

THE EFFECTS OF LAND USE ON PHYSICAL AND CHEMICAL PROPERTIES ON  
TROPICAL SOILS, COSTA RICA

by

BRYAN WALLACE TOWER

Bachelor of Science, 2002  
Colorado State University  
Fort Collins, Colorado

Bachelor of Science, 2008  
Oregon State University  
Corvallis, Oregon

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## INTRODUCTION AND BACKGROUND

*For in the end we will conserve only what we love. We will love only what we understand. And we will understand only what we are taught.*

Baba Dioum, African Conservationist, 1968

It is widely established that deforestation and the resulting land conversion in the tropics is having a significant impact on global terrestrial and atmospheric cycles. As tropical forests are harvested and cleared for multiple purposes, land becomes degraded which jeopardizes the ecosystem services that contribute to human health and planetary sustainability (Sanchez-Azofeifa et al. 2001). Forest conversion results in large inputs of carbon dioxide to the atmosphere as biomass is burned and soil organic carbon is disturbed (Powers et al. 2004). Forest clearing by cutting, drying, and burning vegetation releases 25-35% of above ground vegetative carbon to the atmosphere alone (Steininger et al. 2001). Prior to the 20<sup>th</sup> century, land use change was the dominant source of increasing carbon dioxide levels in the atmosphere. While land use change only contributes a relatively small amount to atmospheric carbon dioxide levels in relation to the combustion of fossil fuels today, land use change is the most significant cause of increasing concentrations of the greenhouse gases methane and nitrous oxide (Vitousek, 1994). Moreover, fires associated with deforestation add carbon monoxide and nitric oxide to the atmosphere, which alters the reactive chemistry and creates conditions of urban-like oxidant air pollution in the tropics. These fires also generate aerosols that affect regional and global climates (Vitousek, 1994).

Deforestation rates continue to climb in countries around the planet, now approaching 13 million hectares a year (FAO, 2005). However, net rates of deforestation have decreased due to natural forest expansion, forest planting, and forest restoration (FAO, 2005). Net forest area from 2000 to 2005 decreased by 7.3 million hectares per year, down from 8.9 million hectares per year from 1990 to 2000. The largest net loss of forests, 4.3 million hectares per year, occurred in South America between 2000 and 2005. This was followed by Africa at 4.0 million hectares per year during the same time period (FAO, 2005).

The most frequently cited motive for deforestation is agricultural expansion (Skole et al, 1994). An ever-burgeoning human population is commonly cited as the reason for agricultural expansion, especially in the developing countries that are home to most of the world's tropical forests (Skole et al. 1994). Much of the land in the neotropics is re-growing into secondary forest, while some is used for tillage agriculture; however, large amounts are being converted to pasture for cattle ranching (Reiners et al. 1994). Presently, approximately 11% (1.5 million hectares) of the planet's 13.4 million hectares of land area are cultivated and approximately 3 million hectares is tillable (Troeh et al. 2005). However, much of the untilled and uncultivated land areas have lower potential yields than those currently being used and vast amounts are already used as grazing land or are forested (Troeh et al. 2005). In order to convert more land for cultivation or grazing, presently forested areas will continue to be deforested (Skole et al. 1994).

Deforestation and land use change significantly impact local and global land-atmosphere interactions, hydrology, sediment transport, global carbon budget, atmospheric chemistry, sustainability, biodiversity, and soil properties. Physical and chemical soil properties are indicators of soil fertility and can be used to examine the soil changes that correlate with changes from primary forest to pasture and abandoned pasture to secondary forest (Reiners et al. 1994). Changes in the hydrologic cycle associated with the conversion of forest to pasture, which are commonly re-vegetated with non-native African grasses, can result in major losses of limiting elements through leaching. Introduced African grasses are also demanding water users that have high photosynthetic rates which produce profuse amounts of biomass. These aggressive exotic grasses can significantly affect the water balance of entire ecosystems and drainage basins (Williams & Baruch, 2000). While land use change results in changes in nutrient cycling, the degree of change varies widely among differing climates, soil types, and management strategies (Cleveland et al. 2003). The higher temperatures and moisture levels, that occur in the tropics, results in high organic matter production and also accelerates the rate of weathering which increases the iron oxide contents in the soils. Organic matter content concentrations are low on the other hand due to rapid rates of decomposition (Troeh et al. 2005).

Since topographic differences can result in major soil differences, it is important to consider slope orientation effects on pedogenesis. When evaluating soil differences within a range of tens of meters, regional climate can be considered constant. It can also be argued that slope aspect has less influence on soils in equatorial regions than

on those that occur between 40 and 60° latitudes (Birkeland, 1999). However, no matter the location it is important to consider the toposequence, or catena, of a landscape. Catena, derived from the Latin word for chain, is a concept that is utilized to describe the interactions between soil materials that result from erosion, transport and deposition of surface materials as well as the results of leaching, translocation and deposition of the chemical components of a soil (Lal, 2002). Since the tropics have high levels of precipitation, understanding these interactions is pivotal to understanding the effects of land use upon soils in a tropical basin.

Often regarded as model for developing nations, Costa Rica has set aside approximately one-fourth of the nation's land for conservation. Presently home to between 4 to 5 percent of the world's animal and plant species, Costa Rica is at the forefront of biological study and conservation (Sanchez-Azofeifa et al. 2001). By attempting to balance economic development and conservation, Costa Rica is an ideal location to study land conversion and resulting environmental issues. Once almost completely covered in forest, the country now bears the scars of colonization and development. However, Costa Rica is currently a working model of ecological protection and home to a successful eco-tourism industry. By setting aside large tracts of land for conservation, Costa Rica is a perfect location to compare changes in soil properties with changes in land use.

In this thesis, questions regarding soil properties and how they relate to land use and land use change will be addressed. Research was completed at the Texas Christian University San Ramon Tropical Research Station (TCU SRTRS) located in

the Tilaran Mountains in the province of Alajuela, Costa Rica. Over a period of three weeks in July of 2009, a series of soil pits were dug in primary forest, secondary forest, and deforested area in order to describe the soil profiles and take core samples for physical and chemical analysis. Local knowledge regarding previous land use change was gained by interviewing the landowner, Gustavo Orozco. After the three types of land use were identified and mapped, a series of four soil pits were dug in each land use following a geomorphological catena (summit shoulder, backslope, footslope, and toeslope) in order to further examine how hill slope position influences soil properties. The study was conducted with the understanding that while soil patterns of the world are controlled largely by climate, topography controls local soil patterns (Troeh et al. 2005). The following questions will be addressed:

1. How does land use change effect physical and chemical soil properties in a tropical basin? Specifically, how will these properties change due to the deforestation of primary forest?
2. How will physical and chemical soil properties change as deforested areas re-grow into secondary forest?
3. How are soils in differing land uses influenced by topographic setting?

## METHODOLOGY

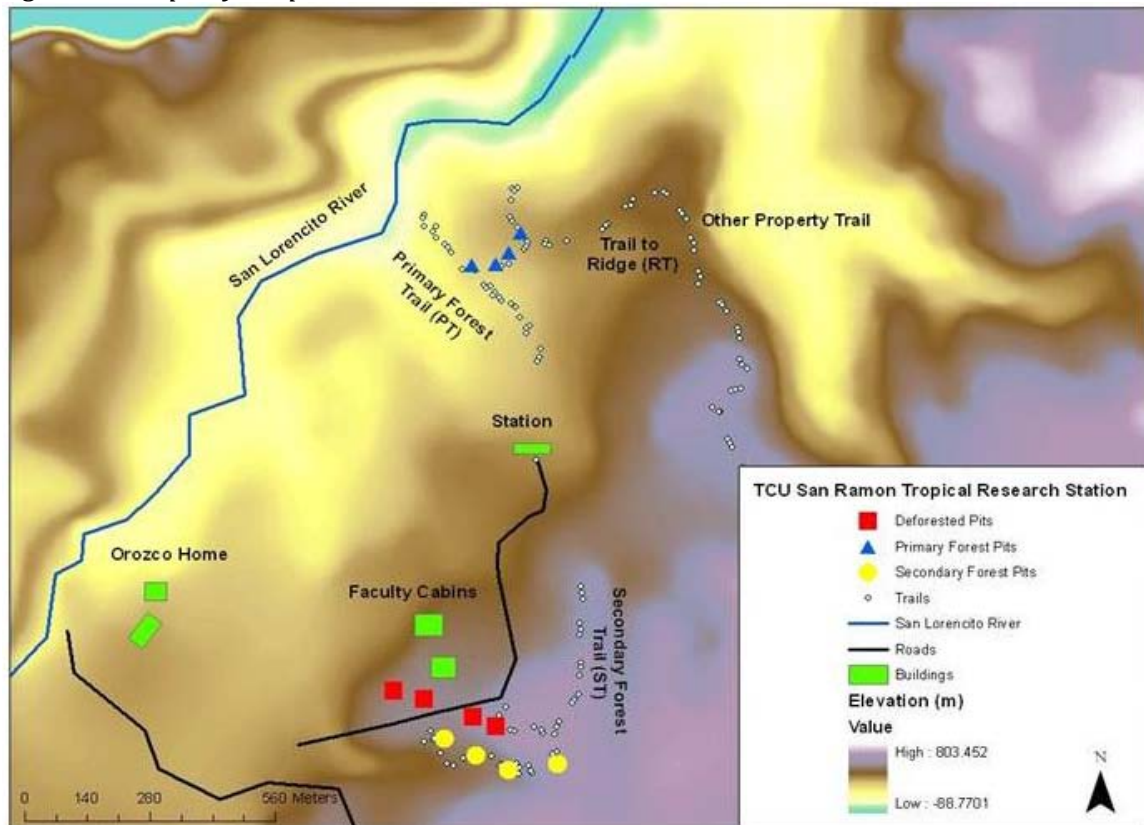
### *Study Site*

The study site is located on the Caribbean slope of the continental divide of the *Cordillera de Tilarán* (The Tilaran Mountain Range) in the province of Alajuela, Costa Rica (Zamora et al., 2009) (Fig. 1). The 100 hectare property (Ozenick, 2010) (Fig. 2), between 720 meters and 760 meters above mean sea level (Schlipmann, 2009), has a tropical climate that is characterized by approximately 247.5 to 497.4 centimeters of rain annually (FAO, 2010) and a mean annual temperature of 22.2° C (Leemans & Cramer, 1991).

*Figure 1. Map of Costa Rica with Research Station*



Figure 2. Property Map with Soil Pit Locations



The climate is further characterized by a rainy season from May to October (196.3 centimeters) and a dry season from November to April (51.8 centimeters). Average temperatures remain relatively constant (22.17° C rainy and 22.8° C dry) during the two seasons (Leemans & Cramer, 1991).

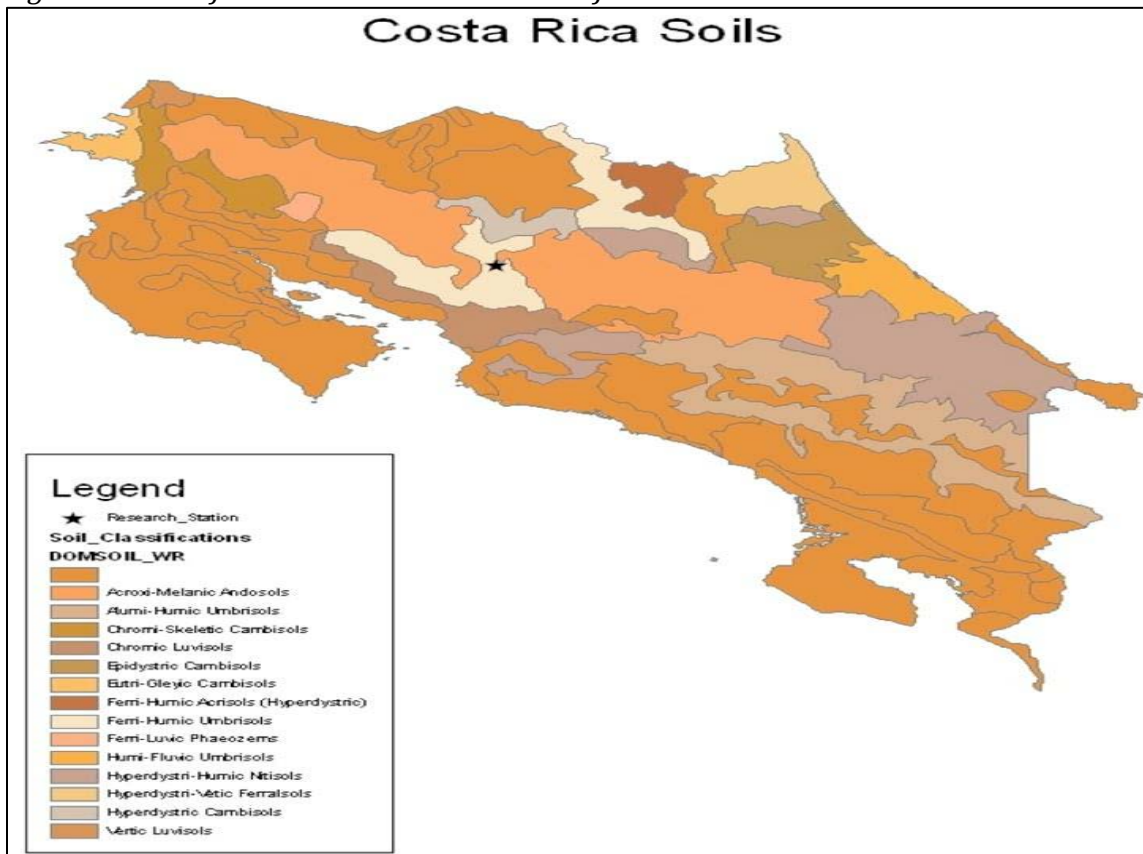
The property was purchased by the current landowner Gustavo Orozco in 1993. Mr. Orozco and Alfonso Orozco, a full-time ranch hand, reside at the property.

Information regarding land use history was gathered by interviewing the land owner. By assuming the three land uses studied can be viewed as a chronological sequence (primary to deforested, deforested to secondary, and secondary to primary), we can use the primary forest as a baseline comparison for the long-term

end result of secondary forest (Reiners et al. 1994). Deforested areas were used for cattle grazing pasture until 2007 when the cattle were removed. The land has since been left fallow and consists primarily of African grasses and small shrubs. Areas of secondary forest are sites where primary forest was harvested for timber, the land was then used as cattle pasture, and then the cattle were removed and the forest was allowed to re-grow. Ages of secondary forest vary between 15 to 30 years in age after the cessation of cattle grazing (Orozco, personal communication, 2009).

Soils within the property's boundaries are classified as ferri-humic umbrisols (Fig. 3) by the Food and Agriculture Organization (FAO, 1998).

Figure 3. Soils of Costa Rica under FAO classification

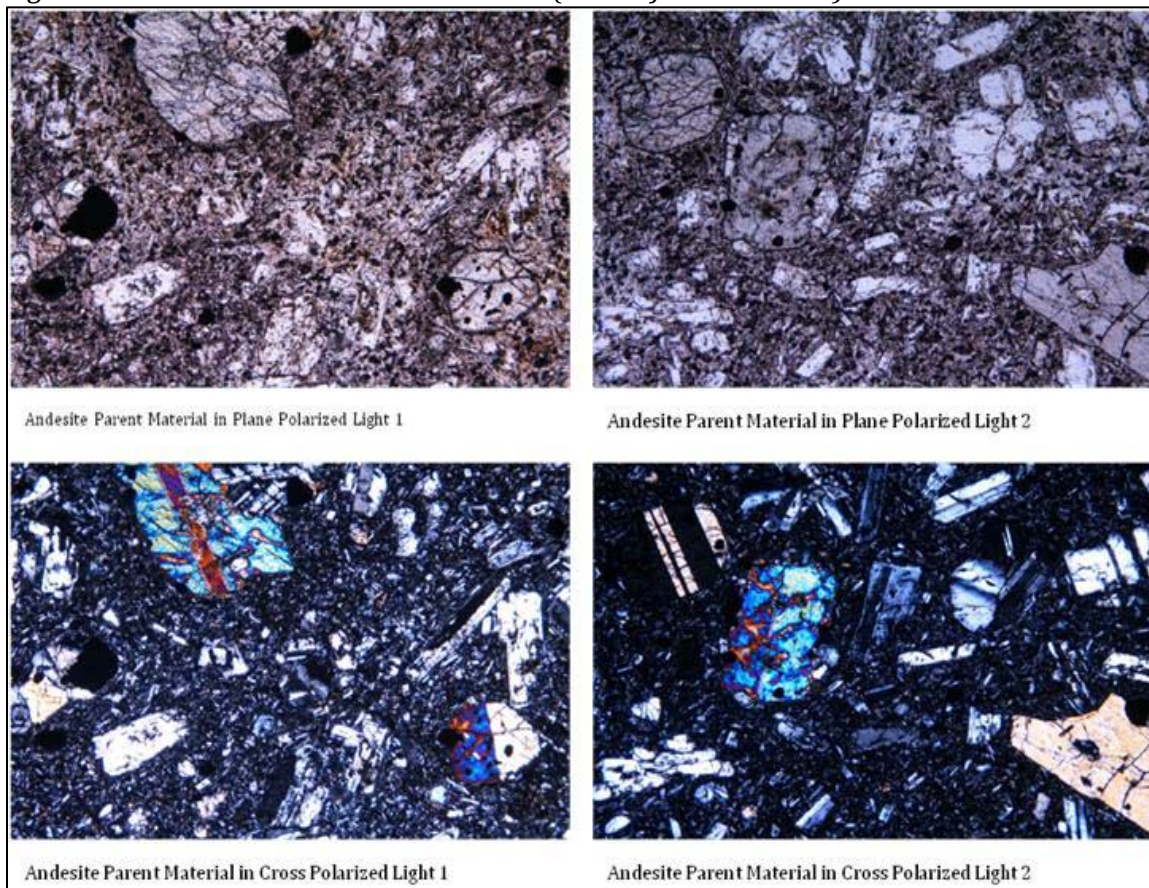


By comparison, a similar soil would be classified as an Inceptisol, suborder Udepts, by the Natural Resource Conservation Service (NRCS) (USDA, 1999). The World Reference Base for soil resources describe umbrisols as:

Soils in which organic matter has accumulated within the mineral surface soil (in most cases with low base saturation) to the extent that it significantly affects the behavior and utilization of the soil. Umbrisols are the logical counterpart of soils with a *mollic* horizon, which have high base saturation throughout. Not previously recognized at such a high taxonomic level, many of these soils are classified in other systems as: several Great Groups of *Entisols* and *Inceptisols* (United States of America). *Parent material*: weathered siliceous rock. *Environment*: humid climates; common in mountainous regions with little or no moisture deficit, in mostly cool areas but including tropical and subtropical mountains (FAO, 1998).

Andesitic parent material was confirmed by rock thin section (Fig. 4).

Figure 4. Parent Material in Thin Section (Field of View = 2mm)



Phenocrysts consist of plagioclase, augite and enstatite. The groundmass is rich in randomly oriented plagioclase microlites. Along edges of the thin section, it appears that hematite and goethite are replacing the igneous phases (Hanson, personal communication, 2010).

### *Field Limitations*

The primary problems considered for research were remoteness of research facility and the lack of sufficient electricity to dry samples in order to calculate bulk density, porosity, and run chemical analyses. It was determined that four hours of generator time per day was the maximum possible due generator capacity and diesel resupply schedule. The Natural Resources Conservation Council (USDA, 2004) states 110° Celsius for 48 hours (or until weight is constant) is necessary for sufficient soil sample drying time. Since this was not possible in the field, an alternative method was created using a conventional convection toaster oven that could dry smaller samples in three hours.

An initial test was run to establish a drying time by saturating nine soil samples in nine soil crucibles for 24 hours and then drying the samples for two hours at 230° Fahrenheit. It was determined that two hours was an insufficient drying time so the test was rerun for three hours at 230° Fahrenheit. Upon reweighing the samples and recording the weights, the samples were then dried for an additional three hours. It was determined that there was no further mass loss between a time of three hours and then again at six hours. Therefore the samples had been completely dried at three hours.

Other problems considered included: language barrier when gathering local knowledge, low accuracy of GPS device due to canopy and cloud cover, and shipping tropical soil to United States.

### *Field Methodology*

Upon arrival at the research station, sites representing all three land uses at the facility were hiked and possible soil pit sites were identified by flagging trees. In order to study soils within three separate land use catenas, four soil pits were dug in succession starting at the highest hillslope elevation location (summit shoulder) and then moving down slope (toeslope). The summit shoulder position was determined by identifying a convex segment at the top of a hillslope and toeslope was identified as where the slope flattened out and terminated. This was designed to create a consistent surveying and sampling method. Sites were chosen based on land use type, topographic location, aspect, accessibility, and safety. Before each pit was dug, preliminary data such as time, temperature, weather, location, and vegetation were noted.

### Soil Morphology Identification and Classification Process:

Pits were dug by hand to a depth of 120cm and a width of 85cm. In a few cases, pits were completed at approximately 100cm due to rocks and heavy clays. After pits were dug, they were photographed and thoroughly described. Three soil cores per soil pit were taken with an AMS soil core slide hammer at depths of 10 cm, 30 cm, and at 100 cm. The cores were sealed in core sleeves with plastic caps and dried at the research station. Weights were recorded before and after drying in order to

measure soil water content which was used to calculate soil bulk density and porosity. Dried samples were bagged and labeled for shipping.

Soil profile morphological descriptions include:

- a) Horizonation
- b) Boundary depth (cm)
- c) Soil texture: ribbon and knife method
- d) Soil color (wet): color identified by hue, value, chroma using a Munsell Color Chart
- e) Soil structure
- f) Roots: size and distribution

Soil drying method:

Soil cores were originally going to be sent to the U.S. for drying and further testing. Due to permitting issues, however, an impromptu method was devised. Using an Oster Countertop Convection Oven, three small samples per core were weighed and then dried and reweighed. The core samples from each pit were emptied into pre-weighed Tupperware containers. Each core sample was broken apart by hand and inspected for macro-invertebrate organisms. Rocks and roots were also removed. The soil filled containers were then weighed and recorded to the thousandth gram. Three small pre-weighed drying crucibles were filled with core material, weighed and recorded, and then baked for three hours at 230°F. After three hours, the core samples were reweighed while still in the drying crucibles. Each set of dry soil was then emptied into labeled Ziploc bags and sealed. The weights of the crucibles were

subtracted from the samples wet and dry weights of each sample. The results were then entered into data sheets for analysis. The volume of the crucibles was determined by filling the crucibles with water and then pouring the water into a graduated cylinder. All crucibles had a volume of 30 ml. Bulk density was calculated by dividing the weight of the oven dried soil by volume of the soil. Soil porosity is calculated by the bulk density divided by the average particle density. This figure is multiplied by 100 and then subtracted from 100 (Sulzman & Frey, 2002). Therefore, soil porosity and bulk density are inversely proportional.

Small amounts of dried samples were used in chemical analyses the following day. Using a LaMotte STH-14 Combination Chemical Kit, tests were run for the following: pH, nitrate, phosphorous, potassium, aluminum, ammonia, calcium, chloride, ferric iron, humus, magnesium, manganese, nitrite, and sulfate. Test instructions provided by the instruction manual were followed. Results were recorded and transferred to data sheets.

Dried samples were transported to Texas Christian University for cation exchange capacity (CEC) and textural analysis. CEC was calculated by displacing the natural exchangeable soil cations with barium (Tan, 2005). Exchange sites were saturated with a barium buffer solution that contained 0.056N p-nitrophenol, 0.1N barium acetate, 0.4N barium chloride dehydrate, 0.1N monochloro acetic acid. The barium was then displaced from the exchange sites by a 1N solution of magnesium acetate. The following steps were completed to collect a solution for analysis (Helling et al., 1964):

1. A sample of approximately 10 grams of mortared and sieved soil was weighed out and transferred into separate centrifuge tubes. Duplicates were made when sample size was sufficient.
2. 15 ml of p-nitrophenol buffer solution were added to the samples which were then mixed by a shaker for five minutes.
3. The samples were then centrifuged for three minutes in order to separate the soil from the supernatant. The supernatant was then disposed of. This was repeated two more times in order to saturate the exchange sites.
4. The previous steps were repeated three more times with ethanol instead of p-nitrophenol buffer in order to wash away excess barium that had not been absorbed by soil particles. The supernatant was again disposed.
5. After the excess barium was removed, the barium was displaced from particle exchange sites by adding 15 ml of magnesium acetate to the samples. The samples were mixed with the magnesium acetate in the shaker for five minutes and then centrifuged for three minutes. The supernatant was then collected into a 50ml volumetric flask. A total of three displacings were completed and collected.
6. The barium in solution was then analyzed with a Perkin Elmer 4000 Atomic Absorption Spectrophotometer. Results were recorded in parts per million (ppm) and then converted to centimoles per kilogram ( $\text{cmol}_c/\text{kg}$ ).

Dried soil samples were analyzed for textural analysis using a pipette method (Jackson, 2005). The following steps were completed to determine soil textural class for each sample:

1. A sample of approximately six to eight grams of mortared and sieved soil was weighed out and transferred into a blender that contained approximately 50 ml of distilled water and a pinch of dispersing agent (sodium hexametaphosphate). The mixture was blended on low speed for 30 seconds.
2. The sample was then poured into a one liter graduated cylinder. Distilled water was then added to bring the cylinder water level to 1000 ml.
3. After the temperature of the soil/water mixture was taken, the mixture was thoroughly mixed.
4. A 50ml sample was taken at the according temperature/time interval as indicated by the appropriate settling time per Stokes' Law. The 50ml sample was placed in a pre-weighed 50ml beaker and placed in an oven at 110°C for 12 hours.
5. A second 50 ml sample was taken over seven hours later and placed in a second pre-weighed beaker, which was also placed in the oven for 12 hours.
6. The beakers were then weighed in order to calculate the percentages of clay, silt, and sand.

Soil samples were classified using the taxonomy guidelines of *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, issued by the Natural Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA) (USDA, 1999). Using the *Field Book for Describing and Sampling Soils Version 2.0* issued by the NRCS, the soils are classified by soil morphological characteristics (Schoeneberger et al. 2002).

### *Statistical Methods*

Statistical differences among sites regarding bulk density and CEC were determined using a general linear model analysis of variance (ANOVA) with 95% confidence intervals. Prior to analysis, residuals were examined and it was determined that the data met the assumptions of ANOVA. ANOVA was run to test the relationship between land use and bulk density. Similar ANOVA tests were run to compare CEC and depth with land use change. Interactions among factors were looked for in both analyses. All profile averages were then compared with land use by using the Tukey-Kramer method with 95% confidence intervals (Whitlock & Schluter, 2009). The analyses were completed using Minitab 15.1.0.0. software.

## RESULTS

### *Description of Soils and Classification*

The soils observed in this study are clay loams and all can be classified as Inceptisols (order) and Udepts (suborder) (USDA, 1999). Mean annual soil temperature is greater than 22° C which is classified under the isohyperthermic soil temperature regime (USDA, 2010). Udept classification for Inceptisols requires the following: (1) a udic moisture regime; (2) an absence of both aquic conditions and a histic epipedon; (3) have neither a plaggen nor and anthropic epipedon; (4) have a soil temperature regime warmer than cryic (USDA, 1999). The soils at the research station meet these classification requirements. Unfortunately, since base saturation was not determined for this study, it is not possible to determine the specific epipedon type and therefore classification beyond suborder is not possible.

However, according to FAO maps, epipedons in this region are classified as Umbric. Similar to a Mollic epipedon, Umbric epipedons have a thick dark-colored upper horizon but less than 50% base saturation (Troeh et al. 2005). FAO taxonomy (Umbrisols) was converted to USDA taxonomy (Inceptisols) in order to compare soil classifications.

Soil texture was determined by hand while in the field using both a ribboning and knife technique. Laboratory pipette methods proved to be ineffective due to difficulties dispersing the soil samples. Textural analyses for soils developed from volcanic parent materials have been found to be unreliable (Mizota & Van Reeuwijk, 1989 ;Reiners et al. 1994).

Soils in deforested areas (Data sheets D1 thru D4) are deep clay loams that are slightly sticky, friable, with plastic consistency. The structure of the soil is generally fine to very fine subangular blocky. Surface horizons were dark brown to gray in color (7.5YR 3/4 to 7.5 YR 2.5/3 wet). The epipedons are siltier than subsurface horizons and more heavily rooted with fine grass roots. B and B2 subsurface horizons are redder in color (7.5YR 4/3 to 2.5YR 3/4 wet) and had a few larger roots but less rooting overall. The last pit of the catena (D4) had cobble and boulder sized rocks at depth. The rocks are subangular to rounded. One thin section from a sample rock was cut and analyzed. Andestic parent material was confirmed (Fig. 4).

Soils in the secondary forest (Data sheets S1 thru S4) are deep clay loams that are slightly sticky, moderately friable, with plastic consistency. The structure of the soil is generally fine to very fine subangular blocky. Surface horizons are dark brown to gray in color (7.5YR 3/3 to 5 YR 3/3 wet) and are heavily rooted with fine, medium, and large roots. B and B2 are reddish brown in color (7.5 YR 3/4 to 7.5YR 3/3 wet) in the summit shoulder and backslope profiles. The soil is a lighter tan brown color (7.5 YR 4/4 to 4/3 wet) in the footslope and toeslope profiles. The bottom two profiles of the catena also had the heaviest clays at depth. Pits S1 and S4 did not have any roots in the B2 horizon while S2 had a few large roots in the B2. A B2 horizon could not be determined in S3. Large cobble to boulder sized rocks are encountered again in the toeslope (S4) profile of the catena.

Soils in the primary forest (Data sheets P1 thru P4) are deep clay loams that are slightly sticky, very friable, and slightly plastic. The structure of the soil is generally

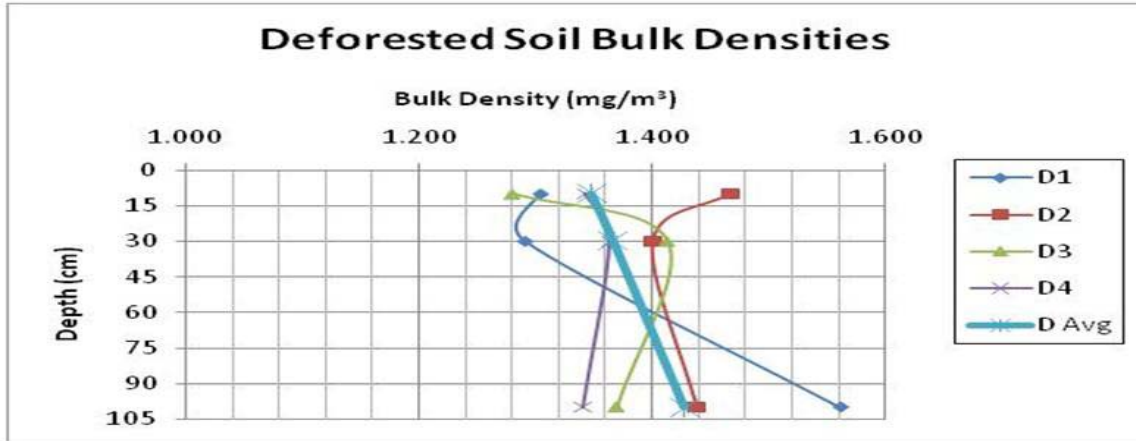
very fine subangular blocky. Surface horizons are brown gray to gray brown in color (7.5 YR 3/3 to 7.5YR 2.5/2 wet) and are moderately rooted with fine roots. B horizons are consistently reddish brown in color (7.5YR 2.5/3 to 5YR 3/4) with fine and medium roots in P1 and P2 and fine, medium, and large roots in P4. B2 horizons are reddish brown in color (7.5YR 2.5/3 to 5YR 3/4 wet) except for P1 which is a noticeably brighter reddish brown (2.5 YR 3/4 wet). In B2, very coarse roots are observed in P1, fine, medium, and large roots are observed in P2, and no roots are observed in either P3 or P4. A fourth horizon, B3, is encountered in P3 at 105cm. The soil is a light brown (7.5 YR 4/6 wet) massive clay with no roots. Cobble and boulder sized rocks are found in B2 of P2 and again in the bottom two pits of the catena.

#### *Bulk Density and Porosity*

Soil bulk densities in the surface horizons of the deforested pits range from a low of 1.28 to 1.47 mg/m<sup>3</sup> at 10cm, 1.29 to 1.41 mg/m<sup>3</sup> at 30cm, and 1.34 to 1.56 mg/m<sup>3</sup> at 100cm in depth. The average bulk density across all horizons is 1.38 mg/m<sup>3</sup>.

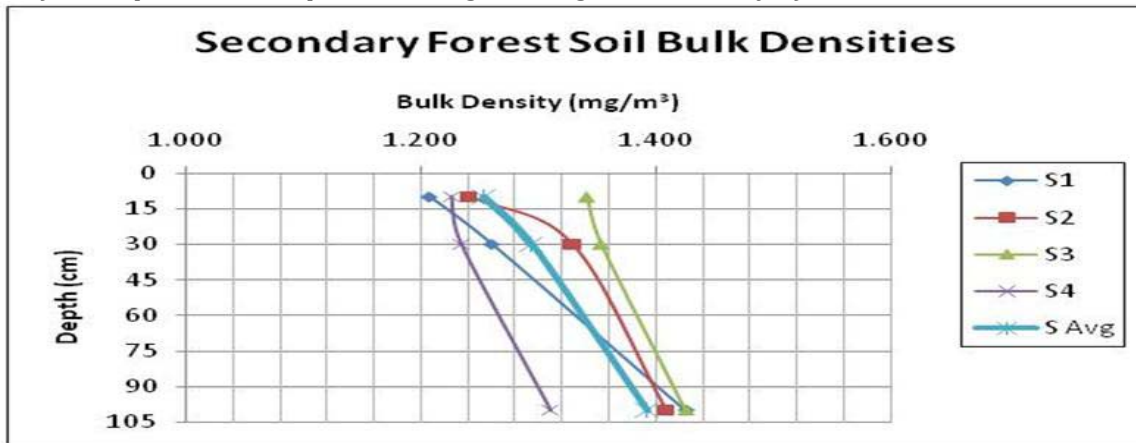
Porosities range from 44.6% to 51.7% at 10cm, 46.7% to 51.3% at 30cm, and 41.1% to 49.4% at 100cm. The average porosity for the deforested soils is 47.9% (see Fig. 5, Table 1, and Data Sheet D1 through D4).

Figure 5. Bulk Densities of Deforested Soils, D1=summit shoulder, D2=back slope, D3=footslope, D4=toeslope, and D Avg=average bulk density of all horizons.



Secondary forest bulk densities range from 1.21 to 1.34 mg/m<sup>3</sup> at 10cm, 1.23 to 1.35 mg/m<sup>3</sup> at 30cm, and 1.31 to 1.43 mg/m<sup>3</sup> at 100cm. The average bulk density across all horizons is 1.31 mg/m<sup>3</sup>. Porosities range from 49.4% to 54.4% at 10cm, 49.0% to 54.4% at 30cm, and 46.2% to 50.6% at 100cm. The average porosity across all soil horizons in the secondary soils is 50.4% (see Fig. 6, Table 1, and Data Sheets S1 through S4).

Figure 6. Bulk Densities of Secondary Forest Soils, S1=summit shoulder, S2=back slope, S3=footslope, S4=toeslope, and S Avg=average bulk density of all horizons.



Primary forest bulk densities range from 1.01 to 1.26 mg/m<sup>3</sup> at 10cm, 1.08 to 1.34 mg/m<sup>3</sup> at 30cm, and 1.19 to 1.41 mg/m<sup>3</sup> at 100cm. The average bulk density across all soil horizons is 1.22 mg/m<sup>3</sup>. Porosities range from 52.6% to 62.0% at 10cm, 49.3% to 59.1% at 30cm, and 46.9% to 55.2% at 100cm. The average porosity across all soil horizons in the secondary soils is 54.0% (see Fig. 7, Table 1, and Data Sheets P1 through P4).

Figure 7. Bulk Densities of Primary Forest Soils, P1=summit shoulder, P2=back slope, P3=footslope, P4=toeslope, and P Avg=average bulk density of all horizons.

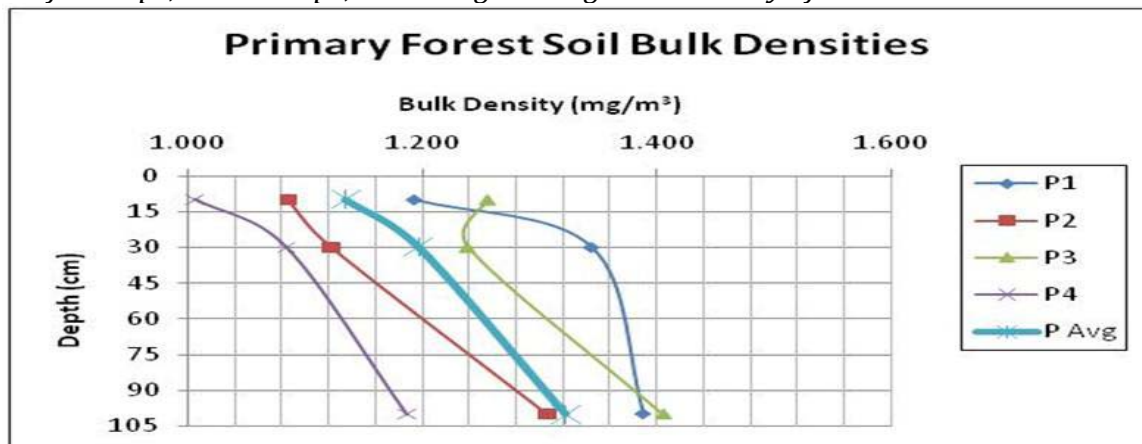


Table 1. Soil bulk density and porosity for three land use types. Each value is the average of the four soil pit samples according to depth.

Depth (cm)	Bulk Density Averages (mg/m <sup>3</sup> )			Porosity Averages (%)		
	Deforested	Secondary	Primary	Deforested	Secondary	Primary
10	1.35	1.25	1.14	49.1	52.7	57.2
30	1.37	1.29	1.20	48.4	51.2	54.8
100	1.43	1.39	1.32	46.1	47.5	50.1
Total	1.38	1.31	1.22	47.9	50.4	54.0

## Chemical Analyses

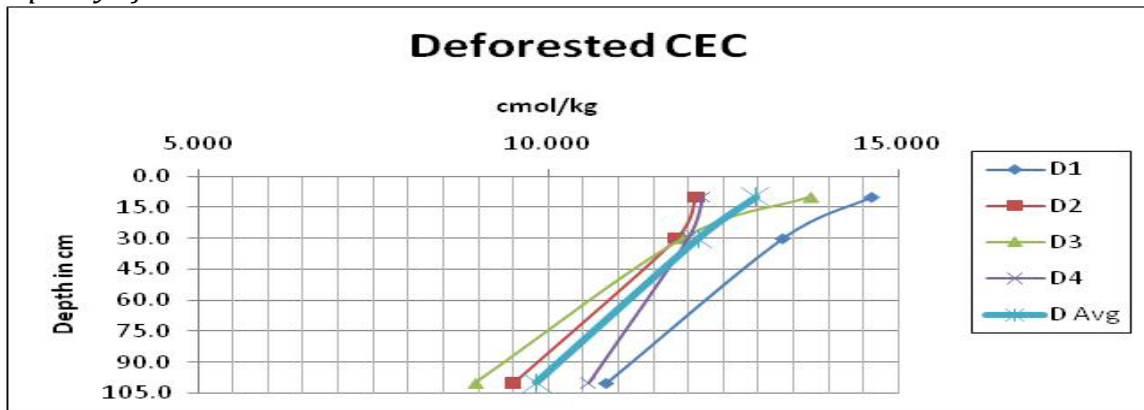
### pH

Deforested soils have a pH range of 5.4 to 6.4 with a mean of 5.8. D1 had a pH of 5.6 throughout the profile while the other 3 soil pits consistently showed increasing pH levels with depth. The highest pH levels recorded were found in D3 which ranged from 6.0 to 6.4. Pit D3 was dug approximately 15 meters down slope of the one service road on the property. The secondary soils are slightly more acidic than the deforested soils. Secondary forest soils range from 5.2 to 5.8 pH with a mean of 5.5. pH levels in the secondary forest soils remained constant with depth. Soil pH in the primary forest soils range from 5.2 to 6.2 with a mean of 5.7. pH levels also remained constant with depth( see Table 2 for summary data).

### Cation Exchange Capacity

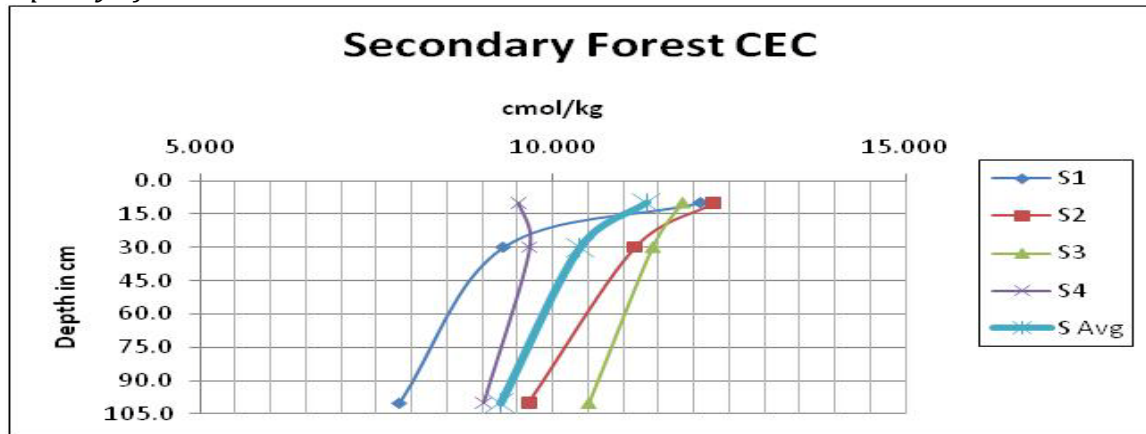
The cation exchange capacity (CEC) of the deforested soils range from 11.4 to 14.6 cmol/kg at 10cm, 9.5 to 12.4 cmol/kg at 30cm, and 11.8 to 14.0 cmol/kg at 100cm. All CECs in the deforested pits decrease with increasing depth (Fig. 8).

Figure 8. Cation Exchange Capacities of Deforested Soils, D1=summit shoulder, D2=back slope, D3=footslope, D4=toeslope, and D Avg=average cation exchange capacity of all horizons.



The CECs of secondary forest soils range from 9.5 to 12.4 cmol/kg at 10cm, 9.2 to 11.5 cmol/kg at 30cm, and 7.7 to 10.6 cmol/kg at 100cm. All CECs in the secondary forest soils decrease with depth except soils at 10cm and 30cm of S4 (Fig. 9).

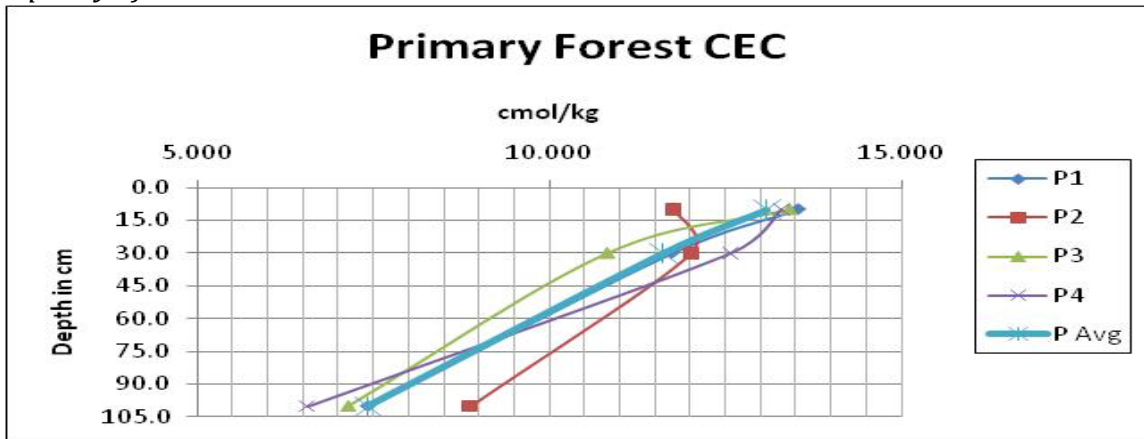
Figure 9. Cation Exchange Capacities of Secondary Forest Soil, S1=summit shoulder, S2=back slope, S3=footslope, S4=toeslope, and S Avg=average cation exchange capacity of all horizons.



These numbers are very close but do show a 0.159 cmol/kg increase from 10 to 30cm. CECs in primary forest soils range from 11.8 to 14.0 cmol/kg at 10cm, 9.4 to 12.8 cmol/kg at 30cm, and 6.6 to 8.9 cmol/kg at 100cm. All CECs in primary forest soils decrease with increasing depth except for 10cm and 30cm of P2 (Fig. 10).

These numbers are also very close but do show an increase of 0.246 cmol/kg from 10cm to 30cm (see Table 2 for summarized data).

Figure 10. Cation Exchange Capacities of Primary Forest Soils, P1=summit shoulder, P2=back slope, P3=footslope, P4=toeslope, and P Avg=average cation exchange capacity of all horizons.



### Soil Nutrients

All three land uses show increasing levels of phosphorous with depth. Deforested and secondary soils have similar ranges (less than 5 to 75 ppm) while primary forest soils are slightly higher (5 to 100 ppm). Potassium concentrations appear to decrease with depth (160 to 200 ppm at the top and 110 to 155 ppm at 100 cm). Aluminum levels are high (80 to 125 ppm) in all samples while ammonia is very low (5 ppm) in all samples. Calcium is below or equal to 2800 ppm in all land uses. Ferric iron levels range from less than 2.5 ppm to a high of 7.5 ppm in S4. Magnesium levels increase with depth in deforested soils (5 ppm to 80 ppm) but remain relatively low (2.5 to 10 ppm) constant with depth in primary and secondary forest soils. However, magnesium levels in P1 increased with depth from a low of 5 ppm to a high of 80 ppm. Nitrite levels are at or below 1 ppm in all samples. Sulfate and chloride were tested for but levels were below method detection limits (50 ppm and 25 ppm respectively). Measureable humus levels are found in the A horizon of

D3, D4, P2, P3, S1, and S4. The measurable levels are consistently low (see Table 2 for summarized data).

*Table 2. Summary of soil pH, CEC, and soil nutrients in the 3 land uses*

Characteristics	Deforested	Secondary	Primary
pH	5.4 to 6.4 (avg. 5.8)	5.2 to 5.8 (avg. 5.5)	5.2 to 6.2 (avg. 5.7)
CEC (10cm)	11.400 to 14.622 (avg. 12.961)	9.507 to 12.386 (avg. 11.339)	11.764 to 13.962 (avg. 13.088)
CEC (30cm)	13.349 to 12.305 (avg. 12.143)	9.180 to 11.462 (avg. 10.390)	9.403 to 12.753 (avg. 11.619)
CEC (100cm)	8.787 to 10.825 (avg. 9.837)	7.749 to 10.569 (avg. 9.258)	6.560 to 8.876 (avg. 7.425)
Nitrate (ppm)	10 to 20	<10 to 10	<10 to 20
Phosphorous (ppm)	<5 in top of profiles, increases to 75 at 100cm	<5 to 12.5 in the top of profiles, increases to 75 at 100cm	5 to 37.5 in the top of the profile to 100 at 100cm
Potassium (ppm)	160 to 200 at top of profiles, decreases to 160	200 at top of profiles, decreases to between 110 and 155 at 100cm	160 to 200 at top of profiles, decreases to between 150 and 160 at 100cm
Aluminum (ppm)	80 to 125	80 to 125	125
Ammonia (ppm)	5	10 to 50	5 to 10
Calcium (ppm)	≤2800	≤2800	≤2800
Ferric Iron (ppm)	7.5 at top of profile, decreases to 0 at 100cm	≤2.5 throughout all profiles	5 throughout P2, otherwise 2.5 to <2.5
Magnesium (ppm)	5 to 80, increases with depth	5 to 10, does not correlate with depth	Very low in all profiles except for 25 at 30cm in P1 and 80 at 100cm in P1
Nitrite (ppm)	≤1	≤1	≤1
Humus	Minimum level detected in top of D3 and D4	Minimum level detected in all profiles of S1 and S4	Minimum level detected in top of P2 and P3

## Statistical Results

Prior to all statistical analyses, residuals were examined and it was determined that the data met the assumptions of ANOVA (Fig. 11 and 13).

Figure 11. Residual Plots for Bulk Density Data

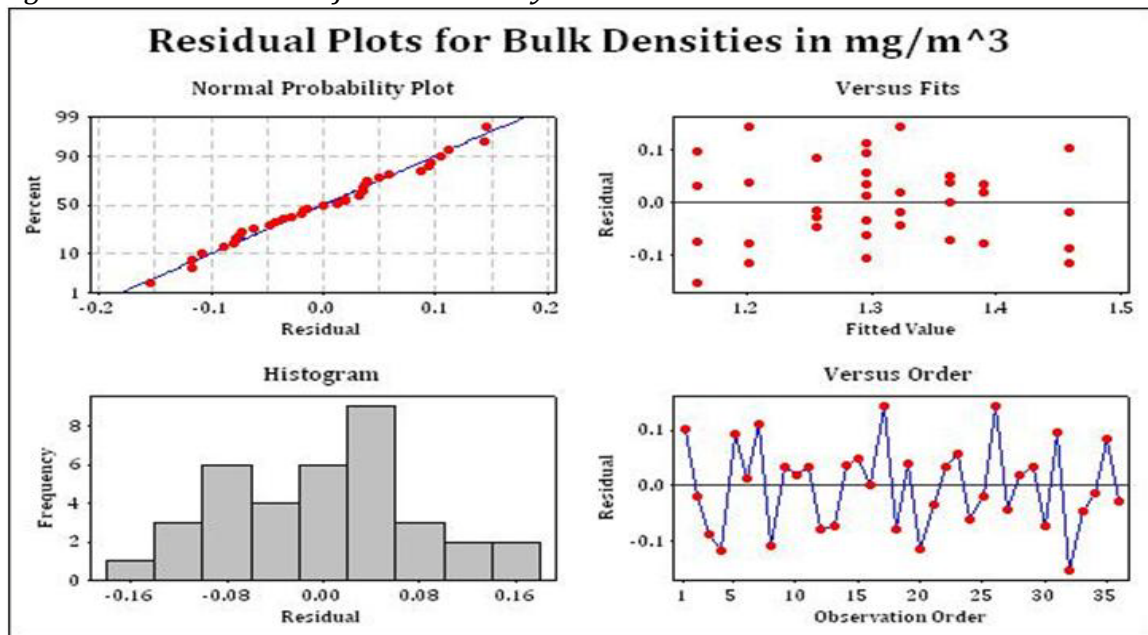
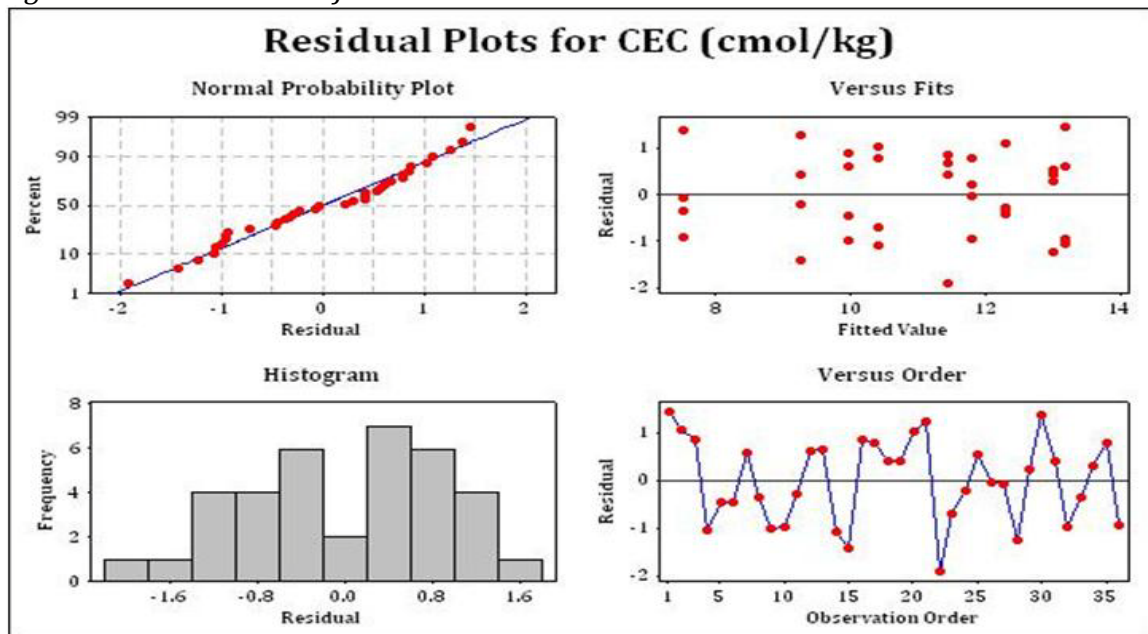


Figure 13. Residual Plots for CEC



ANOVA general linear model (GLM) indicates that there is no significance in the combined relationship between bulk density, depth, and land use (Table 3).

However, there is a significant difference between bulk density and land use (Table 4).

*Table 3.*

Analysis of Variance for Bulk Densities (mg/m <sup>3</sup> ) Versus Depth and Type Using Adjusted Sum of Squares (SS)						
Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Depth	2	0.115266	0.115266	0.057633	7.90	0.002
Type	2	0.160636	0.160636	0.080318	11.01	0.000
Depth*Type	4	0.011884	0.011884	0.002971	0.41	0.802
Error	27	0.196990	0.196990	0.007296		
Total	35	0.484775				
R <sup>2</sup> = 0.5691						

*Table 4.*

Analysis of Variance for Bulk Densities (mg/m <sup>3</sup> ) Versus Depth and Type Using Adjusted Sum of Squares (SS)						
Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Depth	2	0.115266	0.115266	0.057633	8.55	0.001
Type	2	0.160636	0.160636	0.080318	11.92	0.000
Error	31	0.208874	0.208874	0.006738		
Total	35	0.484775				
R <sup>2</sup> = 0.5691						

Tukey –Kramer tests indicate that deforested soil bulk densities differ significantly from primary soils (Table 5), primary soil bulk densities differ significantly from secondary (Table 5), but deforested soil bulk densities do not differ significantly from secondary soils (Table 5 and Fig. 12). As previously stated, soil porosities are calculated from soil bulk density so therefore the statistical results are virtually identical (Table 6).

Table 5.

Tukey Simultaneous Tests: Response Variable Bulk Densities in mg/m <sup>3</sup> , Pairwise Comparisons Among Depth and Type				
Type	Dif. Of Means	SE of Dif.	T-Value	Adjusted P-Value
Deforested Subtracted from:				
Primary	-0.1629	0.03351	-4.860	0.0001
Secondary	-0.0677	0.03351	-2.021	0.1239
Primary Subtracted from:				
Secondary	0.09512	0.03351	2.838	0.0211

Figure 12. Main Effects Plots for Bulk Densities Depth and Land Use Type

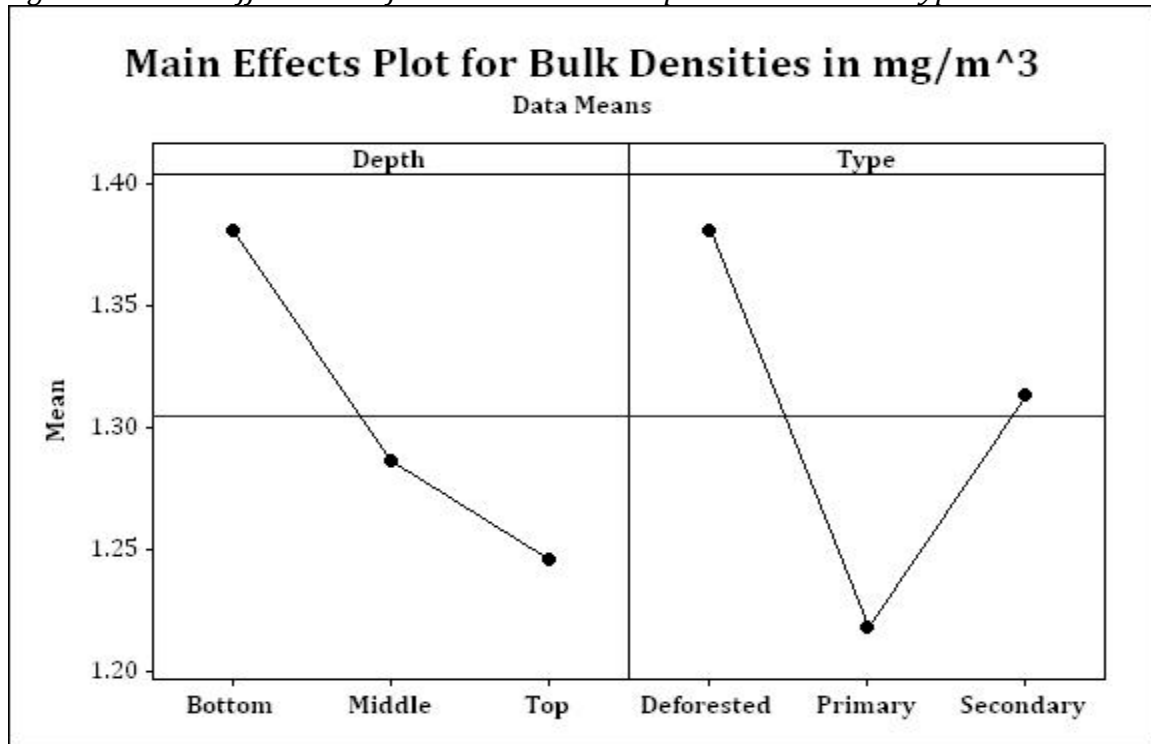


Table 6.

Analysis of Variance for Soil Porosity (%) Versus Depth and Type Using Adjusted Sum of Squares (SS)						
Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Depth	2	0.0164138	0.0164138	0.0082069	8.55	0.001
Type	2	0.0228744	0.0228744	0.0114372	11.92	0.000
Error	31	0.0297435	0.0297435	0.0009595		
Total	35	0.0690317				
R <sup>2</sup> = 0.5691						

ANOVA and Tukey-Kramer analysis was run for CEC and land use type and found a significant relationship between soil depth, land use, and CEC (Table 7). There are also significant differences between CEC and soil depth (Table 7) as well as CEC and land use (Table 7).

Table 7.

Analysis of Variance for CEC (cmol <sub>c</sub> /kg) Versus Depth and Type Using Adjusted Sum of Squares (SS)						
Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Depth	2	83.754	83.754	41.877	41.52	0.00
Type	2	13.250	13.250	6.625	6.57	0.005
Layer*Type	4	14.603	14.603	3.651	3.62	0.017
Error	27	27.231	27.231	1.009		
Total	35	138.838				
R <sup>2</sup> = 0.8039						

Tukey-Kramer analyses of CEC to soil depth are not significant from 10cm to 30cm (Table 8). When CEC averages for 10cm and 30cm are subtracted from CEC averages at 100cm, both are found to be significant (Table 8).

Table 8.

Tukey Simultaneous Tests: Response Variable CEC in cmol <sub>c</sub> /kg, Pairwise Comparisons Among Depths				
Depth	Dif. Of Means	SE of Dif.	T-Value	Adjusted P-Value
100cm Subtracted from:				
10cm	3.631	0.4100	8.856	0.0000
30cm	2.578	0.4100	6.289	0.0000
10cm Subtracted from:				
30cm	-1.053	0.4100	-2.567	0.0413

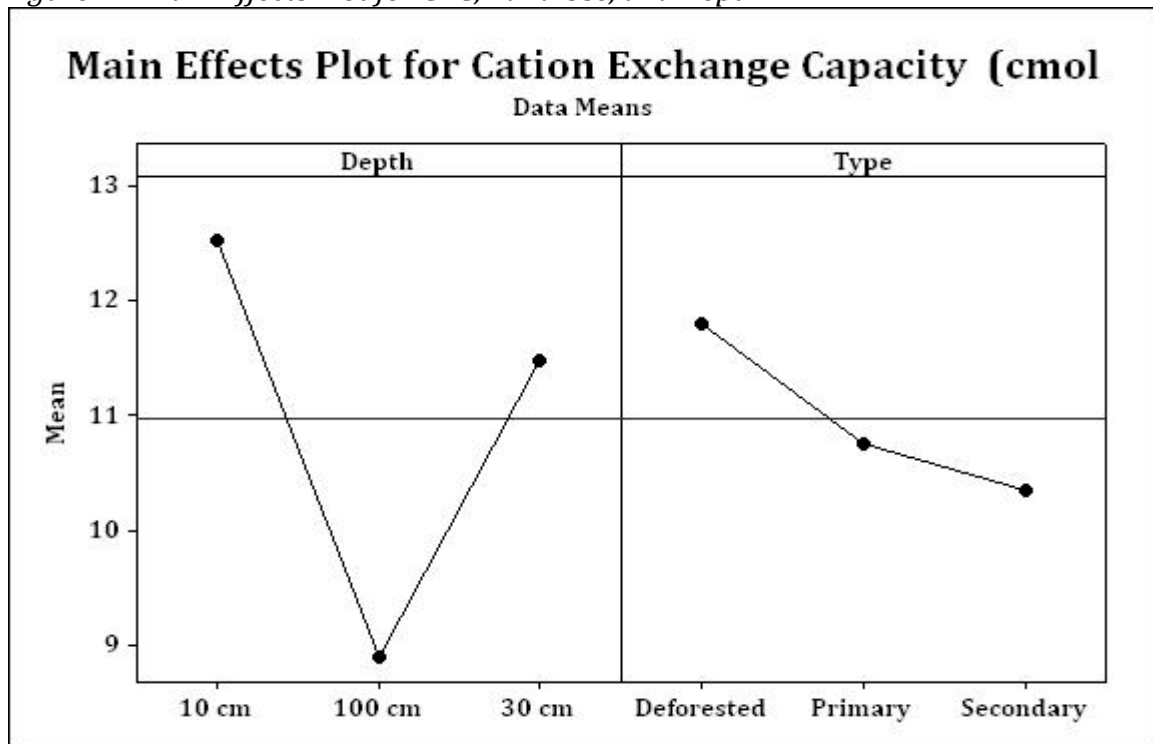
The Tukey-Kramer results for CEC and land use type is significant for deforested soils subtracted from primary soils (Table 9 and Fig. 14) and significant for deforested soils subtracted from secondary soils (Table 9 and Fig. 14). However,

results are not significant when primary soil CECs are subtracted from secondary (Table 9 and Fig. 14). Simply put, primary forest soil CECs are not significantly different from secondary forest soil CECs, but deforested soil CECs are significantly different than both primary and secondary soil CECs.

Table 9.

Tukey Simultaneous Tests: Response Variable CEC in $\text{cmol}_c/\text{kg}$ , Pairwise Comparisons Among Depths and Type				
Depth	Dif. Of Means	SE of Dif.	T-Value	Adjusted P-Value
Deforested Subtracted from:				
Primary	-1.037	0.4100	-2.530	0.0449
Secondary	-1.440	0.4100	-3.513	0.0044
Primary Subtracted from:				
Secondary	-4032	0.4100	-0.9834	0.5935

Figure 14. Main Effects Plot for CEC, Land Use, and Depth



## DISCUSSION

The soils studied at the TCU San Ramon Tropical Research Station are all deep, clay loam isohyperthermic Udepts with fundamental similarities. The catena concept proved useful in planning test pit locations. Pits were sited based primarily on land-use, slope position, and accessibility. While it is possible that soil pits needed to be deeper with an analysis of specific clay minerals in order to extract more information from the profile observations, the consistency with which the pits were completed combined with the uniformity of the soil profiles justify the depth of the soil pits. Also, since the laboratory textural analysis was ineffective due to the inability to effectively disperse the samples, it is not possible to make many correlations between hill slope position and resulting textural soil properties. However, the catena method can be used to explain the boulders and cobbles encountered in footslope and toeslope pits since the concavity results in deposition of material from upslope (Lal, 2002).

The three land-use types represent a chronological sequence from primary forest (original state), to deforested (disturbed state), and secondary forest (successional state) (Reiners et al. 1994). The assumption can be made for primary forest to serve as a baseline comparison for the long-term end-state of secondary forest and therefore deforested land as well (Reiners et al. 1994). Above ground, pit locations vary substantially in terms of land use and, by extension, vegetation. However, below ground differences are more subtle in both physical and chemical soil properties.

Soil bulk densities are highest in deforested areas and lowest in primary forest. As expected, bulk densities generally increase with depth in all primary and secondary forest soil pits. While deforested soil bulk densities are more variable with depth in each soil pit, the mean bulk density does increase with depth. This is attributed to compaction caused by overburden weight of the overlaying layers, lower organic matter content, fewer roots, and less aggregation with increasing depth (Sulzman & Frey, 2002). Organic matter contents of soils are highest in surface horizons due to increased litter fall, increased fine rooting, and soil aeration. Organic matter reduces bulk density because organic material is lighter than the mineral components of soil and organic matter also increases aggregate stability (Troeh & Thompson, 2005). Since both production and decomposition are high in the tropics, organic matter content of the soils should remain relatively stable and low. While there are few obvious patterns between bulk density and corresponding land use along individual catenas, bulk density was consistently lowest in the footslope soils of all three land uses. Soils located in the upper parts of a toposequence are generally well drained, whereas those that are less steep and that form at the bottom part of the sequence are poorly drained and will have increasing amounts of clay and organic matter (Birkeland, 1999). This resulting increase in clay and organic matter content would explain the lower bulk densities along the footslopes. Humus was tested for in the field; however, levels were below detection limits of the LaMotte soil kit in all samples except for the top horizons in D3, D4, P2, and P3. In these samples the level detected was minimal at best. The lack of detection of

humus may be attributed to the actual lack of humus or the inaccuracy of the color plate testing method.

Bulk densities of deforested soils vary considerably more with depth than do the other two land uses. This is most likely attributed to past timber harvest which disturbs and compacts soil (Sulzman et al. 2002) as well as 15 years of cattle grazing on the land (Orozco, personal communication, 2009). Cattle grazing results in the physical force of trampling, which results in the compaction of soils and a reduction in total pore space (Reiners et al. 1994). Statistical analysis of bulk density suggest that human interaction has impacted both deforested soils and secondary forest soils in a significant manner. While these soils are not significantly different from one another, they are significantly different from the primary soils which were used as a baseline comparison for studied soil properties. It is important to note that the erosion of less dense surface soils after deforestation can result in a similar bulk density increase of the profile (Markewitz et al. 2004). Soil porosities are calculated from bulk densities and therefore vary inversely with bulk densities.

It is also possible that bulk density measurements may have been more variable as an outcome of human error resulting from the unconventional drying method developed in the field. However, the impromptu sampling and drying method was used in a consistent manner in order to reduce error and the data met all statistical assumptions (Fig. 11).

Soil pH levels are most acidic in secondary forest and least acidic in deforested soils. Generally, soils with the highest cation exchange capacities have the highest pH values (Troeh & Thompson, 2005). The data in this study produces significant correlation between land use, pH, and CEC. While the means for each land use were very close, the actual pHs recorded varied by 1.2. Possible error was introduced by the LaMotte field kit method for calculating pH levels since natural light at the field station was highly variable. Color interpretation was susceptible to error resulting from light levels that resulted from cloud cover patterns. The comparison of samples to the corresponding color plates was strongly influenced by the amount of light on a particular day. Days were commonly overcast which resulted in liquid samples appearing darker than they may have actually been. However, assuming all the measurements taken in the field are correct, there are other possible reasons for pH levels and corresponding land use.

First, deforested areas may promote a more variable microclimate which would promote increasing fluctuations in soil moisture. This would increase rates of decomposition and mineralization of organic matter. Higher rates of decomposition of organic matter can help maintain the increases in pH that result from the conversion of primary forest to pasture (Reiners et al. 1994). Second, base cations are cycled more rapidly by grasses than by dicotyledonous plants which results in fewer and less persistent organic acids (Reiners et al. 1994). Since grasses are generally more effective at recycling cations than trees are, the more base cations the grasses use the more leaching will be offset. This would therefore result in more basic soils and higher CECs in the deforested areas (Troeh & Thompson, 2005).

Therefore, it seems reasonable that the soils in the primary and secondary forests would be more acidic than those in the deforested areas.

Cation exchange capacities generally decrease with depth. Since CEC values are highest for organic matter and values decrease with increased weathering, the data collected appears accurate and consistent as surface horizons have the highest accumulation of organic matter (Birkeland, 1999) and decreasing CEC with increasing depth (Sollins et al. 1988). There are no significant differences between land use type and CEC at 10cm or 30cm intervals. However, CEC ranges dropped notably at 100cm in primary forest. This indicates a direct result from human interaction on the other two land uses. The highest CEC averages were found in the deforested and primary surface soils. This is due, possibly, to the increased rooting concentration observed in the deforested areas, which are covered in African grasses and increased leaf litter in the primary forest. Since grass roots have higher turnover rates than larger trees roots do, organic matter concentrations may be higher in the deforested surface soils than in the other two land uses. If this is true then the increased humus may result in slightly higher CECs in the deforested soils (Troeh & Thompson, 2005). As previously stated, grasses are better at offsetting leaching since they are better able to recycle cations. This may explain the significant drop in CEC in primary forest at 100cm depth and the overall lower CEC in primary forest soils. When thought of as a chronological sequence, soil CECs will increase after deforestation and the introduction of grasses; they will then decrease as woody plants begin to re-grow, and will continue to decrease as long as the secondary forest continues to grow and remain undisturbed. These observations

are supported by statistical analysis indicating a significantly different CEC level in the deforested area than that seen in the primary or secondary forest areas (Fig. 14).

## CONCLUSIONS

This paper presents the first analysis of physical and chemical soil properties in this region of Costa Rica. Based on extensive field sampling and laboratory analysis, observations have been made on how land use change, resulting from human interaction, has impacted those soil properties.

First, it is apparent that deforestation and compaction from cattle grazing significantly increases bulk density and decreases porosity. It also appears that bulk density will decrease as successional plants are allowed to re-grow and deforested pasture is allowed to return to secondary forest. It is important not to think of pores as empty voids but rather as spaces that hold water, air, nutrient bearing solutes, and living organisms. Since these are necessary for plant growth, decreasing porosity results in decreasing soil quality (Troeh & Thompson, 2005).

Second, the conversion of primary forest to deforested pasture can actually result in increasing CEC levels, which means that more nutrient cations are available to plants. Commonly regarded as a measure of soil quality, in agricultural terms, deforestation and the introduction of grasses has resulted in significant increases of cations and may actually promote soil fertility (Sulzman & Frey, 2002).

The data gathered during this study indicate that distinct changes to soil properties take place as humans alter the original landscape in the tropics. However, the changes to soil porosity and cation exchange capacity appear to be reversible if forests are allowed sufficient time to re-grow. While the degree of alteration from the original state may be dependent on the severity of the land use change and the

length of time it remains changed, these data presented here suggest that soil properties will return to values approaching their original, undisturbed state – that is, primary forest.

## RECOMMENDATIONS

In order to further examine the soils at the TCU research station it will be necessary to expand sampling and refine field methods. First it is recommended that more samples be taken throughout the property in order to capture spatial variability across the landscape, and that significant quantities be shipped back to a soils laboratory in the United States or to a soil analysis facility in Costa Rica. This will require an investment in both time (to obtain the necessary permits through the USDA) and resources to pay for shipping and analysis. Secondary forest needs to be more accurately mapped in order to avoid taking samples from secondary forest that may be anywhere between 15 and 30 years old. This could also be used to study forest rotation and relating soil fertility indicators. It will also be critical to determine the types of clays present and complete a textural analysis. Analyzing exchangeable base data and base saturation will allow for a more thorough soil classification. It will also be advisable to dig some deeper pits and establish depth to bedrock along a catena as well as dig pits in an adjacent deforested area that is currently being grazed by cattle. Testing should also be conducted during both wet and dry seasons to measure any seasonal variations in soil properties. Seasonal net nitrification levels will also shed light on soil fertility among the different land uses.

The Texas Christian University San Ramon Tropical Research Station offers a wonderful study area which provides a wide array of both pristine and anthropogenically disturbed ecosystems. The creation of the Research Station affords unprecedented access to an area that has not been previously studied.

Understanding tropical ecosystems and their functioning is critical to maintaining

and restoring environmental health on a planet that is currently plagued by environmental degradation. By carefully studying this area with a well thought out sampling protocol, a wealth of knowledge will be gained that will help advance human understanding of our beautiful and amazingly resilient planet. As stated at the beginning of this paper, we will conserve what we love, we will love what we understand, and we will understand what we are taught. Never before in human history has understanding our home been so essential. While the task of teaching what we understand may be a colossal one, it is also an amazing and noble one with which to be charged.

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## APPENDIX

### Data Sheet D1(1)

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.480556, Long = -84.67500 **Date:** 07/21/2009

**Elevation:** 2379 feet **Slope:** 15.38 degrees **Aspect:** NW 315

**Position:** Summit shoulder

**General Landform:** Convex linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** tall African grasses, a few small trees under 5m in height

### Profile Description:

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	7	Yes	7.5YR 3/4	Clay loam	No	Yes/f
Dark brown gray, moist, silty clay loam, slightly sticky, very friable, slightly plastic, very fine to fine sub-angular blocky, heavily rooted with fine grass roots							
B	7	21	Yes	5YR 3/3	Clay loam	No	Yes/f & m
Reddish brown, moist, clay loam, sticky, friable, plastic, sub-angular blocky structure, moderately rooted							
B2	21	120	Yes	5YR 3/4	Clay loam	No	Yes/vc
Reddish brown, moist, clay loam, sticky, friable, plastic, sub-angular blocky structure, very few roots, very coarse roots							

### Bulk Densities in mg/m<sup>3</sup>:

Depth	D1
10	1.304
30	1.291
100	1.562
Average	1.386

### Soil Porosity:

Depth	D1
10	50.8
30	51.3
100	41.1
Average	47.7

### Chemical Analysis:

Test	Top	Middle	Bottom
CEC (cmol <sub>c</sub> /kg)	14.622	13.349	10.825
pH	5.6	5.6	5.6
Nitrate (ppm)	5	5	5
Phosphorous (ppm)	<5	<5	37.5-50
Potassium (ppm)	195	175	165
Aluminum (ppm)	125	125	80
Ammonia (ppm)	5	5	5
Calcium (ppm)	<2800	<2800	<2800
Chloride	ND	ND	ND
Ferric Iron (ppm)	7.5	7.5	ND
Humus	ND	ND	ND
Magnesium (ppm)	5	10	25
Manganese	ND	ND	ND
Nitrite (ppm)	≤1	≤1	≤1
Sulfate	ND	ND	ND



D1 Vegetation



D1 Top 1



D1 Top 2



D1 Bottom



D1 Profile



D1 Profile 2

**Data Sheet D2 (2)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.494444, Long = -84.816667 **Date:** 07/22/2009

**Elevation:** 2247 feet **Slope:** 10 degrees **Aspect:** NW 300

**Position:** Back slope

**General Landform:** Linear linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** tall African grasses, widely dispersed shrubs under 1 m

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	6	Yes	7.5 YR 2.5/3	Clay loam	No	Yes/f
Gray brown, moist, silty clay loam, gritty, slightly sticky, heavily rooted with fine grass roots, very friable, slightly plastic, fine angular blocky structure							
B	6	13	Yes	7.5 YR 4/3	Clay loam	No	Yes/f
Gray brown brown, moist, clay loam, no grittiness, sticky, moderately rooted, friable, plastic, subangular blocky structure							
B2	13	122	Yes	7.5 YR 4/2	Clay loam	No	Yes/vc
Light reddish brown, moist clay loam, sticky, very few fine roots, no large roots, friable, plastic, subangular blocky structure							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	D2
10	1.467
30	1.400
100	1.438
Average	1.435

**Soil Porosity:**

Depth	D2
10	44.6
30	47.2
100	45.7
Average	45.8

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample	12.810	11.400	12.105	12.305	11.352	11.829	9.214	9.781	9.498
CEC (cmol <sub>c</sub> /kg)	12.810	11.400	12.105	12.305	11.352	11.829	9.214	9.781	9.498
pH	5.6			5.8			6.0		
Nitrate (ppm)	<5			<5			<5		
Phosphorous (ppm)	<5			25			75		
Potassium (ppm)	90			85			80		
Aluminum (ppm)	125			125			80		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	≤2800			≤2800			≤2800		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	<2.5			ND			ND		
Humus	ND			ND			ND		
Magnesium (ppm)	10			80			5		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



D2 Vegetation 1



D2 Vegetation 2



D2 Top



D2 Bottom



D2 Profile 1



D2 Profile 2

**Data Sheet D3 (3)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.502222, Long = -84.818889, Accuracy = 15ft **Date:** 07/23/2009

**Elevation:** 2158 feet **Slope:** 15.38 degrees **Aspect:** NW 320

**Position:** Footslope

**General Landform:** Convex concave **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Tall African grasses, a few young trees under 2 meters

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	14	Yes	7.5 YR 3/4	Clay loam	No	Yes/f
Brown gray, moist, silty clay loam, slightly sticky, heavily rooted with fine grass roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	14	120	Yes	5 YR 4/6	Clay loam	No	No
Reddish brown, moist, clay loam, no grittiness, sticky, grass roots end at horizon top, friable, plastic, subangular blocky structure, a few small worms							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	D3
10	1.280
30	1.413
100	1.370
Average	1.354

**Soil Porosity:**

Depth	D3
10	51.7
30	46.7
100	48.3
Average	48.9

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample									
CEC (cmol <sub>c</sub> /kg)	14.420	13.075	13.748	11.845	12.019	11.932	9.119	8.787	8.953
pH	6.0			6.2			6.4		
Nitrate (ppm)	≤5			≤5			≤5		
Phosphorous(ppm)	5			5			12.5		
Potassium (ppm)	200			200			125		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			ND		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			≤2.5			≤2.5		
Humus	1			ND			ND		
Magnesium (ppm)	5			10			25		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



D3 Vegetation 1



D3 Vegetation 2



D3 Top



D3 Bottom



D3 Profile 1



D3 Profile 2

**Data Sheet D4 (4)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.505833, Long = -84.693889 **Date:** 07/24/2009 and 7/25/2009

**Elevation:** 2144 feet **Slope:** 0 degrees **Aspect:** NW 295

**Position:** Toeslope

**General Landform:** Concave concave **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Tall grasses, shrubs, ferns

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	13	Yes	7.5 YR 2.5/3	Clay loam	No	Yes/f
Reddish brown gray, moist, silty clay loam, slightly sticky, heavily rooted with fine grass roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	13	61	Yes	7.5 YR 3/3	Clay loam	Yes	Yes/f&m
Reddish brown, moist, clay loam, sticky, very fine roots, friable, plastic, subangular blocky structure							
B2	61	126	Yes	7.5 YR 3/4	Clay loam	Yes/bldrs	Yes/vc
Reddish brown, moist clay loam, sticky, no roots, friable, plastic, subangular blocky structure, slightly rounded cobbles and boulders							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	D4
10	1.343
30	1.364
100	1.341
Average	1.349

**Soil Porosity:**

Depth	D4
10	49.3
30	48.5
100	49.4
Average	49.1

**Chemical Analysis:**

Test	Top A			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample	A	B	Avg	A	B	Avg	A	B	Avg
CEC (cmol <sub>c</sub> /kg)	12.150	12.250	12.200	11.986	ND	11.986	10.747	10.386	10.567
pH	5.4			5.6			5.8		
Nitrate (ppm)	10			5			≤5		
Phosphorous (ppm)	5			12.5			75		
Potassium (ppm)	200			110			140		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			≤2800		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			≤2.5			≤2.5		
Humus	1			ND			ND		
Magnesium (ppm)	5			10			80		
Manganese (ppm)	ND			ND			5		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



D4 Vegetation



D4 Profile 1



D4 Boulders



D4 Top



D4 Bottom



D4 Profile 2

**Data Sheet P1(6)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = N 10.376389, Long = -84.645833, Accuracy 21 ft **Date:** 07/28/2009

**Elevation:** 2185 feet **Slope:** 5 degrees **Aspect:** W 270

**Position:** Summit shoulder

**General Landform:** Convex linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Primary forest, no grasses, a few ferns, ground covered with brown decaying leaf litter, tall trees 10-50 meters, lower veg. mostly broad leafed fish tail palms

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	18	Yes	7.5 YR 2.5/3	Clay loam	Yes	Yes/f
Brown gray, moist, silty clay loam, slightly sticky, few roots, very friable, slightly plastic, very fine to fine subangular blocky structure, soil breaks apart easily, a few small rounded rocks 5 to 8 cm							
B	18	95	Yes	5 YR 3/4	Clay loam	No	Yes/f&m
Reddish brown, moist clay loam, sticky, moderately rooted with medium sized roots, friable, plastic, subangular blocky structure							
B2	95	105	Yes	2.5 YR 3/4	Clay loam	No	Yes/vc
Bright reddish brown, moist clay loam, sticky, friable, plastic, very sticky heavy clay, no roots							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	P1
10	1.192
30	1.344
100	1.389
Average	1.309

**Soil Porosity:**

Depth	P1
10	55.0
30	49.3
100	47.6
Average	50.6

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample	A	B	Avg	A	B	Avg	A	B	Avg
CEC (cmol <sub>c</sub> /kg)	13.545	ND	13.545	10.737	12.753	11.745	7.351	7.498	7.425
pH	6.2			6.2			6.2		
Nitrate (ppm)	5			5			5		
Phosphorous (ppm)	5			50			100		
Potassium (ppm)	160			150			160		
Aluminum (ppm)	125			125			80		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	2800			≤2800			≤2800		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			ND			ND		
Humus	ND			ND			ND		
Magnesium (ppm)	5			25			80		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤		
Sulfate (ppm)	ND			ND			ND		



P1 Vegetation



P1 Profile 1



P1 Top



P1 Bottom



P1 Profile 2



P1 Vegetation 2

**Data Sheet P2 (11)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.372222, Long = -84.650000 **Date:** 08/04/2009

**Elevation:** 2093 feet **Slope:** 18 degrees **Aspect:** SW 240

**Position:** Backslope

**General Landform:** Linear linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** primary forest, tall 50+m trees, few smaller trees between 5 and 15 meters in height, up to 20cm in diameter, small fishtail palms, some ferns, lots of brown decaying leaf litter

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	7	Yes	7.5 YR 3/3	Clay loam	No	Yes/f
Gray brown, moist clay loam, slightly sticky, heavily rooted with fine roots, very friable, slightly plastic, fine subangular blocky structure							
B	7	30	Yes	5 YR 3/4	Clay loam	No	Yes/f&m
Reddish gray brown, moist clay loam, sticky, moderately rooted with fine and medium roots, friable, plastic, subangular blocky structure							
B2	30	105	Yes	5 YR 3/4	Clay loam	Yes	Yes/f,m,l
Reddish brown, moist clay, sticky, fine, medium, and large roots throughout, plastic, unconsolidated massive clay structure, baseball sized angular rocks							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	P2
10	1.086
30	1.122
100	1.307
Average	1.172

**Soil Porosity:**

Depth	P2
10	59.0
30	57.6
100	50.7
Average	55.8

**Chemical Analysis:**

Test	Top	Middle	Bottom
CEC (cmol <sub>c</sub> /kg)	11.764	12.010	8.876
pH	5.2	5.2	5.2
Nitrate (ppm)	≤5	≤5	≤5
Phosphorous (ppm)	5	5	12.5
Potassium (ppm)	160	150	150
Aluminum (ppm)	125	125	125
Ammonia (ppm)	10	10	5
Calcium (ppm)	ND	ND	ND
Chloride (ppm)	ND	ND	ND
Ferric Iron (ppm)	5	5	5
Humus	1	ND	ND
Magnesium (ppm)	5	5	5
Manganese (ppm)	ND	ND	ND
Nitrite (ppm)	≤1	≤1	≤1
Sulfate (ppm)	ND	ND	ND



P2 Vegetation 1



P2 Vegetation 2



P2 Top



P2 Bottom



P2 Profile 1



P2 Profile 2

**Data Sheet P3(12)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.370556, Long = -84.652778 **Date:** 08/05/2009

**Elevation:** 2084 feet **Slope:** 5 degrees **Aspect:** SW280

**Position:** Foothlope

**General Landform:** Linear linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Tall canopy, 50+ meters, rich dark green vegetation, a few smaller trees 5 to 15 meters in height, 2 to 20 cm in diameter, small fishtail palms, lots of ferns, lots of brown decaying leaf litter

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	14	Yes	7.5YR 2.5/2	Clay loam	No	Yes/f
gray brown, moist, clay loam, slightly sticky, heavily rooted with fine roots, very friable, slightly plastic, very fine to fine subangular blocky structure, falls apart							
B	14	70	Yes	7.5YR 2.5/3	Clay loam	No	Yes/f
reddish brown, moist, clay loam, sticky, moderately rooted with fine roots, friable, plastic, subangular blocky structure							
B2	70	105	Yes	7.5YR 2.5/3	Clay loam	Yes	No
reddish brown, moist clay loam, sticky, no roots, friable, plastic, subangular blocky structure, large angular rocks 30cm by 30cm. Some are slightly rounded, heavily weathered							
B3	105	112	Yes	7.5YR 4/6	Clay loam	Yes	No
light brown, moist clay, sticky, no roots, plastic, continuous massive clay, rocks too large to move or dig around							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	P3
10	1.256
30	1.239
100	1.406
Average	1.300

**Soil Porosity:**

Depth	P3
10	52.6
30	53.3
100	46.9
Average	50.9

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample									
CEC (cmol <sub>c</sub> /kg)	13.962	12.873	13.418	9.403	12.240	10.822	6.564	7.703	7.134
pH	6.0			6.0			6.0		
Nitrate (ppm)	≤5			≤5			≤5		
Phosphorous (ppm)	37.5			37.5			75		
Potassium (ppm)	200			200			160		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			ND		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			≤2.5			≤2.5		
Humus	1			NA			NA		
Magnesium (ppm)	5			5			5		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



P3 Vegetation 1



P3 Vegetation 2



P3 Top



P3 Bottom



P3 Profile 1



P3 Profile 2

**Data Sheet P4(13)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.370000, Long = -84.661389 **Date:** 08/06/2009

**Elevation:** 2020 feet **Slope:** 1 degrees **Aspect:** SW240

**Position:** Toeslope (beginning of plateau)

**General Landform:** Linear linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Tall canopy 50+ meters, rich dark green vegetation, a few smaller trees 5 to 15 meters in height, 2 to 20 cm in diameter, small fishtail palms, some ferns, lots of decaying leaf litter. P4 in area with more fishtail palms, ferns, and thicker understory than previous primary pits.

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	15	Yes	7.5YR 2.5/3	Clay loam	No	Yes/f,l
gray brown, moist, clay loam, slightly sticky, heavily rooted with fine and large roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	15	35	Yes	7.5YR 2.5/3	Clay loam	No	Yes/f,m,l
reddish brown, moist, clay loam, sticky, moderately rooted with fine and large roots, friable, plastic, subangular blocky structure							
B2	35	107	Yes	7.5YR 3/4	Clay loam	Yes	No
reddish brown, moist clay loam, sticky, friable, plastic, subangular blocky structure, small angular rocks beginning at 50 cm and continue to bottom							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	P4
10	1.006
30	1.084
100	1.187
Average	1.092

**Soil Porosity:**

Depth	P4
10	62.0
30	59.1
100	55.2
Average	58.8

**Chemical Analysis:**

Test	Top	Middle	Bottom
CEC (cmol <sub>c</sub> /kg)	13.297	12.573	6.560
pH	5.2	5.2	5.2
Nitrate (ppm)	5	5	5
Phosphorous (ppm)	12.5	12.5	25
Potassium (ppm)	200	170	160
Aluminum (ppm)	125	125	125
Ammonia (ppm)	10	10	5
Calcium (ppm)	ND	≤2800	≤2800
Chloride (ppm)	ND	ND	ND
Ferric Iron (ppm)	2.5	5	≤2.5
Humus	ND	ND	ND
Magnesium (ppm)	5	5	5
Manganese (ppm)	ND	ND	ND
Nitrite (ppm)	≤1	≤1	≤1
Sulfate (ppm)	ND	ND	ND



P4 Vegetation 1



P4 Vegetation 2



P4 Top



P4 Bottom



P4 Profile 1



P4 Profile 2

**Data Sheet S1(7)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.460278 acc 22ft , Long = -84.633889 **Date:** 07/29/2009

**Elevation:** 2500 feet **Slope:** 15.38 degrees **Aspect:** NW280

**Position:** Summit shoulder

**General Landform:** Convex linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Understory trees 8 to 10 meters, largely palms, wild avocados, sacropia, balsa, fig. Canopy 20 to 30 meters, same species. No grasses, mainly ferns, palms, and heliconias.

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	16	Yes	7.5YR 2.5/3	Clay loam	No	Yes/f,m,l
dark brown, moist, silty clay loam, slightly sticky, heavily rooted with fine, medium, and large roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	16	80	Yes	7.5YR 3/4	Clay loam	No	Yes/f,m,l
Reddish brown, moist, clay loam, sticky, moderately rooted with fine, med and large, friable, plastic, subangular blocky structure							
B2	80	120	Yes	7.5YR 3/4	Clay loam	No	No
reddish brown, moist clay loam, sticky, no more roots, friable, plastic, subangular blocky structure, no color transition							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	S1
10	1.207
30	1.260
100	1.425
Average	1.298

**Soil Porosity:**

Depth	S1
10	54.4
30	52.4
100	46.2
Average	51.0

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample	A	B	Avg	A	B	Avg	A	B	Avg
CEC (cmol <sub>c</sub> /kg)	12.101	ND	12.101	9.180	9.421	9.301	7.749	7.911	7.830
pH	5.4			5.4			5.4		
Nitrate (ppm)	10			5			5		
Phosphorous (ppm)	≤5			5			5		
Potassium (ppm)	200			195			155		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	10			10			5		
Calcium (ppm)	ND			≤2800			2800		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			≤2.5			≤2.5		
Humus	1			1			<1		
Magnesium (ppm)	5			5			5		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



S1 Vegetation 1



S1 Vegetation 2



S1 Top



S1 Bottom



S1 Profile 1



S1 Profile 2

**Data Sheet S2(8)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.457778, Long = -84.646111 **Date:** 07/30/2009

**Elevation:** 2445feet **Slope:** 10 degrees **Aspect:** NW315 **Accuracy:** 21ft

**Position:** Backslope

**General Landform:** Linear concave **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Understory trees 8 to 10 meters, largely palms, wild avocados, sacropia, balsa, fig. Canopy 20 to 30 meters, same species. No grasses, mainly ferns, palms, and heliconias. More tree fall and woody debris than S1.

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	13	Yes	7.5YR 2.5/3	Clay loam	No	Yes/f,m,l
dark brown gray, moist, silty clay loam, slightly sticky, heavily rooted with fine, med, and large roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	13	33	Yes	7.5YR 3/3	Clay loam	No	Yes/f,m
gray reddishbrown, moist, clay loam, sticky, moderately rooted, friable, plastic, subangular blocky structure, a few fine and med roots							
B2	33	123	Yes	7.5YR 3/4	Clay loam	No	Yes/l
reddish brown, moist clay loam, sticky, no more fine roots, 2 large roots (one 8 cm in diameter), friable, plastic, subangular blocky structure							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	S2
10	1.241
30	1.328
100	1.409
Average	1.326

**Soil Porosity:**

Depth	S2
10	53.2
30	49.9
100	46.8
Average	50.0

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample									
CEC (cmol <sub>c</sub> /kg)	12.386	12.183	12.285	11.215	11.127	11.171	9.647	9.685	9.666
pH	5.8			5.8			5.8		
Nitrate (ppm)	5			5			5		
Phosphorous (ppm)	12.5			12.5			37.5		
Potassium (ppm)	200			175			125		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			ND		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	≤2.5			≤2.5			≤2.5		
Humus	ND			ND			ND		
Magnesium (ppm)	10			10			10		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



S2 Vegetation 1



S2 Vegetation 2



S2 Top



S2 Bottom



S2 Profile 1



S2 Profile 2

**Data Sheet S3(9)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.458611, Long = -84.668611 **Date:** 07/31/2009  
**Elevation:** 2327 feet **Slope:** 5 degrees **Aspect:** W270 **Accuracy:** 23 feet  
**Position:** Footslope

**General Landform: Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Vegetation different that S1 and S2. Mostly thin young trees, 5 to 10 cm in diameter and 3 to 10 meters in height. A few large trees, 30 cm in diameter and 30 to 35 m in height.

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	15	Yes	7.5YR 4/3	Clay loam	No	Yes/f
gray brown, moist, clay loam, slightly sticky, heavily rooted with fine roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	15	107	Yes	7.5YR 4/4	Clay loam	Yes	
tan brown, moist, heavy clay, sticky, few fine roots, moderately rooted with medium roots, friable, plastic, subangular blocky structure, 1 small rounded well weathered rock							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	S3
10	1.341
30	1.353
100	1.425
Average	1.373

**Soil Porosity:**

Depth	S3
10	49.4
30	49.0
100	46.2
Average	48.2

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample									
CEC (cmol <sub>c</sub> /kg)	11.645	12.033	11.839	11.372	11.462	11.417	10.448	10.569	10.509
pH	5.4			5.4			5.4		
Nitrate (ppm)	≤5			≤5			≤5		
Phosphorous (ppm)	5			12.5			12.5		
Potassium (ppm)	200			140			110		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			ND		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	2.5			≤2.5			≤2.5		
Humus	ND			ND			ND		
Magnesium (ppm)	5			5			5		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



S3 Vegetation



S3 Profile 1



S3 Top



S3 Bottom



S3 Profile 2



S3 Profile 3

**Data Sheet S4(10)**

**USDA Soil Taxonomy (2002):** Inceptisol  
**FAO Soil Taxonomy (2009):** ferri-humic umbrisols  
**USDA Moisture Regime:** udic  
**USDA Soil Temperature Regime:** isohyperthermic

**Location:** Lat = 10.462222, Long = -84.671944 **Date:** 08/03/2009

**Elevation:** 2329 feet **Slope:** 5 degrees **Aspect:** NW290 **Accuracy:** 20 feet

**Position:** Toeslope

**General Landform:** Linear linear **Parent Material:** andesitic

**Cover Type and Dominant Vegetation:** Thick understory. Lots of small ferns and young trees. Heavy light green vegetation, herbacious. Canopy 5 to 10 meters. Only a few tall trees of 20 to 30 meters. Lots of vines. Celaginella sapplings, semi precious wood.

**Profile Description:**

Horizon	Top	Bottom	Moist	Color/Hue	Texture	Rocks	Roots
A	0	12	Yes	5YR 3/4	Clay loam	No	Yes/f
gray brown, moist, silty clay loam, slightly sticky, heavily rooted with fine roots, very friable, slightly plastic, very fine to fine subangular blocky structure							
B	12	45	Yes	7.5YR 4/3	Clay loam	No	Yes/l
tan brown, moist, clay loam, sticky, moderately rooted with large roots, friable, plastic, subangular blocky structure							
B2	45	112	Yes	7.5YR 4/4	Clay loam	Yes/l	No
tan brown, moist clay loam, sticky, no roots at all, plastic, continuous massive heavy clay. At approximately 60 cm encountered large rounded rocks, some angular, 45 by 30 cm.							

**Bulk Densities in mg/m<sup>3</sup>:**

Depth	S4
10	1.226
30	1.234
100	1.310
Average	1.257

**Soil Porosity:**

Depth	S4
10	53.8
30	53.4
100	50.6
Average	52.6

**Chemical Analysis:**

Test	Top			Middle			Bottom		
	A	B	Avg	A	B	Avg	A	B	Avg
CEC Sample	9.520	9.507	9.514	9.589	9.756	9.673	8.879	9.172	9.026
CEC (cmol <sub>c</sub> /kg)	9.520	9.507	9.514	9.589	9.756	9.673	8.879	9.172	9.026
pH	5.2			5.2			5.2		
Nitrate (ppm)	≤5			≤5			5		
Phosphorous (ppm)	37.5			37.5			75		
Potassium (ppm)	200			200			150		
Aluminum (ppm)	125			125			125		
Ammonia (ppm)	5			5			5		
Calcium (ppm)	ND			ND			≤2800		
Chloride (ppm)	ND			ND			ND		
Ferric Iron (ppm)	7.5			7.5			≤2.5		
Humus	1			1			1		
Magnesium (ppm)	5			5			5		
Manganese (ppm)	ND			ND			ND		
Nitrite (ppm)	≤1			≤1			≤1		
Sulfate (ppm)	ND			ND			ND		



S4 Vegetation



S4 Profile 1



S4 Top



S4 Bottom



S4 Profile 2



S4 Profile 3

## VITA

Bryan Wallace Tower was born June 3, 1978, in Mission Hills, California. He is the son of Dennis Tower and Susan Tower. A 1997 graduate of Plano Senior High School, Plano, Texas, he received a Bachelor of Science degree with a major in Geology from Colorado State University, Fort Collins, in 2002.

After working for four years in mortgage banking, Bryan decided to attend Oregon State University in Corvallis, Oregon, 2006 to earn a Bachelor of Science degree in Natural Resource Management. While attending OSU he worked as a geological technician for an oil and gas company.

In August, 2008, he enrolled in graduate study at Texas Christian University, to pursue a Master of Science degree in Environmental Science. While working on his masters in Environmental Science he worked as a Teaching Assistant for both Contemporary Environmental Issues and Soils in the Environment.

## ABSTRACT

### THE EFFECTS OF LAND USE ON PHYSICAL AND CHEMICAL PROPERTIES ON TROPICAL SOILS, COSTA RICA

by Bryan Wallace Tower  
Department of Environmental Science  
Texas Christian University

Thesis Advisor: Michael Slattery, Professor of Environmental Science and Chair of  
the Department

It is well documented that changes in land use result in changes in soil properties. Costa Rica offers one of the most unique settings for studying soils and land use changes in the tropics. Once almost completely covered in forest, the country now bears the scars of colonization and development. However, Costa Rica is currently a working model of ecological protection and home to a successful eco-tourism industry. By setting aside large tracts of land for conservation, Costa Rica is a perfect location to compare changes in soil properties with changes in land use.

The soils at the Texas Christian University San Ramon Tropical Research Station in Costa Rica, a private facility dedicated to conservation and research, have never been studied. In order to understand how land use changes have affected them, soil quality analyses were conducted. Soil pits in primary growth forest, secondary growth forest, and deforested land once used for cattle grazing were be dug in order to carry out a suite of soil tests. The results indicate that while bulk density will increase following deforestation and cattle trampling, soil porosity will return with forest succession. Cation exchange capacity results on the other hand indicate that soil fertility increases with the introduction of grasses in deforested areas. Cations

also show a return to pre-disturbance levels with forest succession, which in this case is lower than post-disturbance levels.