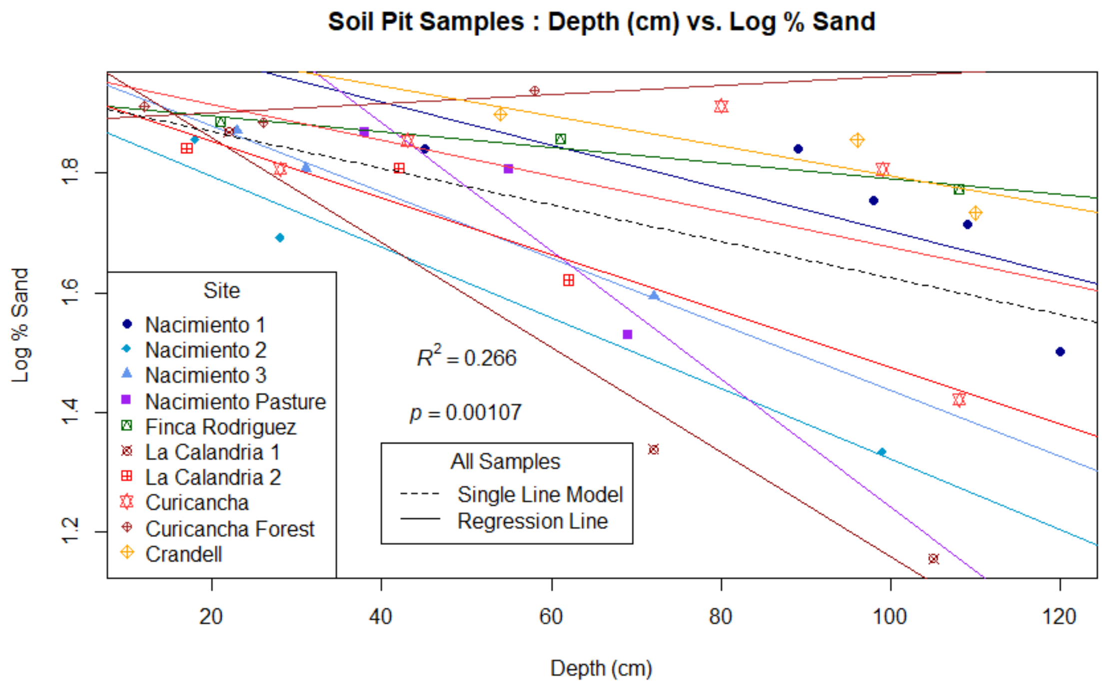


Figure 18. Pit data plotting log % sand and depth indicating a decrease in % sand with depth (cm).

many of my samples given the proximity to the volcano, Arenal. The particle size of volcanic ash is <2mm (Nemeth, 2010) which puts it in the same particle size class as sand. Volcanic ash is able to influence soil organic carbon storage due to its mineralogical composition. Since volcanic ash develops non-crystalline minerals like imogolite and allophane, the material possesses a high specific surface area (Paul et al., 2008). Volcanic ash, despite being a considerably larger particle size, also acts similar to clay. This may be why we see a relationship that runs counter to other studies. It is difficult to determine which sites are more heavily influenced by the presence of volcanic ash due to my low sample sizes for the pit data. It does appear that an increase in sand content is related to an increase in percent carbon.

Particle Size Influence on Nitrogen Dynamics

The variations in nitrogen based on particle size were also examined. There is a positive relationship between percent nitrogen and percent sand (Figure 19). Volcanic soils are nitrogen rich and the data illustrate this. This has implications for landscape properties since it may

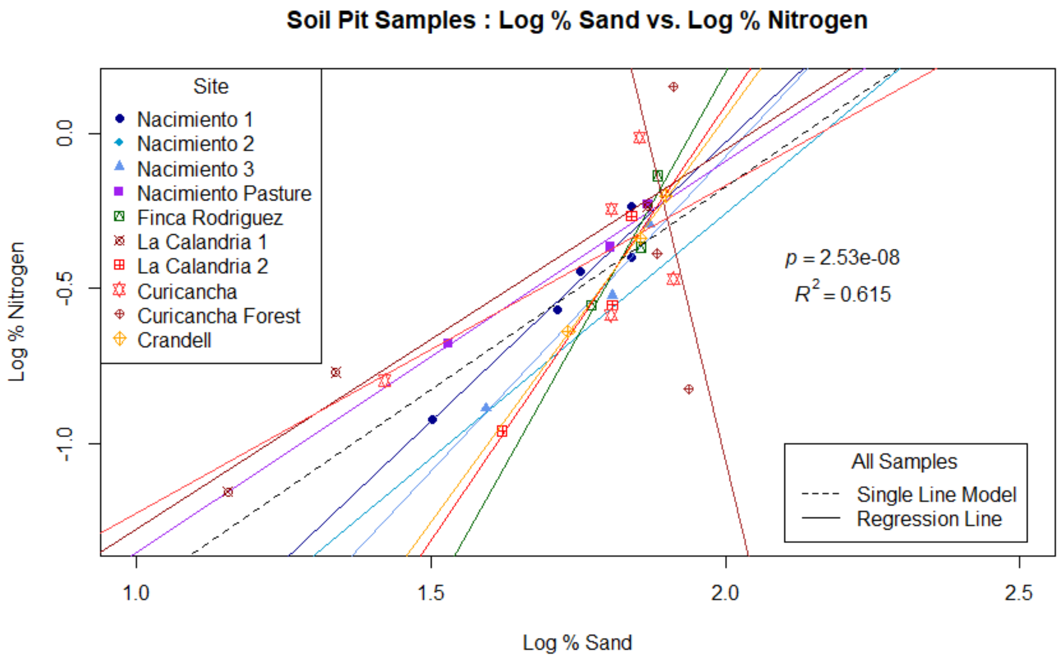


Figure 19. Pit data plotting log % sand and log % nitrogen. The resulting positive relationship matches the positive relationship seen between log % sand and log % carbon.

indicate the soil possesses a greater capacity to contain higher levels of nutrients like carbon and nitrogen.

The relationship between percent nitrogen and percent clay was also similar to the comparison between percent carbon and percent clay. There was a negative relationship between percent nitrogen and percent clay (Figure 20). This may indicate that higher levels of

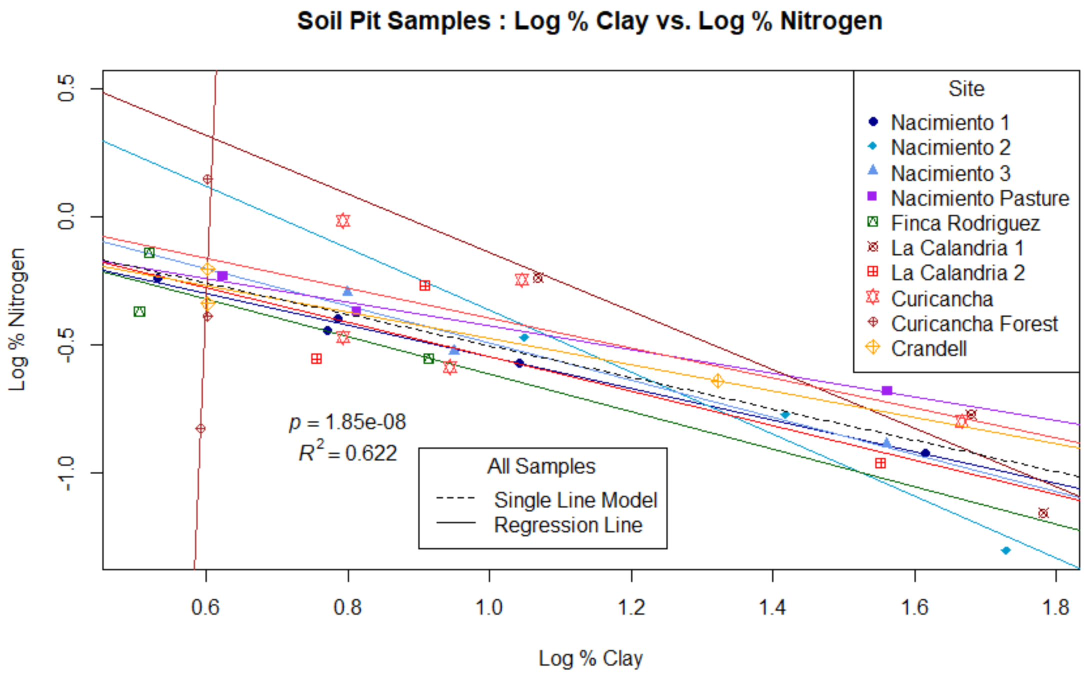


Figure 20. Pit data plotting log % clay and log % nitrogen. The resulting negative relationship matches the negative relationship seen between log % clay and log % carbon.

clay found at my sites will likely be related to lower levels of nitrogen. This makes the task of restoring degraded slopes increasingly difficult. A degraded site will not only have a shallow depth to the root restrictive clay, but will also have lower levels of carbon and nitrogen than sites that are more dominated by sand. The pursuit of sandy locations may be a fast way to determine areas with a greater likelihood of containing carbon and nitrogen.

<u>Analysis of Nutrients</u>

Lab analysis pf pit samples provided information on C, N, pH, Ca, Mg, K, P, Cu, Zn, Mn, and Fe. If pits located in the low slope and footslope positions have higher nutrient levels in the upper horizons, that might suggest that landscape position can be a tool to determine other nutrient levels as well. The relationship between A horizon depth and N was shown to be insignificant. The relationship between N and depth was significant (Figure 21). This

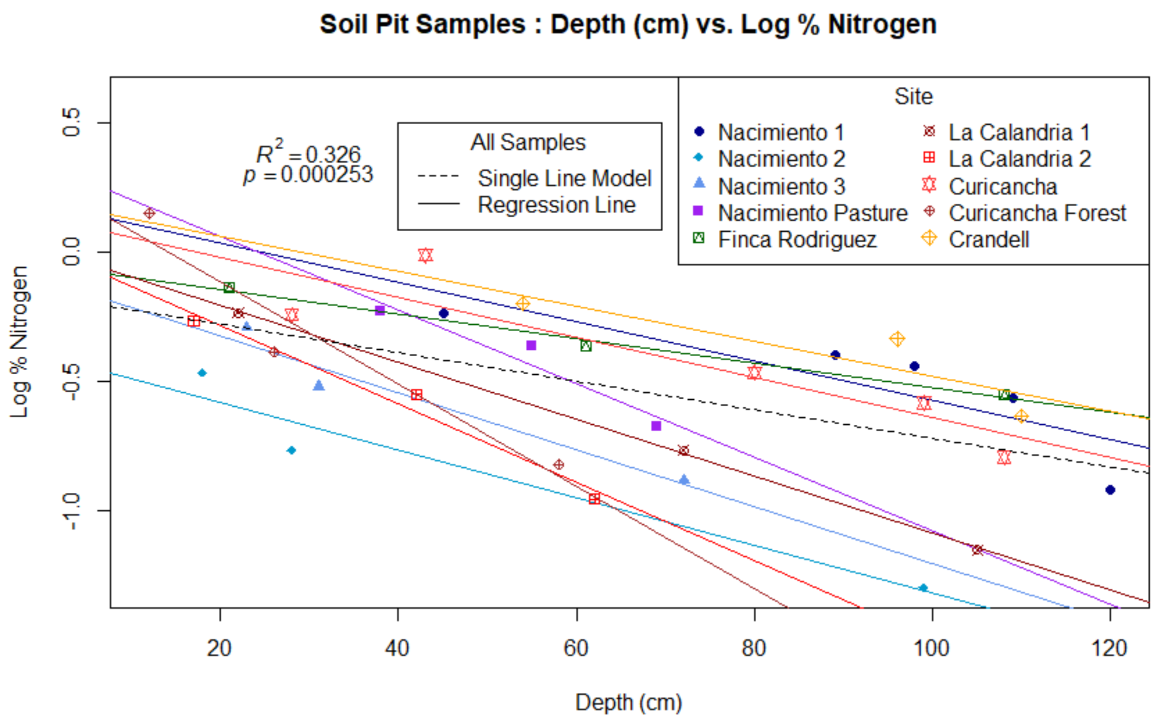


Figure 21. Pit data plotting Log % Nitrogen and Depth (cm).

was similar to the relationship between C and depth which yielded a negative relationship as well (Figure 22). Carbon to Nitrogen ratios (C:N) were all low, indicating an accommodating environment for active microbial communities. The highest C:N ratio reported was 17.03 found at the footslope pit at Nacimiento pit from 89-98 cm, and the lowest was 6.28 found at the first La Calandria pit from 72-105 cm. Analysis of pH, Ca, K, P, Zn, and Mn with depth all yielded insignificant results.

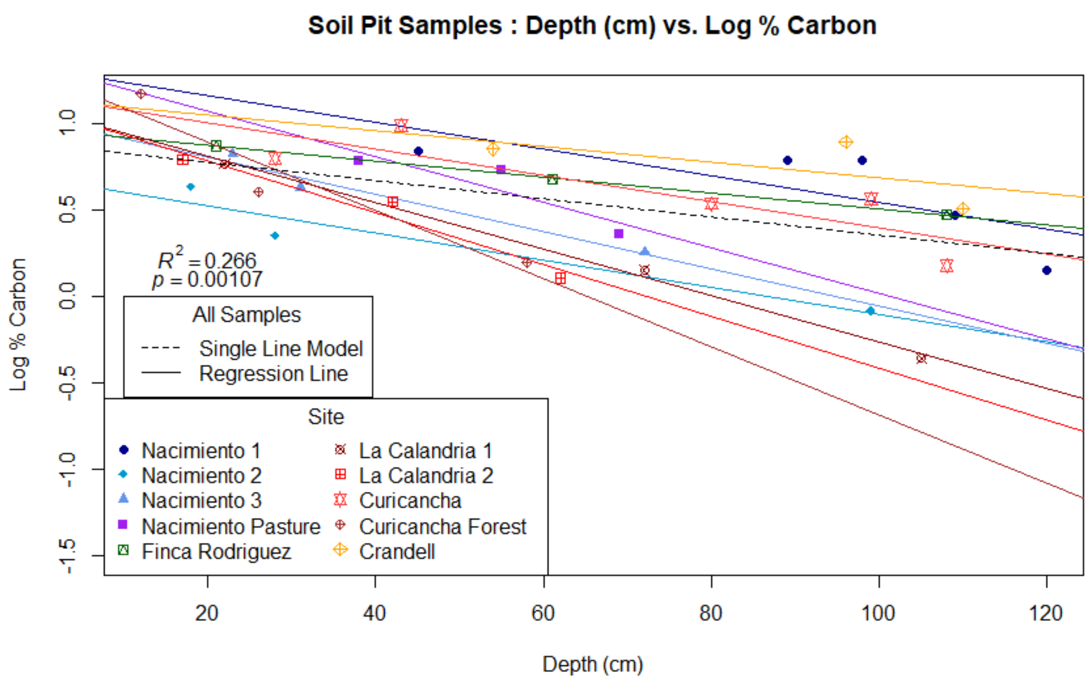


Figure 22. Pit data plotting log % nitrogen and depth (cm).

Only N, C, Cu, and Mg had significant relationships with depth. N builds up in soil over time coming mostly from bacterial N fixation, or from the breakdown of detritus. N is also closely tied to C levels (Jobbágy and Jackson, 2001), which are higher at the surface due to organic material inputs. If soil is eroded to another location, the N and C in the upper horizons will be transported with it, leading to higher levels of N and C at footslope locations. The relationships between Carbon and Nitrogen and Depth may explain their relationships with sand and clay.

Cu had a non-linear relationship with depth (Figure 23). Generally speaking, Cu can have both a positive and negative relationship with depth, as it depends on the soil type and the source rock material (Reuther, 1957). Cu can bind with organic matter, leading to higher levels of Cu in organically rich horizons (Mohammed et al., 2010; Duplay et al., 2014). Cu can also bind to carbonates, leading to higher concentrations of Cu in horizons containing carbonates, which are sometimes associated with less altered parent material (Duplay et al., 2014). The data indicate higher levels of Cu in the center of the profile, rather than at the surface or at the bottom of the profile. This relationship is likely more influenced by the mineralogy for the soil rather than the binding of Cu to organic matter or an association with Cu and parent material.

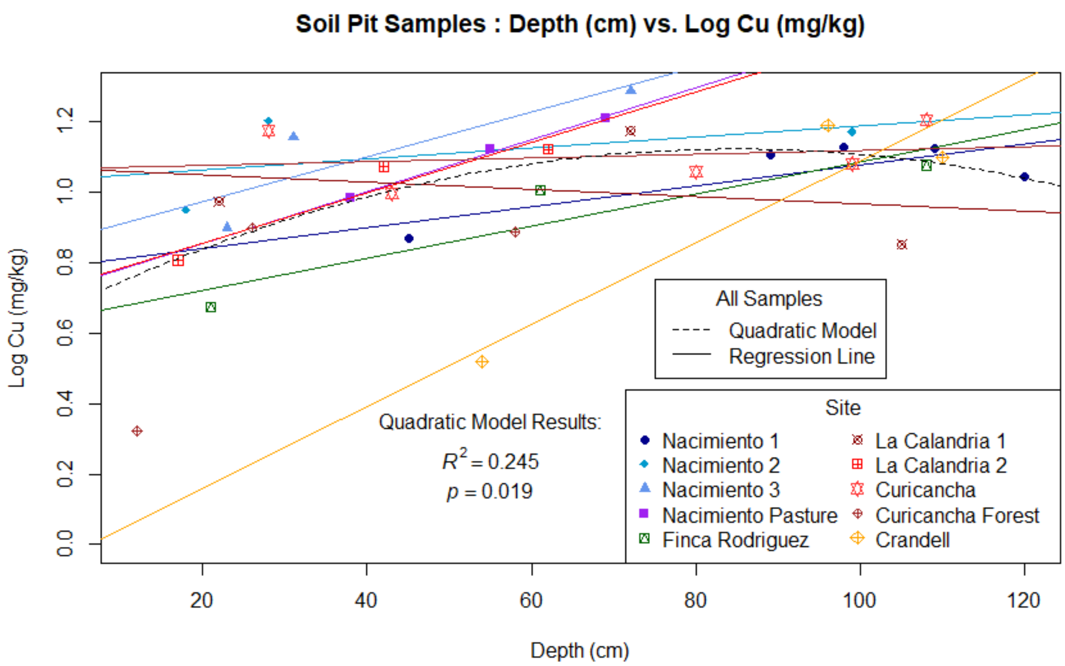


Figure 23. Pit data plotting log copper (mg/kg) and depth (cm).

Mg had a non-linear relationship with depth as well, indicating higher levels at both the surface and near the bottom of the profile (Figure 24). Mg levels are determined by the chemical properties of source rock, climatic and anthropogenic factors

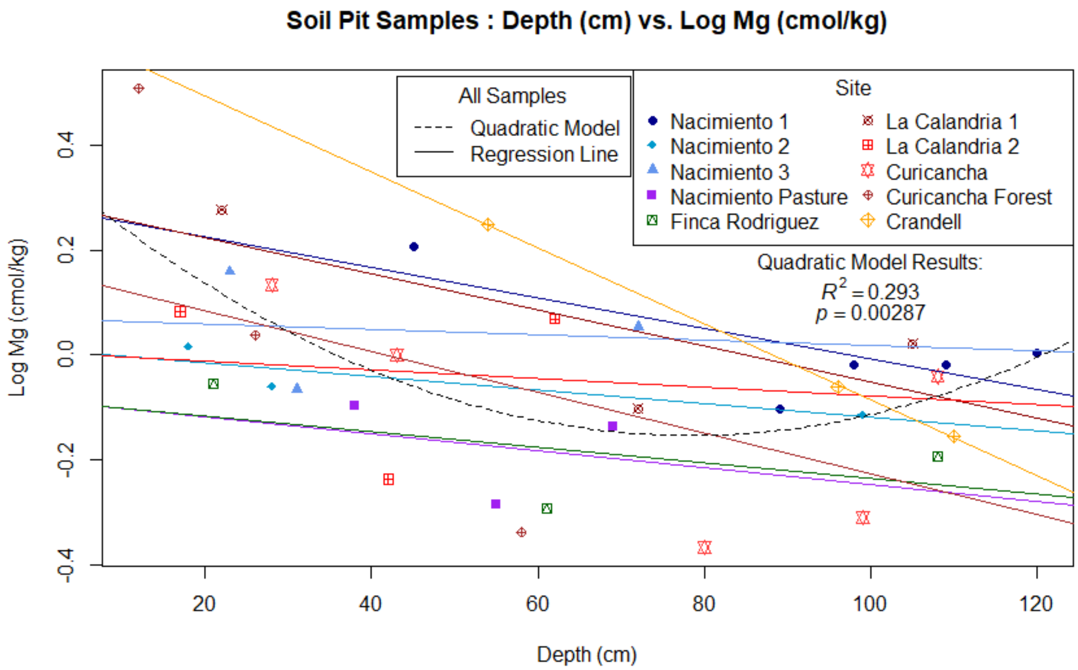


Figure 24. Pit data plotting log magnesium (cmol/kg) and depth (cm).

related to the site's location, the degree of weathering of source rock, and agricultural management practices (Gransee and Führs, 2013). Due to the association between Mg and its source rock material, Mg is found in higher levels in more clay and silt heavy soils rather than sandier soils and is only released into the soil through mineral weathering processes since Mg bound in rocks source material is not mobile (Gransee and Führs, 2013). The higher levels of Mg near the soil surface is likely related to the relationship between organic matter and Mg (Brady and Weil, 2010).

Another possibility for explaining the distribution of Mg lies in the levels of Ca, K, and Mn. When these nutrients are more available, this can lead to pronounced decreases in the uptake of Mg (Gransee and Führs, 2013). Normal levels of K are typically in the 150-250 ppm range, normal levels of Ca are typically in the 1000-2000 ppm range, and normal levels of Mn are typically in the 1-5 ppm range (Horneck et al., 2001) (Tree Fruit Research & Extension Center 2004). My nutrient data shows that the levels of K throughout my site are all below 250 ppm. The levels of Ca throughout my sites are generally below 2000 ppm. The levels of Mn for my nutrient data show the that majority of my samples exceed 5 ppm. Looking at my nutrient data holistically, it does not appear that there are consistent levels of K, Ca, and Mn exceeding normal limits. It is more likely that the non-linear relationship between Mg and depth is the result of organic matter inputs near the surface and influence of source rock material near the bottom of the profile.

pH levels throughout all my samples ranged from 5.8-6.6. My sites appear to not affected adversely by extreme pH levels. While each plant requires different pH conditions for optimal growth, there is not a great deal of pH variability between my sites with pH ranging from 5.8 to 6.6.

Other Soil Nutrients and Particle Size

Comparisons between sand and clay particle size and Cu, Ca, Mg, K, P, Zn, Mn, and Fe were also conducted. There was a non-linear relationship between Cu and clay (Figure 25). This was the only significant relationship found between comparisons of sand and clay with the aforementioned nutrients. This relationship reflects the relationship between Cu and Depth,

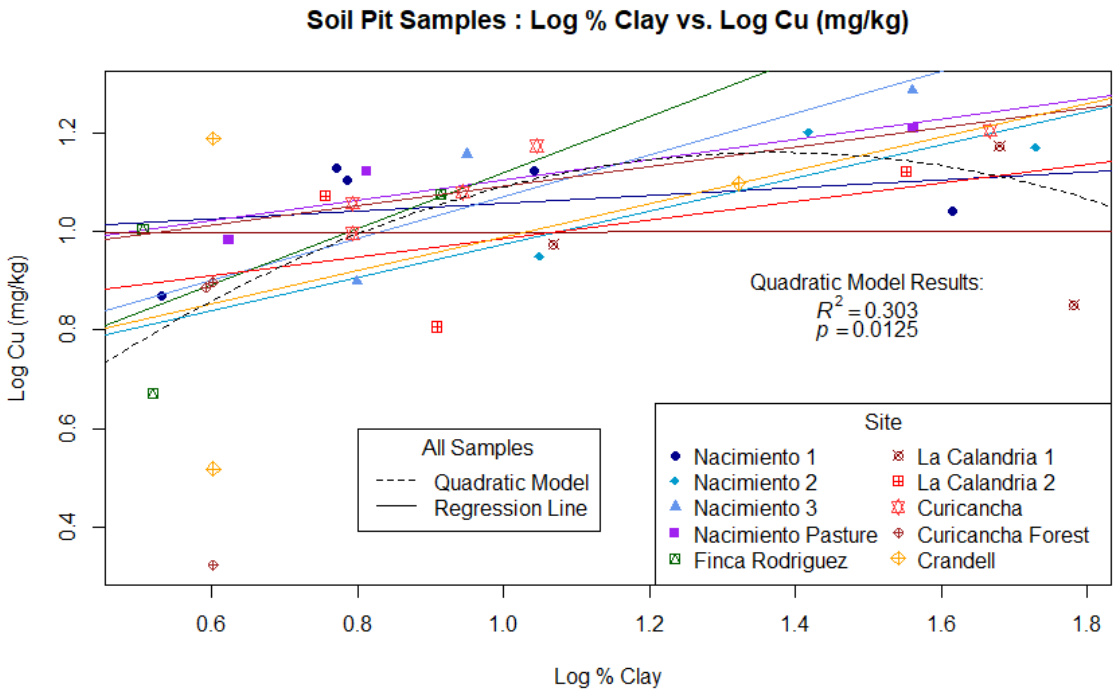


Figure 25. Pit data plotting log copper (mg/kg) and log % clay.

showing a similar trend. Concentrations of Cu increase with clay until reaching a plateau, upon which concentrations of Cu begin to decrease.

Depth plots of each nutrient did not reveal conclusive results. This is likely due to several factors. All my pit depths were different. The depth of a pit typically has an influence over the number of total horizons present. Smaller pits were more restricted in their total amount of data. Furthermore, there were differences among sample depths due to the natural irregularity of soil horizons. Of the relationships that were statistically significant, they were weak. My results indicate that clay and sand cannot be reliably used to determine levels of macro or micro nutrients other than carbon and nitrogen.

Conclusions

Soil property variations in Monteverde, Costa Rica are complex. While we had an excellent example of a topo-sequence with Nacimiento, our other sites did not present as clear soil-landscape relationships. The existence of complex slope profiles in Monteverde makes the identification of soil property variations with landscape properties difficult.

At Nacimiento, there was evidence of transportation of material from up-slope positions to down-slope positions. There was a large difference between the depth to clay at the backslope pit compared to the footslope. That would suggest that the restoration of areas affected adversely by past soil and land management may want to focus on areas which have accumulated significant amounts of material from the surface horizons of upslope positions. Consequently, more resilient species may be placed at locations that have experienced more degradation and erosion.

Each of the sites in the study were different. Their complexities made the analysis of PDI and slope difficult. Information from RR also proved to be limited due to the method used to calculate it. The lack of a clear relationship between the indicies used and slope should serve as caution to future studies that would use color indicies as a mapping tool in this region.

Our data suggest that percent sand may indicate levels of percent carbon and nitrogen which is likely due to the presence of volcanic material and landscape history. This might be a tool for land managers in the future in attempting to quickly determine appropriate sites for the planting of more vulnerable species.

References

Brady, N. C., R. R. Weil. 2010. Elements of the Nature and Property of Soils 3rd edition. Prentice Hall, San Fransisco.

Burras, C.L., and W.H. Scholtes. 1987. Basin Properties and Postglacial Erosion Rates of Minor Morraines in Iowa. Soil Science Society of America. 51 : 1541-1547.

Calandria Lodge. 2012. Calandria Lodge and Sanctuary, Monteverde, Costa Rica. https://sites.google.com/site/calandrialodge/

Daniels W.L., C.J. Everett, and L.W. Zelazny. Virgin Hardwood Forest Soils of the Southern Appalachian Mountains : I. Soil Morphology and Geomorphology. Soil Science Society of America Journal 51 : 722 – 729.

Duplay, J. K. Semhi, E. Errais, G. Imfeld, I. Babscanyi, T. Perrone. 2014. Copper, zinc, lead, and cadmium bioavailability and retention in vineyard soils (Rouffach, France): The impact of cultural practices. Geoderma 230-231: 318-328.

Franzmeier, D.P. 1988. Relation of organic carbon content to texture and color of Indiana soils. Proceedings of the Indiana Academy of Science. 98:463–471.

Gransee, A., and H. Führs. 2013. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant and Soil 368(2): 5-21.

Horneck, D.A., D.M. Sullivan, J.S. Owen, and J.M. Hart. 2011. Soil Test Interpretation Guide. Oregon State University Extension Service. 1-12.

Huggett, R.J. 1976. Soil Landscape Systems : A Model of Soil Genesis. Geoderma 13 : 1 – 22.

Jobbágy E.G., and R.B. Jackson. 2001. The Distribution of Soil Nutrients with Depth: Global Patterns and the Imprint of Plants. Biogeochemistry 53: 51-77.

Konen, M.E., C.L. Burras, J.A. Sandor. 2003. Organic Carbon, Texture, and Quantitative Color Measurement Relationships for Cultivated Soils in North Central Iowa. Soil Science Society of America 67 : 1823-1830.

Moore, I.D., A. Lewis, J.C. Gallant. 1993. Terrain Attributes : Estimation Methods and Scale Effects. In : Modelling Change in Environmental Systems. John Wiley & Sons Ltd. 1 – 26.

Nemeth, Karoly. 2010. Volcanic Glass Textures, Shape Characteristics, and Compositions of Phreatomagmatic Rock Units from the Western Hungarian Monogenetic Volcanic Fields and their Implications for Magma Fragmentation. Central European Journal of Geosciences. 2 : 399-419.

Mohammed, I., B. Ahamadou, M. Li, C. Gong, P. Cai, W. Liang, Q. Huang. Fractionation of copper and cadmium and their binding with soil organic matter in a contaminated soil amended with organic materials. Journal of Soils and Sediments 10(6): 973-982.

Nichols, J.D. 1984. Relation of organic carbon to soil properties and climate in the southern Great Plains. Soil Science Society of America Journal 164: 293 – 301.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Dep. of Agric. Circ. 939.

Paul, S., E. Veldkamp, H. Flessa. 2008. Soil Organic Carbon in Density Fractions of Tropical Soils Under Forest – Pasture – Secondary Forest Land Use Changes. European Journal of Soil Science. 59 : 359- 371.

Pennock, D.J and E. De Jong. 1990. Regional and Catenary Variations in Properties of Borolls of Southern Saskatchewan, Canada. Soil Science Society of America 54: 1697 – 1701.

Reserva Curi-cancha. 2017. “About Curi-cancha Reserve. https://reservacuri-cancha.com/about-us/.

Reuther, W. 1957. Copper and Fertility. USDA Yearbook of Agriculture, 1957. 128-135.

Sanchez-Azofeifa, G.A., Pfaff, A., Robalino, J.A., Boomhower, J.P. 2007. Costa Rica’s Payment for Environmental Services Program: Intention, Implementation, and Impact. Conservation Biology. 21 (5): 1165 – 1173.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and Soil Survey Staff. 2012. Field book for describing and sampling soils, version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Smithsonian Institution. 2013. National Museum of Natural History : Global Volcanism Program.

https://volcano.si.edu/volcano.cfm?vn=345033. Accessed 12/28/17.

Sollins, P., and J. Gregg. 2017. Soil Organic Matter Accumulation in Relation to Changing Soil Volume, Mass, and Structure : Concepts and Calculations. Geoderma. 301 : 60-71.

Steinwand, A.L. 1992. Soil Geomorphic, Hydrologic, and Sedimentologic Relationships and Evaluation of Soil Survey Data for a Mollisol Catena on the Des Moines Lobe, Central Iowa. PhD. Dissertation, Iowa State University, Ames.

Thompson, J. A., J.C. Bell, C.A. Butler. 1997. Quantitative Soil-Landscape Modeling for Estimating the Areal Extent of Hydromorphic Soils. Soil Science Society of America 61 : 971 – 980.

Tree Fruit Research and Extension Center. 2004. Washington State University. http://soils.tfrec.wsu.edu/webnutritiongood/soilprops/soilnutrientvalues.htm. Accessed 2/11/18.

USDA Natural Resource Conservation Service. 2004. Soil Survey Laboratory Methods Manual. Version 5.0. Lincoln, NE.

Volcano World. 2017. Arenal. Oregon State University. http://volcano.oregonstate.edu/arenal. Accessed 12/28/17.

Willis, S.A., C.L. Burras, J.A. Sandor. 2007. Prediction of Soil Organic Carbon Content Using Field and Laboratory Measurements of Soil Color. Soil Science Society of America 71 : 380-388.

Chapter 3 : Conclusions

My data has provided interesting insights into the nature of Costa Rican soils at Monteverde. Due to the nature of my sampling methods, project design, and limited time for conducting the study, I was unable to build a statistical model for predicting the influence of erosion at a particular point in the landscape. However, my data does allow for descriptive statistical analysis and regression analysis which has helped to illuminate some interesting relationships and trends.

Each site was different and in identifying soil-landscape relationships in Monteverde, there is no single set of rules that will apply for all sites. Nacimiento represents a typical catena. As slope degrees increase, A horizon depth decreases. This, coupled with the large difference in A horizon thickness between the pit at the footslope position and the pit at the shoulder position indicates that the site has experienced a large amount of soil movement from upslope positions to downslope positions. This has implications for restoration activities going forward. Species that require a deeper, more root accommodating material for growth should be focused in areas that tend to accumulate organic soil material rather than areas that have become eroded over the past decades. Eroded slopes at Nacimiento would be best utilized by planting more resilient species that can handle the high clay content found in those locations. Once eroded slopes have been stabilized with specialized vegetation, it will become easier over time to regenerate those sections with a more diverse set of plants.

Implications of Volcanic Influence

The soils at Monteverde have been impacted by historic eruptions originating from the nearby volcano, Arenal. My results showed a positive relationship between soil carbon and sand size particles. This suggests the soils in Monteverde are influenced by the presence of coarse volcanic ash and pumice which is instigating the accumulation of soil carbon due to its high porosity and surface area.

Working with volcanically influenced soils may be a blessing and a curse. While they have the capacity to accumulate and store soil carbon, they also have an equally impressive ability to erode. Soils that are influenced by volcanic material are lighter in weight than other soils. This makes them vulnerable to loss by erosion. This unfortunate truth may be part of what exacerbated soil loss. Moving forward with restoration will require considerable care. In tropical systems, soil carbon accumulation during restoration of pasture is still susceptible to loss and restoration efforts could be reversed if special attention is not paid to the stabilization of vulnerable slopes in pasture sites in particular (Paul et al., 2008). This is because the most recently incorporated organic material bound to mineral surfaces often binds to sites with less affinity since most high affinity sites are already occupied by pre-existing organic material (Paul et al., 2008).

Influence of Mature Trees and Tree Throws

The data indicate that in high slope areas, there may be pockets of darker and deeper A horizons compared to surrounding areas. This process is present at Finca Rodriguez on the north side of my sampling area and also at Nacimiento between the backslope and footslope positions. High slope areas vegetated by larger trees have been shown to trap soil organic matter (Daniels et al., 1987). Considering the older forest and larger trees found at Finca Rodriguez I believe they are playing a role in the pockets of darker and deeper soils found at high slope positions. These areas may be utilized for restoration planting as they present small pockets of accumulated soil organic material. Identification of these locations for future restoration plans is impractical, however, as restorers would need to seek out potential sites and sample near the trees in question to confirm the presence of the localized pocket of organic material.

Influence of Land Use History

Land use can have a large impact on the level of soil erosion and degradation in a given area. My sites were all slightly different in their land use history. Nacimiento contained a restored and active pasture. During the clearing of the forest for the establishment of the pasture at Nacimiento, a large amount of soil erosion occurred, changing the distribution of soil properties across the landscape. After cutting, Nacimiento would have had little vegetation to stabilize the soil on its slopes, leading to movement of soil downslope. Rain likely exacerbated this process and considering that this region receives significant amounts of rain annually, erosion would have occurred frequently.

Finca Rodriguez has been managed differently than Nacimiento. This is most evident when examining the vegetation present at the site. In comparison to Nacimiento, the trees at Finca Rodriguez are much older and the overall forest is more extensive. This has been a driving factor in this site's ability to prevent high levels of soil erosion and loss. Despite having high slopes, Finca Rodriguez has been able to retain much of its soil.

The undulating nature of Curi-cancha makes it difficult to make soil property and landscape predictions. The site does provide valuable information however. The importance of the intact forest is not to be overlooked. We see much more organic rich material in the soil from the intact forest compared to the soil from the restored pasture. The depth to clay in and around the intact forest is very deep. Some probes in that area were unable to reach clay, which would indicate there is a considerable amount of soil sitting above the root restrictive clay in that portion of the site.

La Calandria was purchased in 1999 for use as tropical habitat. The land was used as farmland and pasture prior to that time. The disparity between the west and east sides of the site is intriguing. The west side of the site appears to be at a slightly more advanced stage of restoration than the east side. The west side's success may be driven by either the influence of erosion from the east side, or the temporal disparity between the two sides of the site.

Crandell was once used for agriculture. There are identifiable wind breaks and evidence of terracing present at the site. It has been many years since that time as the rest of the vegetation that makes up that area's forest appears to be mature. Like Finca rodriguez, Crandell has not been as heavily influenced by slope driven erosion and appears have successful and healthy vegetation.

Nutrient Dynamics

Nutritionally speaking, the positive effect of K and P on growth are dependent on the level of N that is present (FAO, 1998). Therefore, the success of vegetation is dependent on sufficient levels of N in order to able to utilize K and P. Unfortunately, N is leached fairly easily into surface or ground water, or lost through denitrification; bad news for a region which receives 240.3 cm of rainfall annually (FAO, 1998). However, this does not necessarily mean that nutrient levels in tropical soils are inherently low due to climate. A study conducted in Hawaii in 2002 was able to show that low nutrient levels are associated with older, more stable landscapes (Porder et al., 2005). The study also indicated that areas with low slopes and catchment areas had higher levels of soil nutrients (Porder et al., 2005). This is important to consider when attempting to explain soil nutrient levels based on landscape and land use history.

Future Work

Future studies should more thoroughly examine the differences between land-use histories on soil properties in the tropics. Sites should be selected based on extensive available information about land use so that stronger linkages can be made between soil property variations across the site's landscape and prior land management practices. Site should also be selected to ensure a full topo-sequence is sampled as this will provide more comprehensive information on each site. Mineralogical analysis can also confirm the presence of volcanic ash in these tropical soils, which would provide clarification on the andic soil properties found in the study area.

References

Daniels W.L., C.J. Everett, and L.W. Zelazny. Virgin Hardwood Forest Soils of the Southern Appalachian Mountains : I. Soil Morphology and Geomorphology. Soil Science Society of America Journal 51 : 722 – 729.

Food And Agriculture Organization of the United Nations. 2010. Global Forest Resources Assessment 2010: Main report. FAO Forestry Paper 163. United Nations.

Paul, S., E. Veldkamp, H. Flessa. 2008. Soil Organic Carbon in Density Fractions of Tropical Soils Under Forest – Pasture – Secondary Forest Land Use Changes. European Journal of Soil Science. 59 : 359- 371.

Porder, S., G.P. Asner, and P.M. Vitousek. 2005. Ground-based and remotely sensed nutrient availability across a tropical landscape. Proceedings of the National Academy of Sciences of the United States of America 102 (31): 10909 – 10912.

Bibliography

Aide, T. M. et al. 2013. Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). Biotropica 45 : 262 – 271.

Aide, T. M., J.K. Zimmerman, J.B. Pascarella, L. Rivera, H. Marcano-Vega. 2000. Forest Regeneration in a Chronosequence of Tropical Abandoned Pastures : Implications for Restoration Ecology. Restoration Ecology 8 : 328 – 338.

Aide, T.M., J.K. Zimmerman, L. Herrera, M. Rosario, M. Serrano. 1995. Forest recovery in abandoned tropical pastures in Puerto Rico. Forest Ecology and Management 77: 77 – 86.

Allen, K. M.D. Corre, S. Kurniawan, S.R. Utami, E. Veldkamp. 2016. Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia. Geoderma 284 : 42 - 50.

Andriamananjara, A. N Ranaivosonm T. Razafimbelo, J. Hewson, N. Ramifehiarivo, A. Rasolohery, R. H. Andrisoa, M.A. Razafindrakoto, M. P. Razafimanantsoa, N. Rabetokotany, and R.H. Razakamanarivo. 2017. Towards a better understanding of soil organic carbon variation in Madagascar. European Journal of Soil Science 68 : 930 – 940.

Belsky, A.J., R.G. Amundson, J.M. Duxbury, S.J. Riha, A.R. Ali, and S.M. Mwonga. 1989. The Effects of Trees on Their Physical, Chemical and Biological Environments in a Semi-Arid Savanna in Kenya. Journal of Applied Ecology 26 : 1005 – 1024.

Birkel, C., C. Soulsby, D. Tetzlaff. 2012. Modelling the impacts of land-cover change on streamflow dynamics of a tropical rainforest headwater catchment. Hydrological Sciences 57: 1543 – 1561.

Bohlrnan S.A., T. J. Matelson, N.M. Nadkarni. 1995. Moisture and Temperature Patterns of Canopy Humus and Forest Floor Soil of a Montane Cloud Forest, Costa Rica. Biotropica 27 : 13 – 19.

Brady N.C. and R.R. Weil. 2010. Elements of the Nature and Properties of Soils, 3rd Edition. Prentice Hall, San Fransisco, CA.

Burras, C.L., and W.H. Scholtes. 1987. Basin Properties and Postglacial Erosion Rates of Minor

Morraines in Iowa. Soil Science Society of America. 51 : 1541-1547.

Calandria Lodge. 2012. Calandria Lodge and Sanctuary, Monteverde, Costa Rica. https://sites.google.com/site/calandrialodge/

De Camino, R, O Segura, LG Arias, and I Pérez. 2000. Costa Rica: Forest Strategy and the Evolution of Land Use. Evaluation Country Case Study Series. The World Bank, Washington, D.C.

Carpenter, F.L., J.D. Nichols, and E. Sandi. 2004. Early growth of native and exotic trees planted on degraded tropical pasture. Forest Ecology and Management 196: 367-378.

Carter, J.B., and E.J. Ciolkosz. 1991. Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. Geoderma 49: 199-213.

Clark, D.B. D.A. Clark. 2000. Landscape – scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137 : 185 – 198.

Daniels W.L., C.J. Everett, and L.W. Zelazny. Virgin Hardwood Forest Soils of the Southern Appalachian Mountains : I. Soil Morphology and Geomorphology. Soil Science Society of America Journal 51 : 722 – 729.

Dieleman, W.I.J., M. Venter, A. Ramachandra, A.K. Krockenberger, M.I. Bird. 2013. Soil carbon stocks vary predictably with altitude in tropical forests : Implications for soil carbon storage. Geoderma 204 – 205 : 59 – 67.

Duplay, J. K. Semhi, E. Errais, G. Imfeld, I. Babscanyi, T. Perrone. 2014. Copper, zinc, lead, and cadmium bioavailability and retention in vineyard soils (Rouffach, France): The impact of cultural practices. Geoderma 230-231: 318-328.

Eaton, W.D., M. Roed, O. Chassot & D. Barry. 2012. Differences in soil moisture, nutrients and the microbial community between forests on the upper Pacific and Caribbean slopes at Monteverde, Cordillera de Tilaran: implications for responses to climate change. Tropical Ecology 53(2): 235-240.

Eaton, W.D. 2010. Microbial Community Indicators of Soil Development in Tropical Secondary Forests (Costa Rica). Ecological Restoration 23 : 236 – 238.

Food And Agriculture Organization of the United Nations. 2010. Global Forest Resources

Assessment 2010: Main report. FAO Forestry Paper 163. United Nations.

Franzmeier, D.P. 1988. Relation of organic carbon content to texture and color of Indiana soils. Proceedings of the Indiana Academy of Science. 98:463–471.

Gallant, J.C., J.P. Wilson. 1996. TAPES-G : A Grid Based Terrain Analysis Program for the Environmental Sciences. Computers & Geosciences 22 : 713 – 722.

Gee, G. W., and J. W. Bauder. 1986. Particle-size Analysis. P. 383 – 411. In Methods of soil analysis, Part1, Physical and mineralogical methods. Second Edition, Agronomy Monograph 9, American Society of Agronomy, Madison, WI.

Girmay, G., B.R. Singh. 2012. Changes in soil organic carbon stocks and soil quality : land-use system effects in northern Ethiopia. 62 : 519 – 530.

Gransee, A., and H. Führs. 2013. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant and Soil 368(2): 5-21.

Häger, A., A. Dohrenbusch. 2011. Hydrometeorology and structure of tropical montane cloud forests under contrasting biophysical conditions in north-western Costa Rica. Hydrological Processes 25 : 392 – 410.

Harvey, C., and W. Haber. 1999. Remnant trees and the Conservation of Biodiversity in Costa Rican pastures. Agroforestry Systems 44 : 37 – 68.

Holl, K. D., M.E. Loik, E.H.V. Lin, I.A. Samuels. 2000. Tropical Montane Forest Restoration in Costa Rica : Overcoming Barriers to Dispersal and Establishment. Restoration Ecology. 8 : 339 – 349.

Holl, K. D., Zahawi, R. A., Cole, R. J., Ostertag, R., & Cordell, S. 2011. Planting Seedlings in Tree Islands Versus Plantations as a Large-Scale Tropical Forest Restoration Strategy. Restoration Ecology, 19(4), 470-479.

Hook P.B. and I.G. Burke. 1999. Biogeochemistry in a Shortgrass Landscape: Control by Topography, Soil Texture, and Microclimate. Ecology 81(10) : 2686 – 2703.

Honey, M. 2008. Ecotourism and Sustainable Development : Who Owns Paradise? Second edition. Island Press. Washington D.C.

Horneck, D.A., D.M. Sullivan, J.S. Owen, and J.M. Hart. 2011. Soil Test Interpretation Guide. Oregon State University Extension Service. 1-12.

Huggett, R.J. 1976. Soil Landscape Systems : A Model of Soil Genesis. Geoderma 13 : 1 – 22.

Hughes R. F. J. B. Kauffman, V.J. Jaramillo. 1999. Biomass, Carbon, and Nutrient Dynamics of Secondary Forests in a Humid Tropical Region of Mexico. Ecology 80 : 1892 – 1907.

IUCN Red List of Threatened Species. Ocotea monteverdensis. http://www.iucnredlist.org/details/full/48724260/0, accessed 5/2/18.

Jobbágy E.G., and R.B. Jackson. 2001. The Distribution of Soil Nutrients with Depth: Global Patterns and the Imprint of Plants. Biogeochemistry 53: 51-77.

Johnson I.R., A.J. Guswa, A.L. Rhodes. 2005. Meteorology of Monteverde. Technical Report Submitted to the Monteverde Institute.

Johnson K.D., F.N Scatena, W.L. Silver. 2011. Atypical soil carbon distribution across a tropical steepland forest catena. Catena 87 : 391 – 397.

Konen, M.E., C.L. Burras, J.A. Sandor. 2003. Organic Carbon, Texture, and Quantitative Color Measurement Relationships for Cultivated Soils in North Central Iowa. Soil Science Society of America 67 : 1823-1830.

Leopold, A.C. 2005. Toward Restoration of a Wet Tropical Forest in Costa Rica : A Ten-Year Report. Ecological Restoration. 23 : 230 – 234.

Lozada, J.R., E. Arends, D. Sanchez, A. Villarreal, P. Soriano, M. Costa. 2012. Vegetation Succession of Logged Forest in the Western Alluvial Plains of Venezuela. Journal of Tropical Forest Science 24 (3) : 300 – 311.

Melillo, J.M, R.A. Houghten, D.W. Kicklighter, A.D. McGuire. 1996. Tropical Deforestation and the Global Carbon Budget. Annual Review of Energy and the Environment 21 (1) : 293 – 310.

Menkhaus, S. D.J. Lober. 1995. International Ecotourism and the Valuation of Tropical Rainforests in Costa Rica. Journal of Environmental Management. 47: 1-10.

McDonald, M.A., J.R. Healey, P.A. Stevens. 2002. The effects of secondary forest clearance and subsequent land-use on erosion losses and soil properties in the Blue Mountains of

Jamaica. Agriculture, Ecosystems and Environment 92 : 1 – 19.

Mohammed, I., B. Ahamadou, M. Li, C. Gong, P. Cai, W. Liang, Q. Huang. Fractionation of copper and cadmium and their binding with soil organic matter in a contaminated soil amended with organic materials. Journal of Soils and Sediments 10(6): 973-982.

Montagnini, F. 2008. Management for Sustainability and Restoration of Degraded Pastures in the Neotropics. In: RW Myster (ed) Post Agricultural Succession in the Neotropics. Springer. New York.

Moore, I.D., A. Lewis, J.C. Gallant. 1993. Terrain Attributes : Estimation Methods and Scale Effects. In : Modelling Change in Environmental Systems. John Wiley & Sons Ltd. 1 – 26.

Nadkarni, N.M., W.A. Haber. 2009. Canopy Seed Banks as Time Capsules of Biodiversity in Pasture-Remnant Tree Crowns. Conservation Biology. 23 : 1117 – 1126.

Nadkarni, N.M., D. Schaefer, T.J. Matelson, R. Solano. 2004. Biomass and nutrient pools of canopy and terrestrial components in a primary and a secondary montane cloud forest, Costa Rica. Forest Ecology and Management 198 : 223 – 236.

Nave, L.E., G.M. Domke, K.L. Hofmeister, U. Mishra, C.H. Perry, B.F. Walters, C.W. Swanston. Reforestation can sequester two petagrams of carbon in US topsoils in a century. Proceedings of the National Academy of Sciences 115(11): 2776-2781.

Nemeth, Karoly. 2010. Volcanic Glass Textures, Shape Characteristics, and Compositions of Phreatomagmatic Rock Units from the Western Hungarian Monogenetic Volcanic Fields and their Implications for Magma Fragmentation. Central European Journal of Geosciences. 2 : 399-419.

Nichols, J.D. 1984. Relation of organic carbon to soil properties and climate in the southern Great Plains. Soil Science Society of America Journal 164: 293 – 301.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Dep. of Agric. Circ. 939.

Paul, S., E. Veldkamp, H. Flessa. 2008. Soil Organic Carbon in Density Fractions of Tropical Soils Under Forest – Pasture – Secondary Forest Land Use Changes. European Journal of Soil Science. 59 : 359- 371.

Pennock, D.J and E. De Jong. 1990. Regional and Catenary Variations in Properties of Borolls of Southern Saskatchewan, Canada. Soil Science Society of America 54: 1697 – 1701.

Porder, S., G.P. Asner, and P.M. Vitousek. 2005. Ground-based and remotely sensed nutrient availability across a tropical landscape. Proceedings of the National Academy of Sciences of the United States of America 102 (31): 10909 – 10912.

Ray, D. K., S. N. Udaysankar, R.O. Lawton, R. M. Welch, R. A. Pielke Sr. 2006. Impact of land use on Costa Rican tropical montane cloud forests: Sensitivity of orographic cloud formation to deforestation in the plains. Journal of Geophysical Research 111: 1 – 16.

Reserva Curi-cancha. 2017. "About Curi-cancha Reserve. https://reservacuri-cancha.com/about-us/.

Reuter, R. 2017. Soil and tropical forest restoration, Costa Rica: project proposal. Oregon State University. 1-5.

Reuther, W. 1957. Copper and Fertility. USDA Yearbook of Agriculture, 1957. 128-135.

Rhoades, C.C., G.E. Eckert, D.C. Coleman. 1998. Effect of Pasture Trees on Soil Nitrogen and Organic Matter: Implications for Tropical Montane Forest Restoration. Restoration Ecology 6 : 262 – 270.

Rosemary F., U.W.A. Vitharana. S.P. Indraratne, R. Weerasooriya., U. Mishra. 2017. Exploring the spatial variability of soil properties in an Alfisol soil catena. Catena 150 : 53 – 61.

Sanchez-Azofeifa, G.A., Pfaff, A., Robalino, J.A., Boomhower, J.P. 2007. Costa Rica's Payment for Environmental Services Program: Intention, Implementation, and Impact. Conservation Biology. 21 (5): 1165 – 1173.

Schedlbauer, J.L., K.L. Kavanagh. 2008. Soil carbon dynamics in a chronosequence of secondary forests in northeastern Costa Rica. Forest Ecology and Management 255 : 1326 – 1335.

Schlawin, J. R.A. Zahawi. 2008. "Nucleating" succession in recovering neotropical wet forests: The legacy of remnant trees. Journal of Vegetation Science 19 : 485 – 492.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and Soil Survey Staff. 2012. Field book for describing and sampling soils, version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Seibert J., J. Stendahl, R. Sorensen. 2007. Topographical influences on soil properties in boreal forests. Geoderma 141 : 139 – 148.

Sheldon, K.S. and N.M. Nadkarni. 2013. The use of pasture trees by birds in a tropical montane landscape in Monteverde, Costa Rica. Journal of Tropical Ecology 29: 459 – 462.

Sierra, J. and F. Causeret. 2018. Changes in soil carbon inputs and outputs along a tropical altitudinal gradient of volcanic soils under intensive agriculture. Goederma 320 : 95 – 104.

Smithsonian Institution. 2013. National Museum of Natural History : Global Volcanism Program. https://volcano.si.edu/volcano.cfm?vn=345033. Accessed 12/28/17.

Sollins, P., and J. Gregg. 2017. Soil Organic Matter Accumulation in Relation to Changing Soil Volume, Mass, and Structure : Concepts and Calculations. Geoderma. 301 : 60-71.

Spracklen, B.D., M. Kalamandeen, D. Galbraith, E. Gloor, D.V. Spracklen. 2015. A Global Analysis of Deforestation in Moist Tropical Forest Protected Areas. Plos One : 1 – 16.

Steinwand, A.L. 1992. Soil Geomorphic, Hydrologic, and Sedimentologic Relationships and Evaluation of Soil Survey Data for a Mollisol Catena on the Des Moines Lobe, Central Iowa. PhD. Dissertation, Iowa State University, Ames.

Tanner, L.H., D.L. Smith, J. Curry, J. Twist. 2014. Effect of Land Use Change on Carbon Content and CO_2 Flux of Cloud Forest Soils, Santa Elena, Costa Rica. Open Journal of Soil Science 4 : 64 – 71.

Tobón, C., L.A. Bruinjnzeel, K.F.A. Frumau, J.C. Calvo-Alvarado. 2010. Changes in soil physical properties after conversion of tropical montane cloud forest to pasture in northern Costa Rica. Tropical Montane Cloud Forests : Science for Conservation and Management. Cambridge University Press : 502 – 515.

Torrent, J., U. Schwertmann, H. Fechter, and F. Alvarez. 1983. Quantatative relationships between soil color and hematite content. Soil Science 136 : 354 – 358.

Torrent, J., U. Schwertmann, and D.G. Schultze. 1980. Iron oxide minerology of some soils of two river terrace sequences in Spain. Geoderma 23 : 191 – 208.

Thompson, J. A., J.C. Bell. 1996. Color Index for Identifying Hydric Conditions for Seasonally

Saturated Mollisols in Minnesota. Soil Science Society of America. 60 : 1979-1988.

Thompson, J. A., J.C. Bell, C.A. Butler. 1997. Quantitative Soil-Landscape Modeling for Estimating the Areal Extent of Hydromorphic Soils. Soil Science Society of America 61 : 971 – 980.

Tree Fruit Research and Extension Center. 2004. Washington State University. http://soils.tfrec.wsu.edu/webnutritiongood/soilprops/soilnutrientvalues.htm. Accessed 2/11/18.

Tropical Scientific Center. "Ecological Map of Costa Rican Life Zones" [map]. 1 : 400,000. https://www.mediafire.com/view/?jr1lmsey0uu288z. Accessed 5/3/18

Ugolini, F.C. and R.A. Dahlgren. 2002. Soil Development in Volcanic Ash. University of Florence and University of California, Davis. Manuscript draft.

Volcano World. 2017. Arenal. Oregon State University. http://volcano.oregonstate.edu/arenal. Accessed 12/28/17.

Wang, Z., T. Hoffman, J. Six, J.O. Kaplan, G. Grovers, S. Doetteri, & K.V. Oost. 2017. Human-induced erosion has offset one-third of carbon emissions from land cover change. Nature Climate Change 7 : 345-349.

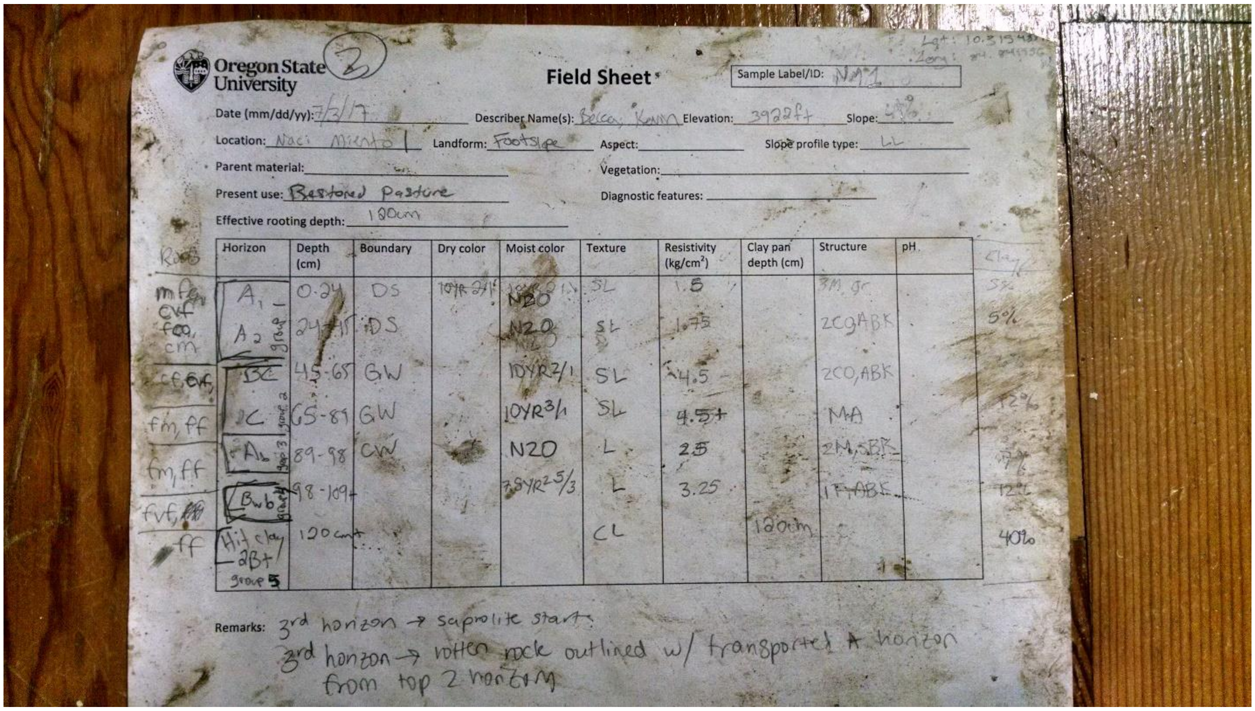
Wheelwright, N.T. 1983. Fruits and the Ecology of Resplendent Quetzals. American Ornithological Society 100: 286 - 301.

Willis, S.A., C.L. Burras, J.A. Sandor. 2007. Prediction of Soil Organic Carbon Content Using Field and Laboratory Measurements of Soil Color. Soil Science Society of America 71 : 380-388.

Wijdeven, S.J. and M.E. Kuzee. 2000. Seed availability as a limiting factor in forest recovery processes in Costa Rica. Restoration Ecology 8 : 414-424.

Zhou, W.P., W.J. Shen, Y.E. Li, D.F. Hui. 2017. Interactive Effects of Temperature and Moisture on Composition of the Soil Microbial Community. European Journal of Soil Science 68: 909-918.

Appendix



Oregon State University

Field Sheet

Sample Label/ID: NM1

Date (mm/dd/yy): 7/3/17 Describer Name(s): Becca, Kevin Elevation: 3922ft Slope: 4%

Location: Naci Miento 1 Landform: Footslope Aspect: Slope profile type: LL

Parent material: Vegetation:

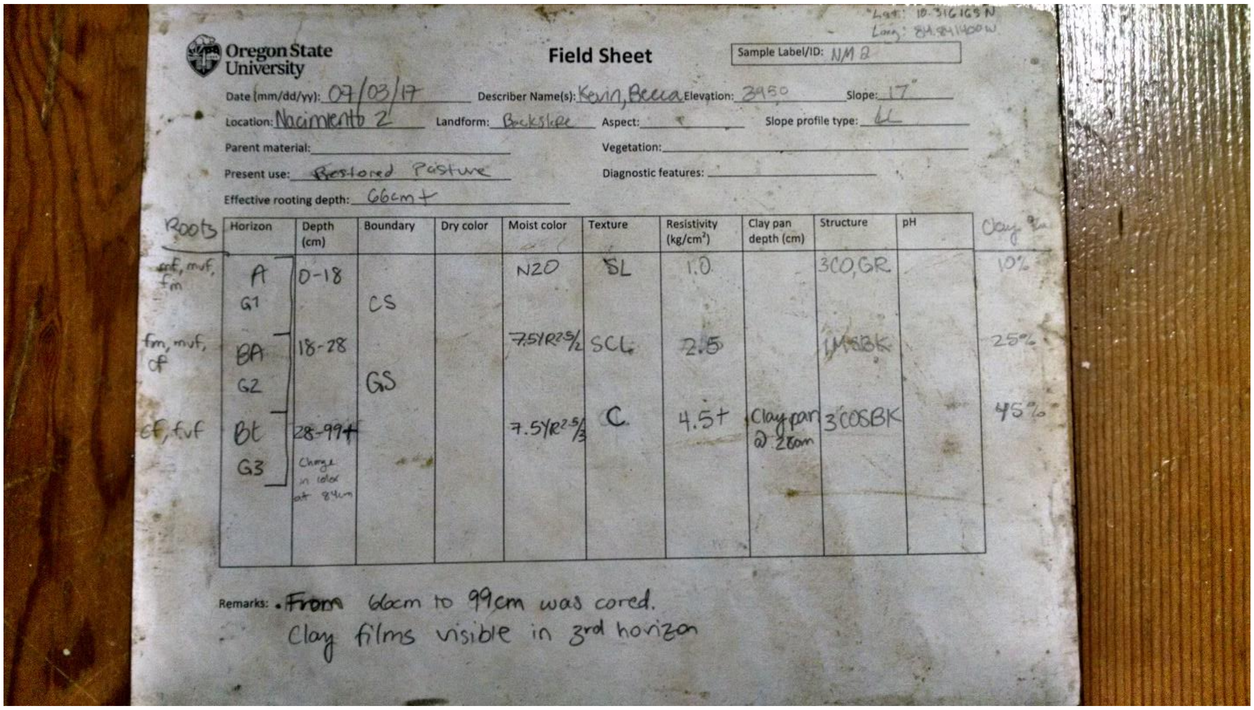
Present use: Restored pasture Diagnostic features:

Effective rooting depth: 120cm

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
m fc, cvf	A1 (group 1)	0-24	DS	10YR 2/1	N2O	SL	1.5		3M, gr		5%
fco, cm	A2 (group 1)	24-45	DS		N2O	SL	1.75		2CO, ABK		5%
cf, cvf	BC (group 2)	45-65	GW		10YR2/1	SL	4.5		2CO, ABK		
fm, ff	C (group 2)	65-89	GW		10YR3/1	SL	4.5+		MA		12%
fm, ff	Ab (group 3)	89-98	CW		N2O	L	2.5		2M, SBK		7%
fvf	Bwb (group 4)	98-109+			7.5YR 2.5/3	L	3.25		1F, ABK		12%
ff	Hit clay 2Bt (group 5)	120cm+				CL		120cm			40%

Remarks: 3rd horizon → saprolite starts
3rd horizon → rotten rock outlined w/ transported A horizon from top 2 horizons

Figure 1. Nacimiento footlsope pit description sheet.



Lat: 10.316163 N
Long: 84.841400 W

Oregon State University

Field Sheet

Sample Label/ID: NM 2

Date (mm/dd/yy): 07/03/17 Describer Name(s): Kevin, Becca Elevation: 3450 Slope: 17°

Location: Nacimiento 2 Landform: Backslope Aspect: Slope profile type: LL

Parent material:

Vegetation:

Present use: Restored Pasture

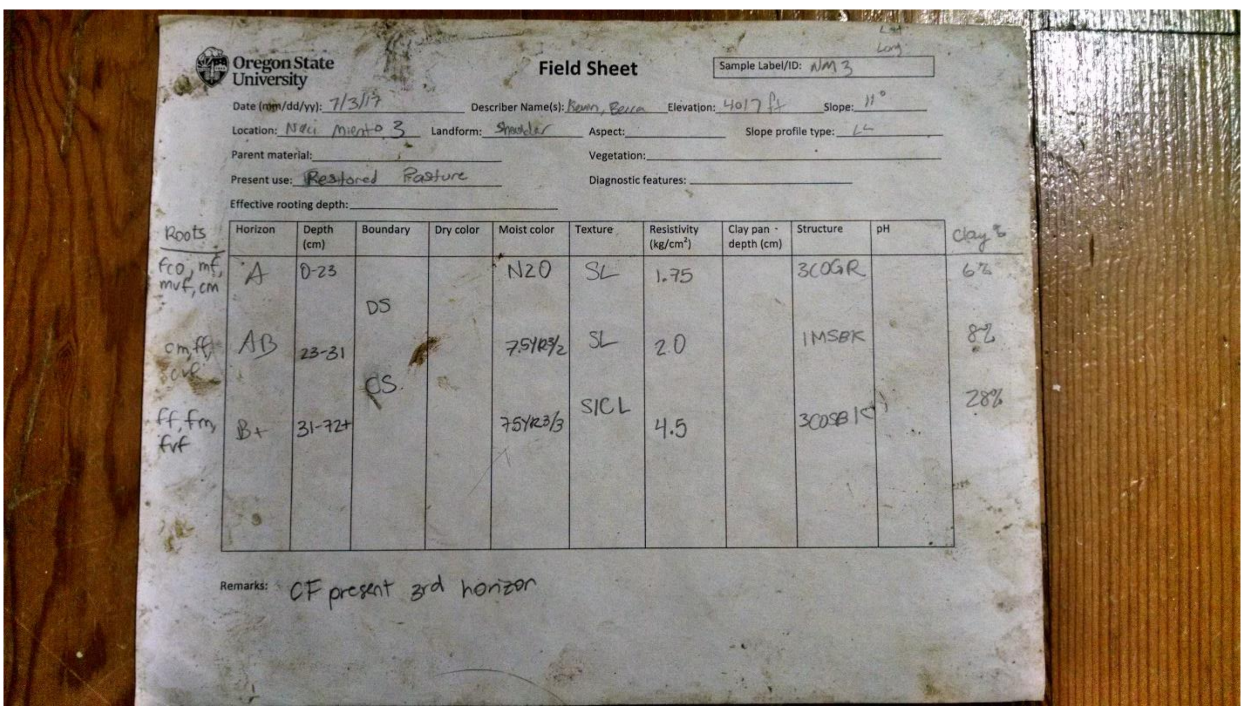
Diagnostic features:

Effective rooting depth: 66cm +

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
cf, mvf, fm	A G1	0-18	CS		N2.0	SL	1.0		3CO,GR		10%
fm, mvf, cf	BA G2	18-28	GS		7.5YR2.5/2	SCL	2.5		1MSBK		25%
cf, fvf	Bt G3	28-99+ Change in color at 84cm			7.5YR2.5/3	C	4.5+	Claypan @ 28cm	3COSBK		45%

Remarks: • From 66cm to 99cm was cored.
Clay films visible in 3rd horizon

Figure 2. Nacimiento backslope pit description sheet.



Lat
Long

Oregon State University

Field Sheet

Sample Label/ID: NM 3

Date (mm/dd/yy): 7/3/17 Describer Name(s): Kevin, Becca Elevation: 4017 ft Slope: 11°

Location: Naci miento 3 Landform: Shoulder Aspect: Slope profile type: LL

Parent material:

Vegetation:

Present use: Restored Pasture

Diagnostic features:

Effective rooting depth:

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
fco, mf, mvf, cm	A	0-23	DS		N2.0	SL	1.75		3COGR		6%
cm, ff, cvf	AB	23-31	CS		7.5YR3/2	SL	2.0		1MSBK		8%
ff, fm, fvf	Bt	31-72+			7.5YR3/3	SICL	4.5		3COSBK		28%

Remarks: CF present 3rd horizon

Figure 3. Nacimiento shoulder pit description sheet.

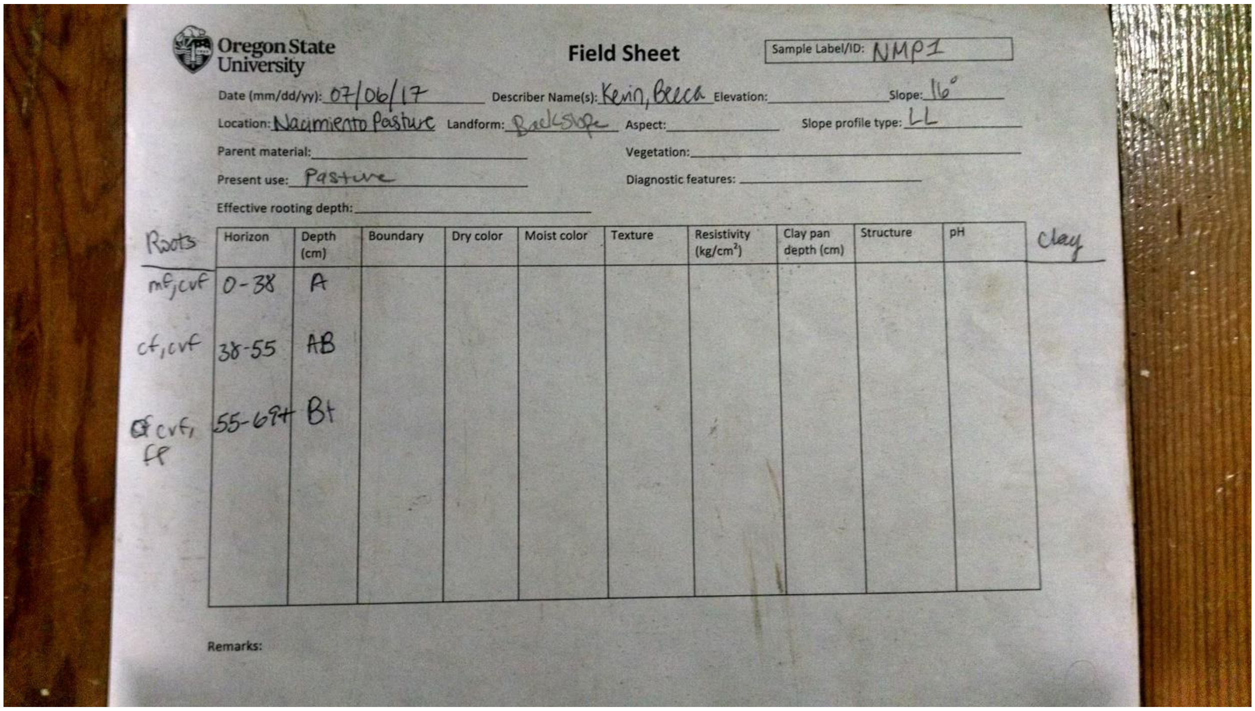


Figure 4. Nacimiento active pasture pit description sheet.

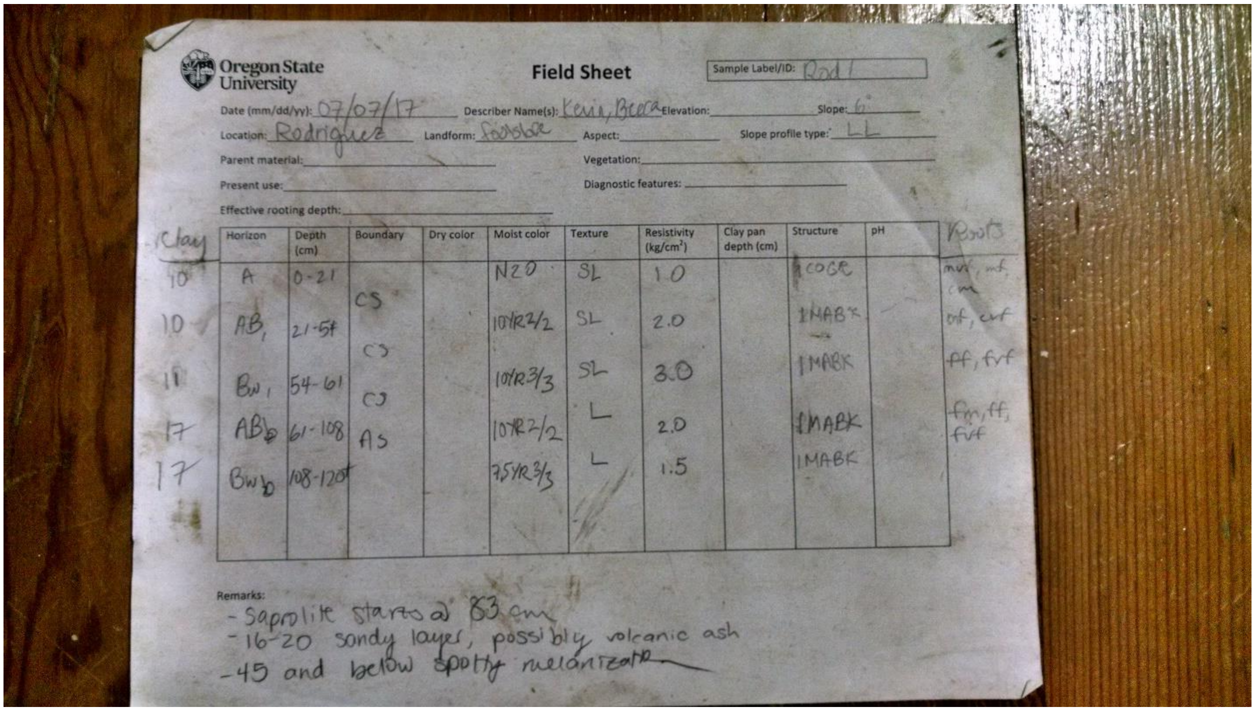
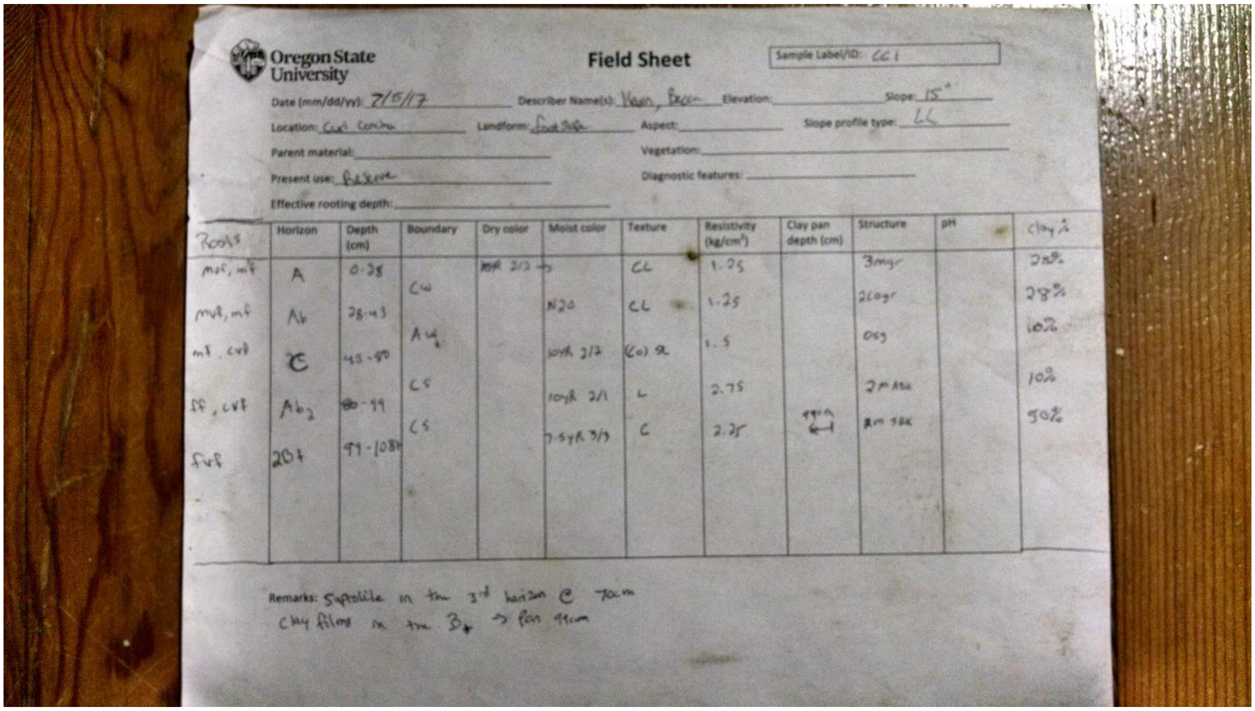


Figure 5. Finca Rodriguez pit description sheet.



Oregon State University

Field Sheet

Sample Label/ID: CC1

Date (mm/dd/yy): 7/5/17 Describer Name(s): Kevin, Becca Elevation: Slope: 15°

Location: Curi Cancha Landform: Foot Slope Aspect: Slope profile type: LL

Parent material: Vegetation:

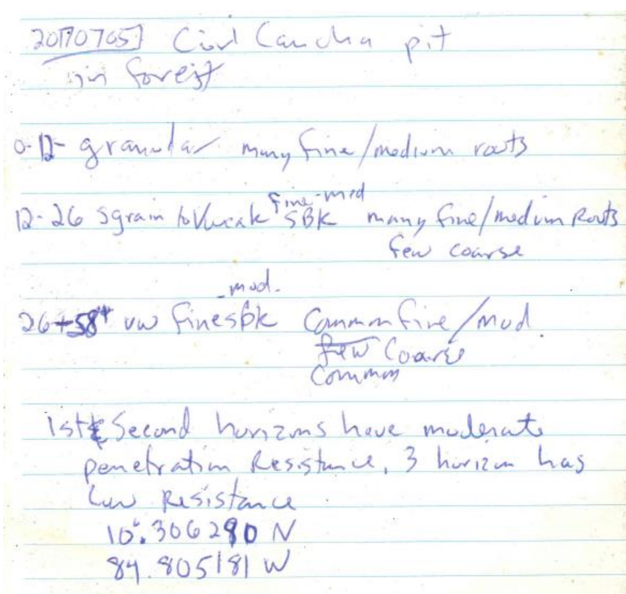
Present use: Reserve Diagnostic features:

Effective rooting depth:

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
mvf, mf	A	0-28	CW	10YR 2/2 →		CL	1.25		3mgr		28%
mvf, mf	Ab	28-43			N20	CL	1.25		2Cogr		28%
mf, cvf	C	43-80	AW		10YR 2/2	(Co) SL	1.5		osg		10%
ff, cvf	Ab2	80-99	CS		10YR 2/1	L	2.75		2mAbk		10%
fvf	2Bt	99-108+	CS		7.5YR 3/3	C	2.25	99cm ↔	2m sbk		50%

Remarks: Saprolite in the 3rd horizon @ 70cm
Clay films in the Bt → from 99cm

Figure 6. Curi-cancha restored pasture pid description sheet.



20170705 Curi Cancha pit
in forest

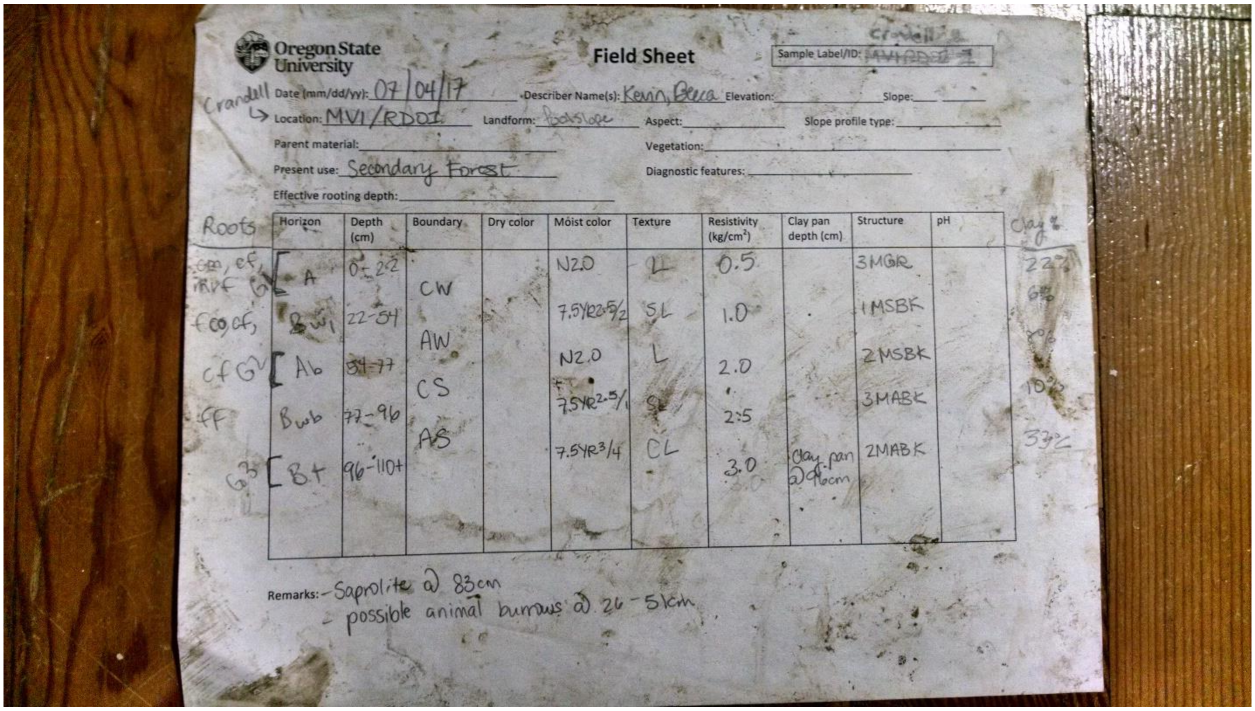
0-12 granular many fine/medium roots

12-26 sgran to weak fine-med SBK many fine/medium Roots
few coarse

26-58+ vw fine mod. SBK Common fine/mod.
~~few~~ Common Coarse

1st & Second horizons have moderate
penetration Resistance, 3 horizon has
low Resistance
10°.306280 N
84.805181 W

Figure 7. Curi-cancha in-tact forest pit description sheet.


Oregon State University

Field Sheet

Sample Label/ID: Crandell

Date (mm/dd/yy): 07/04/17 Describer Name(s): Kevin, Becca Elevation: Slope:

Location: MVI/RDDI Landform: Backslope Aspect: Slope profile type:

Parent material: Vegetation:

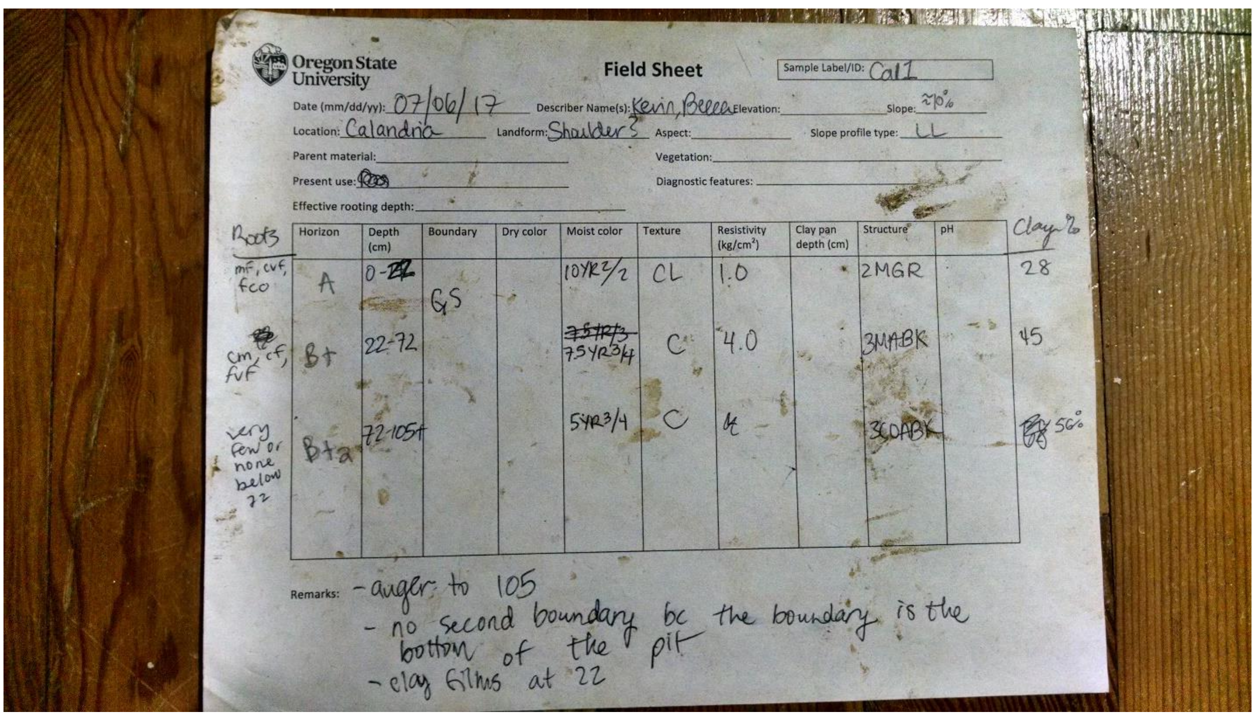
Present use: Secondary Forest Diagnostic features:

Effective rooting depth:

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
cm, cf, mvf	A	0-22	CW		N2.0	L	0.5		3MGR		22%
fco, cf	Bw1	22-54	AW		7.5YR2.5/2	SL	1.0		1MSBK		6%
cf	Ab	54-77	CS		N2.0	L	2.0		2MSBK		
ff	Bwb	77-96	AS		7.5YR2.5/1	SL	2.5		3MABK		10%
	Bt	96-110+			7.5YR3/4	CL	3.0	Clay pan @ 96cm	2MABK		33%

Remarks: - Saprolite @ 83cm
- possible animal burrows @ 26-51cm

Figure 8. Crandell pit description sheet.


Oregon State University

Field Sheet

Sample Label/ID: Cal1

Date (mm/dd/yy): 07/06/17 Describer Name(s): Kevin, Becca Elevation: Slope: ~10%

Location: Calandria Landform: Shoulder? Aspect: Slope profile type: LL

Parent material: Vegetation:

Present use: [illegible]

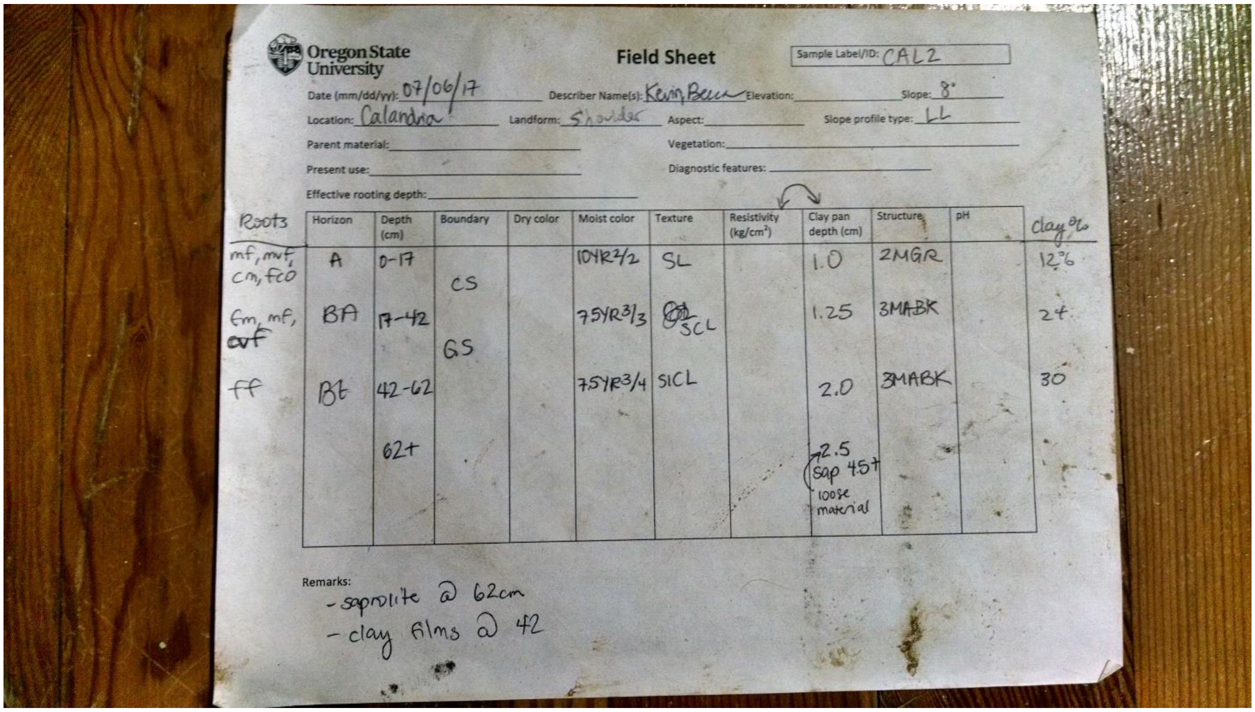
Diagnostic features:

Effective rooting depth:

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	Clay %
mf, cvf, fco	A	0-22	GS		10YR2/2	CL	1.0		2MGR		28
cm, cf, fvf	Bt	22-72			~~7.5YR3/3~~ 7.5YR3/4	C	4.0		3MABK		45
very few or none below 72	Bt2	72-105+			5YR3/4	C	[illegible]		3COABK		56%

Remarks: - auger to 105
- no second boundary bc the boundary is the bottom of the pit
- clay films at 22

Figure 9. La Calandria first pit description sheet.



Oregon State University

Field Sheet

Sample Label/ID: CAL2

Date (mm/dd/yy): 07/06/17 Describer Name(s): Kevin Bean Elevation: Slope: 8°

Location: Calandria Landform: Shoulder Aspect: Slope profile type: LL

Parent material: Vegetation:

Present use: Diagnostic features:

Effective rooting depth:

Roots	Horizon	Depth (cm)	Boundary	Dry color	Moist color	Texture	Resistivity (kg/cm²)	Clay pan depth (cm)	Structure	pH	clay %
mf, mvf, cm, fco	A	0-17	CS		10YR2/2	SL		1.0	2MGR		12%
fm, mf, cvf	BA	17-42	GS		7.5YR3/3	SCL		1.25	3MABK		24
ff	Bt	42-62			7.5YR3/4	SICL		2.0	3MABK		30
		62+						2.5 Sap 45+ loose material			

Remarks:
- saprolite @ 62cm
- clay films @ 42

Figure 10. La Calandria second pit description sheet.