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Soil succession: Short and long-term impacts of grazing on soil properties in a Tropical Montane Cloud Forest

June Curtis
SIT Study Abroad

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ABSTRACT

Cattle ranching is the leading cause of deforestation in South America, causing long-lasting alterations to the continent's landscape and ecology. Tropical montane cloud forests (TMCFs) are a rare ecosystem particularly vulnerable to the effects of land conversion to pasture, a process which has implications ranging from biodiversity loss to soil degradation. Grazing is known to significantly alter soils' physical structure through processes of compaction and erosion as well as significant additions of organic matter. Silvopasture, or the integration of pasture and forest, has emerged as an alternative to traditional grazing practices with the hope of mitigating environmental and soil degradation. Still, the differing effects of traditional and silvopastoral grazing systems on soil health are not widely studied. This study analyzed the short and long-term effects of grazing at 12 active and abandoned pasture and silvopasture sites in an Ecuadorian TMCF. Comparing their physical properties to those of primary forest soils, research examined pasture soil recovery after abandonment. Twelve soil profiles were analyzed for horizon depth, distinction and development as well as color and compositional gradients. Samples from each horizon were analyzed for bulk and particle density, color, moisture content, texture and composition. Pasture soils were found to be most vulnerable to erosion in the early stages of abandonment. Active and abandoned pastures showed evidence of significant and long-lasting compaction. Soil degradation was less visible in silvopastures, and preliminary data showed a faster recovery from compaction.

RESUMEN

La ganadería es responsable por lo más de la deforestación en Sudamérica, con alteraciones a largo plazo a la tierra y ecología del continente. El bosque nublado es un ecosistema raro que es particularmente vulnerable a los efectos de la conversión de la tierra a pastos, un proceso cuyos implicaciones varían entre la pérdida de biodiversidad y la degradación de los suelos. Es un hecho conocido que el pastoreo altera la estructura física de los suelos con los procesos de compactación y erosión, además de una adición considerable de materia orgánica. La silvopastura, o la integración de pastos con bosque, ha emergido como alternativa a la ganadería tradicional con la esperanza de disminuir su degradación ambiental– incluso lo de los suelos. Sin embargo, los efectos diferentes de los sistemas tradicionales y silvopastorales no han sido estudiados a profundidad. Este estudio analizó los efectos a corto y a largo plazo de la ganadería en 12 sitios de pastura y silvopastura activa y abandonada en el bosque nublado de Ecuador. Con una comparación de sus características físicas, la investigación examinó la recuperación de los suelos después del abandono de los pastos. Doce perfiles fueron analizadas según la profundidad, distinccíon y desarollo de sus horizontes además de sus gradientes de color y de composición. Muestras de cada horizonte fueron analizadas en términos de densidad, color, humedad, textura y composición. Los suelos pastorales fueron encontrados de ser más vulnerables en las etapas inmediatas del abandono. Las pasturas activas y abandonadas mostraron evidencias de compactación importante a largo plazo. La

degradación del suelo era menos visible en silvopasturas, y los datos preliminares mostraron una recuperación más rápida de la compactación.

INTRODUCTION

Cattle ranching has been common practice in the northern Ecuadorian Andes since the animals" introduction to the region during the Spanish conquest of the 1500s. A natural grassland, the high Andean *páramo* is more naturally suited to grazing than the tropical montane cloud forests on the low-elevation fringes of the mountain range (Joslin, 2021).Tropical montane cloud forests (TMCFs) are starkly different from the Andean highlands, located in a perpetual mist that supports incredible epiphyte biomass and diversity (Dodge, 2023). TMCFs are considered the most biodiverse place on Earth and provide Ecuador with the essential ecosystem services like freshwater capture (Bubb et al., 2004). They require significant land modification and deforestation to be suitable for grazing, but this hasn't stopped cattle ranching from becoming one of the biggest threats to the ecosystem (Bubb et al., 2004, X. Silva, personal communication, 2023). Conversion from forest to pasture for beef production was responsible for 71% of South America's deforestation between 1990 and 2015 (De Sy et al., 2015). In addition, grazing has the potential to significantly alter pasture soil structure through compaction, erosion and a considerable addition of organic matter (Greenwood & McKenzie, 2001, Smit & Kooijman, 2001, Donovan & Monaghan, 2021). Silvopasture has emerged as an alternative to clear-cutting forests for pastures. An ancient farming practice, silvopasture is the integration of forest and pasture, where trees may be either planted in existing pastures or left when clearing new land for grazing. Still, there is a lack of knowledge of how sustainable agricultural practices like this one affect a soil when compared to 'traditional' agriculture, especially with respect to local soil types and structures (Silva-Oloya 2022). Through a comparative soil analysis of undisturbed as well as active and abandoned pastures, this study aims to understand the alterations and recovery of animal agricultural soils in the Cloud Forest.

The soils of the Ecuadorian Cloud Forest are allophanic andisols, a classification determined by previous studies of the area (Silva-Yumi et al., 2021, *see Figure 1)* and confirmed by observations of their physical properties in this study. One of the twelve major soil orders, an andisol is defined by the USDA as a soil whose primary parent material is volcanic ash (USDA, 1999). Allophanic andisols are high in allophane, a metamorphic mineraloid formed by the weathering of volcanic aluminum silicates (Eswaran 1972). These minerals are formed in the explosive volcanic eruptions typical of the Andes. When weathered, volcanic aluminum silicates chemically bond with water molecules to become hydrous clay minerals, giving them soft and soil-forming properties. Allophane ($Al_2O_3 \cdot (SiO_2)1.3\text{-}2 \cdot (2.5\text{-}3)H_2O$) is one such product of this weathering, but is classified as a mineraloid instead of a mineral because it lacks a defined atomic and crystalline structure– note the variable numbers of atoms in its chemical formula (Z. Page, P.h.D, personal communication, 2023). Allophanic andisols are highly porous (low bulk density– 0.3-0.8 g/cm3) and hold a lot of water despite being well-drained. Coupled with chemical properties that facilitate organic carbon accumulation, this has earned them a reputation for being productive agricultural soils. Besides their abnormally low bulk density, allophanic andisols can be identified in the field by their greasy texture, high silt content, and well-aggregated particles (Juo & Franzluebbers, 2003).

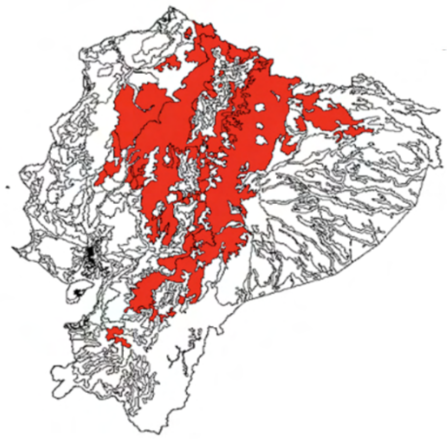


Figure 1: A map showing the distribution of allophanic andisols (highlighted in red) in Ecuador. Tropical montane cloud forests are found on either side of the Andes. *Source: Silva-Yumi et al. 2021.*

The andisols of the Ecuadorian Cloud Forest were formed over the past thousand years from the ash of explosive stratovolcanoes Cayambe and Pichincha (N. Morales, personal communication, 2023, and X. Silva, personal communication, 2023). Cayambe has been intermittently active since the beginning of the Holocene, with an estimated 20 major eruptions in the last 4000 years. The most recent covered the northwestern cloud forest region with a layer of ash in 1785 (IGEPN, 2023). Volcano Guagua Pichincha has had a number of notable eruptions in the past few thousand years: 3700 and 1000 years ago, and more recently in 1660 and 1999. The eruption of 1660 is particularly notable in the geologic history of the region (IGEPN, 2023) Given the recency of these eruptions, soils of the Ecuadorian Cloud Forest are young and therefore retain many physical and chemical properties of their parent material– volcanic ejecta (Gray & Murphy, 1999). Knowing a region's geologic history is essential to understanding its soil properties and composition, which determine how it will react to disturbance.

These structural properties are some of the most important determinants of a soil's ecosystem functions, from its ability to drain to how well it supports decomposition and nutrient cycling (Rabot et al., 2018). Looking at moisture content, more compact soils such as those rich in clay have smaller pores, enabling them to hold more water at shallower depths. Materials like silt and sand have pores larger than a molecule of water, meaning water that penetrates into these types of soils will percolate into deeper layers. This property is known as drainage, and is one of the key characteristics to consider when thinking about soil structure (Fausey, 2005). Drainage class determines what types of plants will grow in an ecosystem– by nature of their root structure, some require more well-drained soils, and others prefer a more saturated substrate (Abd-Elmabod et al., 2017). In investigations like this one, looking at a soil's moisture content, composition and color can help determine its degree of drainage. A well-drained soil will have a relatively even color throughout. A soil in which water accumulates over longer periods of time will have mottled patches of black, gray or rust-colored material throughout the matrix (Franzmeier, 2008). The coloring of a highly saturated soil can also be referred to as a "gleyed" matrix.

In addition to drainage and moisture content, color is an important indicator of a soil's composition in terms of mineral and organic components, which along with oxygen content determine most of its color. Organic material tends to make soil darker, while oxidized iron adds red and oxygen adds brown. In the absence of these components, soil takes on the color of most other minerals: gray. We can see these differentiations in the simple examination of a soil profile– the top layers will be darker than the lower ones due to their elevated levels of decomposition and organic matter present (Owens, 2005). Depending on their mineral composition and oxygen content, the lower soil layers range from gray to brown to red.

We have identified erosion and compaction as two principal sources of potential soil degradation in grazed sites. When a soil is compacted, the pore spaces between particles shrink, hindering its ability to drain and aerate– essential processes for moving water, nutrients and oxygen throughout plant root systems. Compaction is often observed as high bulk density in the subsoil. This is caused by the illuviation of the A-horizon's clay particles into the B-horizon– they are small and pass through the surface layers' pore spaces when soil is compacted. Compaction can be further confirmed by increased moisture content when compared to an undisturbed site (van den Akker & Soane, 2005).

As a soil is compacted and loses its ability to drain, runoff increases, in turn accelerating erosion (European Union, 2009). One type of erosion occurs when the soil comes in contact with more water than it can absorb. This runoff detaches and carries soil particles with it. Wind removes soil grains in a similar manner (Al-Kaisi, 2000). Some soils are more susceptible to erosion than others– sand, for example, is more easily eroded than clay because its particles are poorly aggregated. Organic matter helps aggregate a soil– mineral particles clump around organic particles, forming a structure resilient to erosion. A silty soil is an example of such (Gilley, 2005).

Although disturbed soils can be expected to be more exposed to weathering than their undisturbed counterparts, erosion is actually less of a concern while a plot of land is being actively grazed. According to Don Vicente, cattle rancher and co-founder of Santa Lucía Reserve, this region's type of pasture grass has an aggressive root structure that holds the soil in place J.E. Gilley confirms this in his 2005 essay on the subject, stating that the "dense sod" typical of pastures in humid areas–including tropical montane cloud forests– actually helps to prevent erosion (Gilley, 2005) It's in the early stages of abandonment that pasture soils are most vulnerable to erosion. Without cows to keep the land clear, opportunistic and aggressive plant species shade the area and prevent grass from growing. It is in this period– when early successional species make up most of the plant cover, and trees are not yet present– that the soil is most prone to erosion (D.V., personal communication, 2023).

Hypothesis

This study aims to determine how the soils of tropical montane cloud forests respond to and recover from grazing-induced compaction and erosion. It is essential to understand a soil's structural properties in order to determine how it will react to disturbance. Here, allophanic andisols' high porosity makes them resistant to erosion– rainwater permeates the soil instead of becoming surface runoff. This ability may be reduced in active pastures due to grazing-induced compaction and its reduction of pore spaces. In this examination of soil profiles, the effects of compaction are expected to be more evident and long-lasting than the effects of erosion– allophanic andisols' previously stated ability to accumulate organic matter protects them from erosion to some degree. Long-term compaction may show up as elevated bulk density even tens of years after the pasture is abandoned, and as the mottled color characteristic of poorly drained soils.

In line with Don Vicente's words about the action of erosion on abandoned pastures, a slight decline in soil health is expected in the first five years of abandonment, followed by a recovery. Active pastures are expected to have high amounts of silt in their surface horizons formed from the organic matter of cow excrements. Clay will likely be more concentrated in the subsurface horizons, as it is pushed through the A-horizon's pores with compaction from animal traffic. Recently abandoned pastures will likely show evidence of erosion in the form of shallow horizons and high clay content. As soil recovers, a rise in sand content coupled with a decrease in silt content is expected. This should be accompanied by an increase in clay content of the surface horizons, as it is no longer being illuviated into the B-horizon by compaction, and a decrease in subsoil clay. Depth of the O-horizon will increase as decomposing plants are allowed to accumulate undisturbed on the soil's surface. Sand content will likely be high across the board given the recency of volcanic eruptions that formed these soils. Primary forest sites are expected to have the highest sand content as they've been least exposed to erosion.

Silvopastures likely respond to and recover from grazing somewhat differently. Silvopasture sites are expected to show characteristics of both pastures and primary forest, although their soils will likely more closely resemble those of traditional pastures. In silvopastures, we anticipate a significant reduction in erosion and a slight reduction in compaction. A significant improvement in drainage is also likely due to the increased and diversified presence of large plant roots. Silvopasture soils will probably recover faster from grazing and not have the same initial decline in health after abandonment caused by the disappearance of grass without the presence of trees in traditional pastures. Silvopasture is a relatively new practice in the Ecuadorian cloud forest, and its soil recovery is even less understood than that of traditionally grazed pastures. This study examines one silvopasture site abandoned four years ago with the hopes of using traditional pasture recovery data as a tool to predict future silvopasture recovery.

MATERIALS, METHODS AND ETHICS

Site Terminology

We examined three types of sites for this study: actively grazed pastures, abandoned pastures, and primary forest. A *primary forest* is one that has not, as far as we know, been significantly disturbed by human activity since its origin. The names *primary forest site* and *undisturbed site* are used interchangeably in this study. An *active pasture* is defined in this study as one that has been grazed by cows and/or mules in the last three months. An *abandoned pasture* is a site that was once regularly grazed but has been left undisturbed for a year or longer. All pastures left abandoned for longer than fifteen years have had some degree of reforestation. This surely has an effect on soil quality– for the purposes of data analysis, we consider reforestation to be a natural step in the ecological process of recovery. For the purposes of this investigation, all active grazing sites examined are defined as either a *traditional pasture* or a *silvopasture*. We define a *traditional pasture* as a grazed site without intentionally planted trees, and where greater than 90% of the plant cover is grass. Occasional large trees leftover from when the forest was cleared to make the pasture may be present. In all traditional pasture sample sites, no trees (intentionally planted or not) were present within a 10m radius. We define a *silvopasture* as a grazed area intentionally integrated with forest, where between 60 and 89% of the plant cover is grass. As well as being deliberately planted with trees, the silvopastures at Santa Lucía Cloud Forest Reserve where this study was conducted contain non-grass forage such as plants of the families *Araceae* (elephant ears) and *Aspleniaceae* (ferns). The reserve's silvopastures are used for both mule and cow grazing; those in this study are currently only grazed by mules.

Sites

All research sites are located on the Santa Lucía Cloud Forest Reserve (SLCR) in Nanegal, Ecuador. Sites range in altitude from 1770 m to 1930 m, and are located between (0°07'05.9"N–0°06'56.4"N; 78°36'51.2"W–78°35'54.9"W). The region has a bimodal climate, with rainy seasons peaking in November and February (personal communication, Xavier Silva). Site descriptions are as follows. For specific site coordinates, see Appendix 4.

- GAC_1, GAC_2, and GAC_3 are pastures actively grazed by cows.
- SAC_2 and SAC_3 are silvopastures actively grazed by mules.
- GAB7, GAB12, GAB15, GAB23, and GAB33 are formerly grazed traditional pastures abandoned 7, 12, 15, 23, and 33 years ago, respectively. The pasture abandoned 15 years ago was minimally reforested to protect the stream running through it, which will be taken into account in the analysis. All other pastures were left to rest without grazing or other human activity.
- SAB4 is an abandoned silvopasture that was grazed by mules.
- BP_1 is a primary forest site.

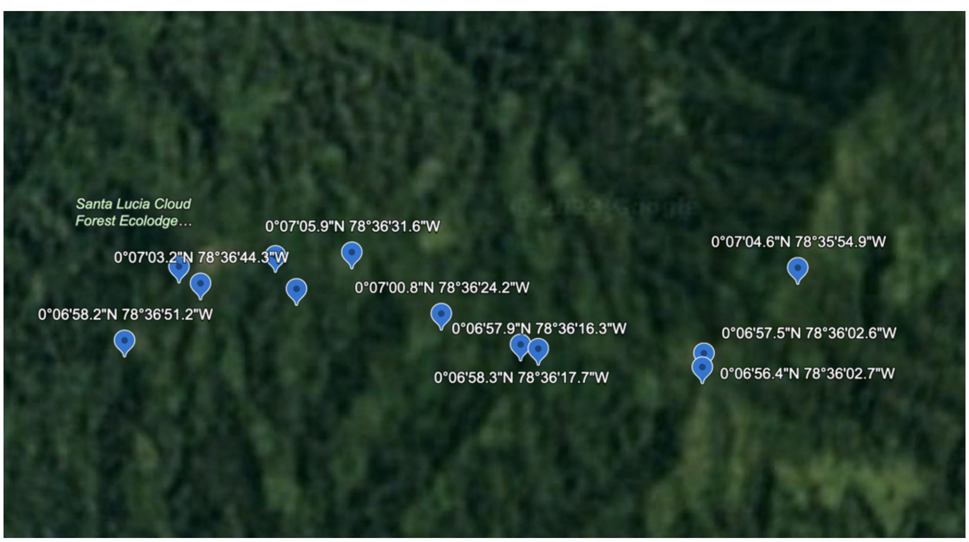


Figure 2: Map showing the coordinates of study sites at SLCR. *Source: Google Earth.*

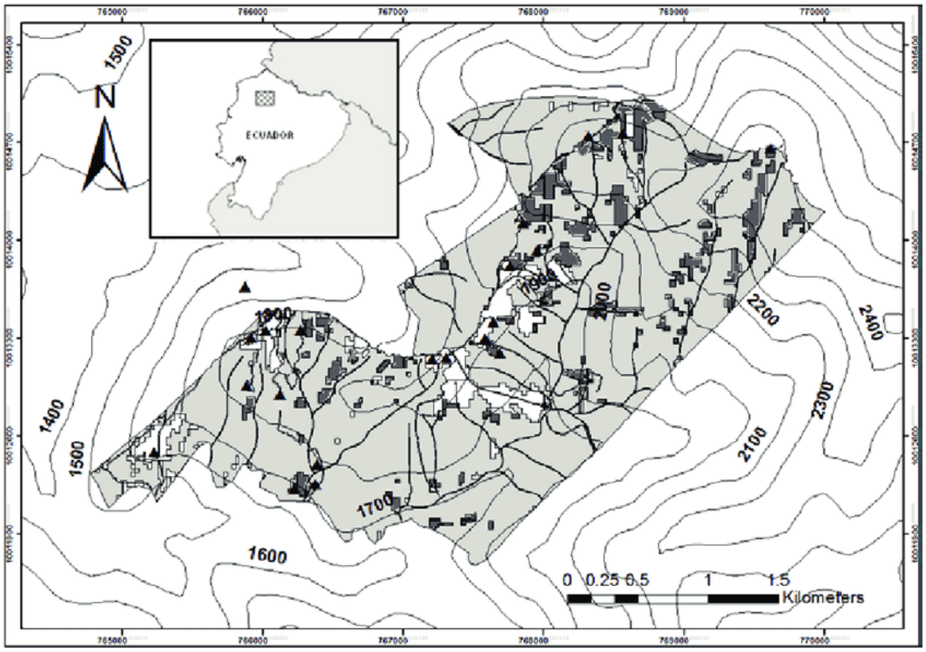


Figure 3: A map of the Santa Lucía Cloud Forest Reserve. *Source: Tolhurst et al., 2016.*

Materials

- shovel
- tape measure
- 20mL, 250 mL and 800 mL volumetric flasks
- digital balance
- water
- powdered laundry detergent
- powdered dish detergent
- plastic bowls, for drying samples
- metal sieve
- small plastic bags for sample collection
- permanent marker
- notebook & pen
- phone
- laptop

Field Methods

A meter-deep hole was dug at each site to obtain a vertical profile and analyze the soil horizons: depth of each (cm), distinction between the layers, development of sub-layers, and presence of mineral accumulations from illuviation. Samples were taken from each horizon in plastic bags, and analyzed in the lab according to five parameters: bulk density, particle density, composition, moisture content, and color, as well as general qualitative remarks. *Bulk density* is defined by the USDA as the dry weight of a sample per a given volume of that sample, expressed in g/cm3 (USDA, 2008). Volume for bulk density was measured using powder displacement. An undisturbed clod of soil was placed into a volumetric flask containing a known volume of powdered laundry detergent, and soil's volume was extrapolated from the change in volume of the powder. To ensure accuracy, the clod was buried completely in the powdered detergent.

Each bulk density sample was collected in its own plastic bag to preserve the pore spaces and original volume. After being measured for volume, samples were crushed and left to air dry for 24 hours or until completely dry. *Moisture content* refers to a soil's water content by weight as a percentage. It was measured by air drying a 50g sample for 24 hours or until completely dry and weighing again to determine percent moisture content. Each sample's *color* was determined as defined by Munsell's color chart, a resource designed specifically for the quantitative measurement of soil colors using hue (color), value (lightness or darkness) and chroma (intensity) (Rowe, 2005). *Particle density* (PD) is a measure of the mass of a given volume of soil particles in g/cm3 (Haan et al., 1994). PD was measured by crushing and sieving an air-dried soil sample, then measuring its mass with a balance and its volume by water displacement. 10 mL of water was used in a 20 mL volumetric flask. *Composition* refers to the sample's makeup of the three basic soil types: sand, silt and clay. Soil composition was determined using both a feel-in-hand ribbon test and a sedimentation test. The ribbon test is a preliminary way to determine soil class based on felt texture. The USDA's soil texturing flow chart (Appendix 1) was used as a guide. A small ball of soil between the researcher's thumb and forefinger and pushed upward to form a ribbon until the ribbon broke under its own weight. The length of the ribbon together with the texture of the sample in hand (smooth to gritty) can be used to assign a soil class. For precise sample composition details, a sedimentation test was used in reference with the USDA's standard soil composition triangle (Figure 4), which indicates soil class based on this percent composition. Two different sizes of volumetric flask were used for this. For the 250 mL flasks, 150 mL of water was added to an approximately 75 mL sample along with a half teaspoon of powdered dish detergent and a pinch of powdered laundry detergent. This was based on methodology from a Loyola Marymount University resource. These were detergent quantities which yielded the best results after trial and error. Quantities of sample, water and detergent were proportionally increased for the 800 mL flasks. Once submerged in water, soil aggregates were crushed with the hand and tests were mixed vigorously with a spoon to dissolve soil particles. In between 24 and 48 hours, the water clears as the soil settles out into layers of sand, silt and clay according to particle density. Measurements were taken once the water cleared, and percent composition was calculated from the volume of each layer.

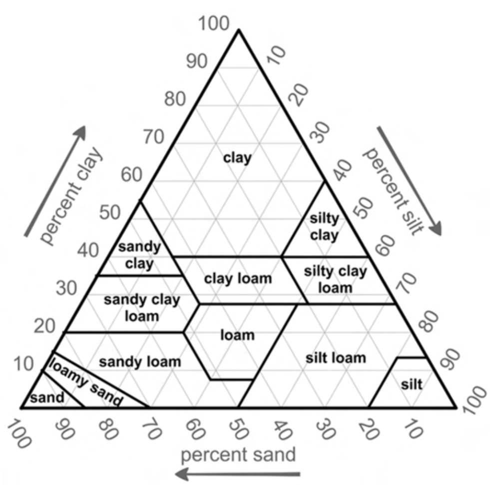


Figure 4: The standard composition triangle used to determine soil class. *Source: USDA*.

Methods of Analysis

Data were analyzed using Excel and Google Sheets. All graphs were made in Google Sheets. Results were analyzed for correlation using a correlation coefficient (R^2), calculated in Google Sheets. However, the limits of using an R^2 test here should not be ignored– R^2 creates a linear regression line for a dataset and compares it to the actual data points in the set. It's important to note that variables– i.e, particle density and depth– may be correlated in a nonlinear way.

Ethics

This investigation did not cause significant harm to the ecosystem in which it was conducted. Researchers acknowledge potential localized disturbances from digging the soil profiles. Holes were filled immediately following data collection, and dig sites were used with the permission of the Santa Lucía Reserve staff. The reserve's natural spaces, laboratory, materials and community were treated with utmost respect. This study did not involve human subjects.

RESULTS

Visual Comparison of Soil Profiles

Figure 6: Soil profiles of two active silvopastures (left) and one abandoned silvopasture (right).

Visual differences are evident between active traditional pastures and active silvopastures. In traditional pasture profiles, the boundary between A and B horizons is abrupt, with no AB transition horizon present. This is especially pronounced in site GAC3. In site GAC1, the A-horizon is slightly shallower with a somewhat broken lower boundary. Evidence of leaching at the B1-B2 barrier is also present in this profile– iron has leached out of the now-pale B1 horizon and accumulated at the top of B2. GAC2 and GAC3 show brighter-colored B-horizons and no leach marks. In the two active silvopasture sites, the boundary between A and B horizons is more diffuse, and the B-horizons below retain more of the surface layer's dark brown color. No AB horizon is present, although this transition layer does appear in the four-year abandoned silvopasture. Changes between horizons are even less evident in this abandoned site. There is some iron accumulation between the B horizons, similarly to the first traditional pasture profile.

Figure 7: Soil profiles from five abandoned pastures and one primary forest. Top, from left to right: abandoned five, twelve and twenty years. Bottom from left to right: abandoned twenty-three years and thirty years. Bottom right: Primary forest.

Although the last two abandoned profiles are comparable, each profile in this sequence of abandoned pastures is distinct. The profile of the pasture abandoned 5 years ago (GAB5) lacks an A horizon. Below the O-horizon is a thick B1 of high-clay silt loam, becoming a sandy clay loam in the B2 horizon. This layer consists of pockets of soft, white and orange sandy stone in a purple-tinted clay matrix. No horizon with these characteristics was present in any other soil profile. The pasture abandoned 12 years ago (GAB12) has a profile characterized by clear and distinct horizons with an orange tint throughout the soil profile. It shows a defined line of iron accumulation between the B layers. The pasture abandoned 20 years ago (GAB20) has the wettest profile upon initial examination– a trickle of water from one of the dug walls appeared at approximately 70 cm down. This was not observed in any other profile in this study. Similarly to GAB12, this site shows high iron accumulation in the B2 horizon, presumably from leaching. The pastures abandoned 23 and 30 years ago show a similar arrangement of layers, with a dark A horizon followed by a paler B1 below, and soil becoming darker and sandier with depth as it transitions to the B2 horizon. Of the two, GAB30 has a darker and deeper A-horizon. The primary forest profile follows a similar color sequence, although there are stark compositional differences that become apparent upon analysis (see Figures 8 and 9).

Changes in composition with depth and soil recovery

Figure 8: Sand, Silt & Clay Composition of Abandoned Pastures With Depth

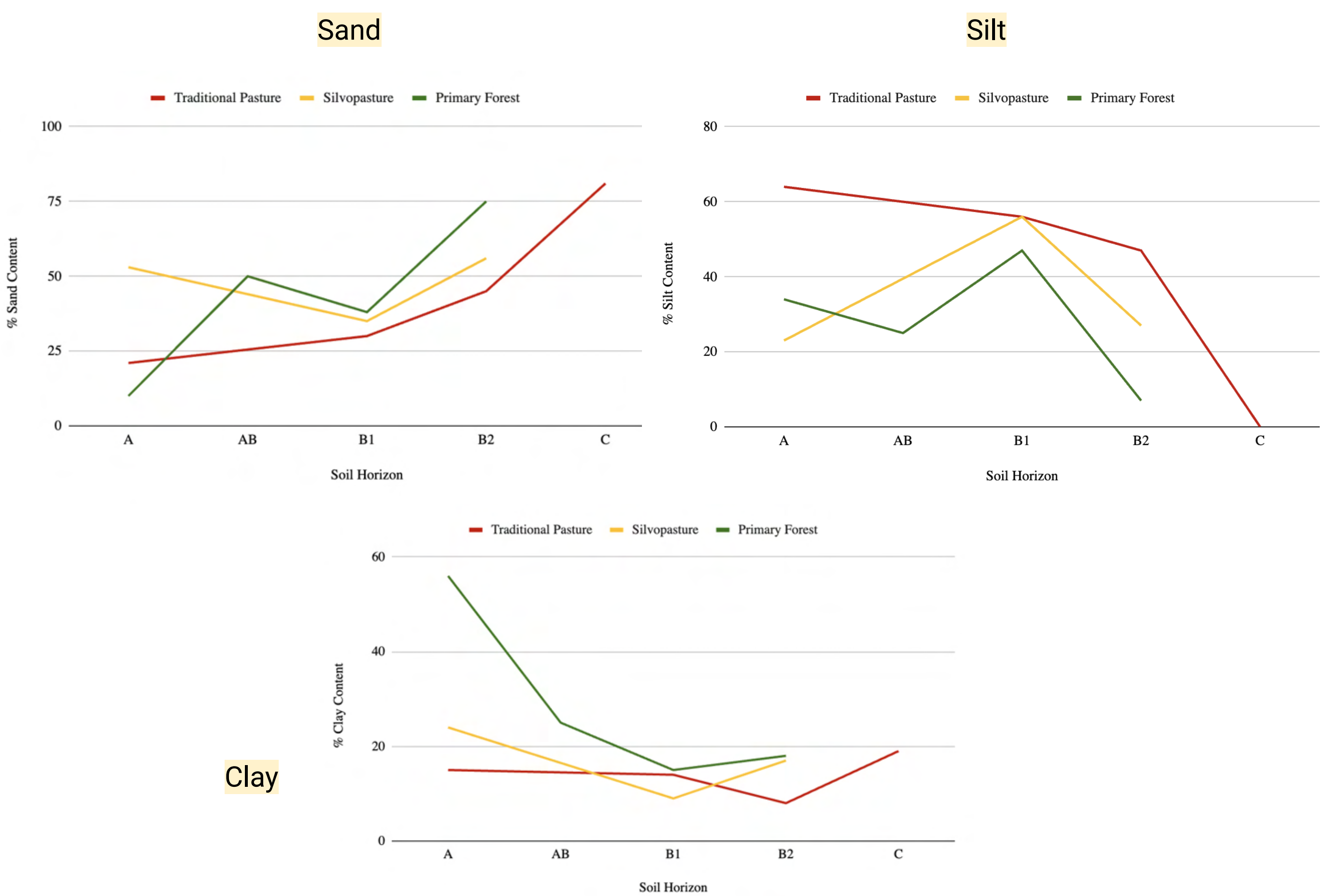


Figure 8: Graphs showing percent composition of sand, silt and clay of active pastures and primary forest for comparison. R^2 values for sand content are 0.795 (TP), 0.003 (SP) and 0.766 (PF). R^2 values for silt content are 0.698 (TP), 0.088 (SP) and 0.206 (PF). R^2 values for clay content are 0.007 (TP), 0.391 (SP) and 0.725 (PF). R^2 shows the amount of correlation between variable 1– percent composition of a given soil component– and variable 2– the soil horizon. Here, an R^2 value of greater than 0.4 is considered to have a moderate correlation, and an R^2 of greater than 0.7 is considered to have a strong correlation..

In traditional pastures and primary forest sites, sand content is strongly correlated to depth ($R^2 > 0.7$ for both sites). Sand content of traditional pastures increases with depth at each horizon. Silvopasture and forest soils show a similar dip in sand content between the A to B horizons. It's interesting to note changes in sand content with depth appear most pronounced in the least disturbed site– primary forest– and least pronounced in the most disturbed site– traditional pasture, *suggesting a potential correlation between level of disturbance and sand sorting.* The sample with the highest sand content came from one active pasture's C horizon and was 81% sand. C horizons were not present in silvopasture or primary forest soil profiles.

Silt content is strongly correlated to depth only in traditional pastures. The average A horizon of a traditional pasture had almost three times more silt than the average silvopasture A horizon and nearly twice as much silt as the same horizon in primary forest. Silt content decreased with depth at each horizon in traditional pastures until its disappearance from the profile in the C horizon, *suggesting a concentration of young, silt-forming organic matter in the surface layers.* Silvopastures and forests showed a proportionally similar change in silt content from horizon B1 to B2, just as with sand. Silvopasture was the only type of site where the average silt content in the deepest layer was higher than in that of the shallowest.

Clay content shows a strong correlation to depth in primary forest and a small correlation to depth in silvopastures. The primary forest site's A horizon had the highest clay content of any site horizon in the study– it was nearly four times higher in clay than the average traditional pasture's A horizon, and more than twice as high in clay as the average silvopasture's A horizon. In traditional pastures, mean clay content showed almost no change from the A to the B1 horizon, decreasing by 1%. In silvopasture sites, mean clay content dropped from 24% in the A horizon to 9% in the B1. This decrease in clay from A to B horizons was also observed in the primary forest profile, where it was the most pronounced. Percent clay values dropped from 56% in the A horizon to 15% in horizon B1. It's interesting to note that percent composition values in silvopastures fall between those of primary forest and traditional pasture composition most of the time. This is especially true for the composition of the B2 horizons, where average silvopasture silt, sand and clay content are all intermediate to the other two site types.

Figure 9: Sand, Silt & Clay Composition of Abandoned Pastures Over Time

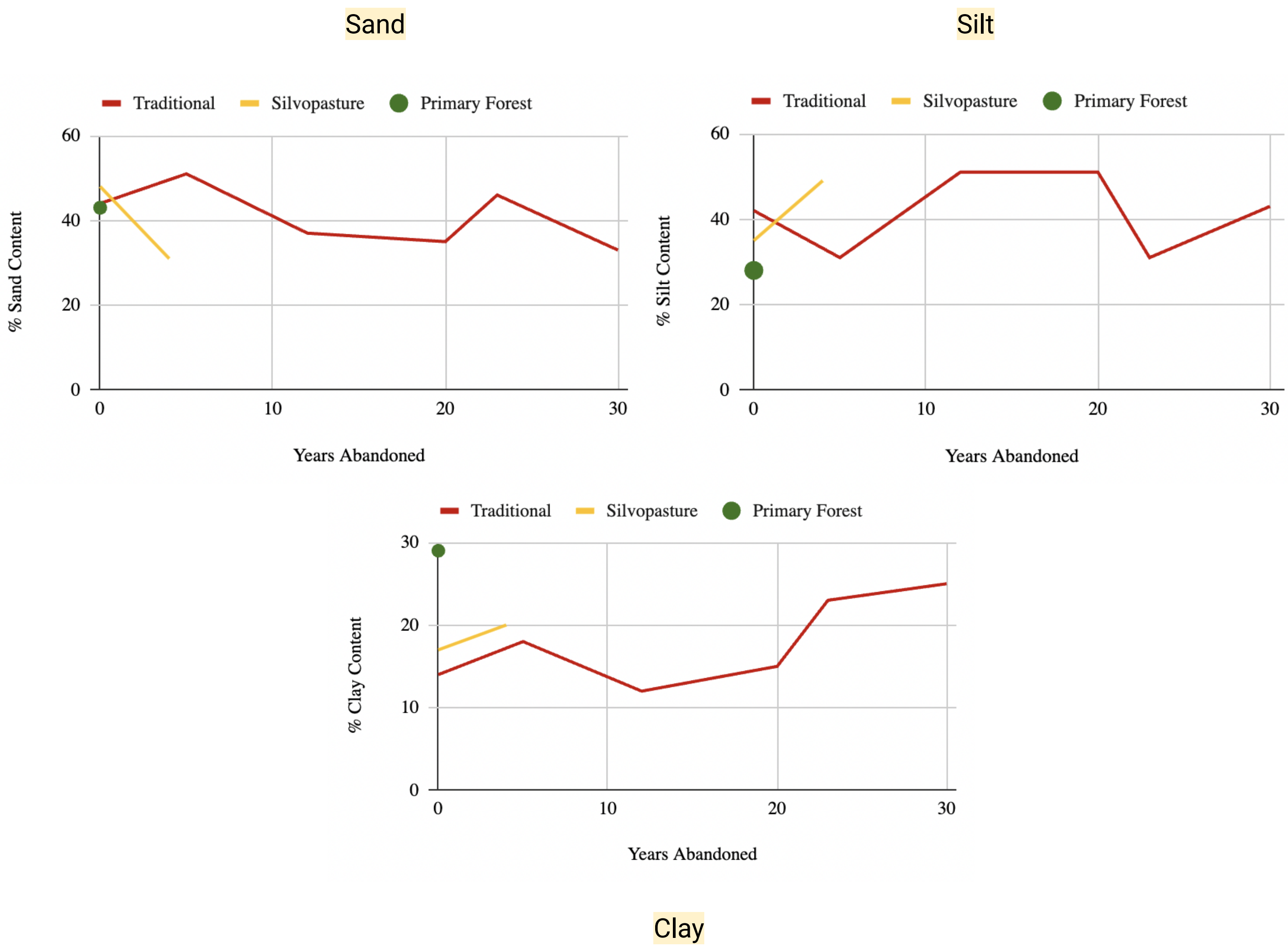


Figure 9: Graphs showing changes in composition of the soil overtime in abandoned pastures. Top, from left to right: sand, silt. Bottom: clay. Percent composition data is derived from the mean of all soil horizons in each site. R^2 values for traditional pasture regression lines are as follows: 0.365 (sand), 0.012 (silt), 0.495 (clay). Silvopasture and primary forest sites have no R^2 values as there are too few data points in time, shown for comparison only.

The only soil component that shows a strong correlation to pasture recovery time is clay (R^2 = 0.495). The average clay content of an active traditional pasture is 14%, and this rises to 25% in the pasture abandoned 30 years ago, nearly an 80% increase. Mean clay content is still lower than the 29% observed in primary forest. In terms of clay content, the recovery of silvopastures closely mirrors that of traditional pastures: after 4 years of recovery, the average silvopasture clay content rose by 3%, compared to 4% in five years in the average traditional pasture.

Sand and silt content show less obvious correlations to pasture recovery time. Mean sand content is almost identical in all three site types, although as we saw previously its distribution between the layers differs in each profile (Figure #, the other 3 graphs). In the first five years of abandonment, mean sand content in traditional pastures rises from 44 to 51%. It then decreases to 35% in 20-year abandoned site before spiking to 46% in the 23-year site and then declining again to its lowest yet of 33% in the 30-year site. In silvopastures, mean sand content drops by just over a third between the active and abandoned sites. Although it fluctuated, silt content showed no statistical correlation to pasture abandonment time. Mean silt content rose imperceptibly from 43% in active pastures to 44% after 30 years. It was significantly higher in the pastures abandoned 12 and 20 years ago– both had a 51% silt content. Silvopastures saw an increase in silt content from 35% to 49% in the first four years of abandonment. All active and abandoned pasture sites (of both types) had higher silt content than the primary forest site. *This is likely due to the silt-forming organic matter added to pasture soils during grazing.*

Looking at each horizon separately, the most common soil classification in this study was silt loam (see Appendix 3).

Changes in active pasture and primary forest soil properties with depth

Figure 10: Moisture Content of Pasture and Forest Soils with Depth

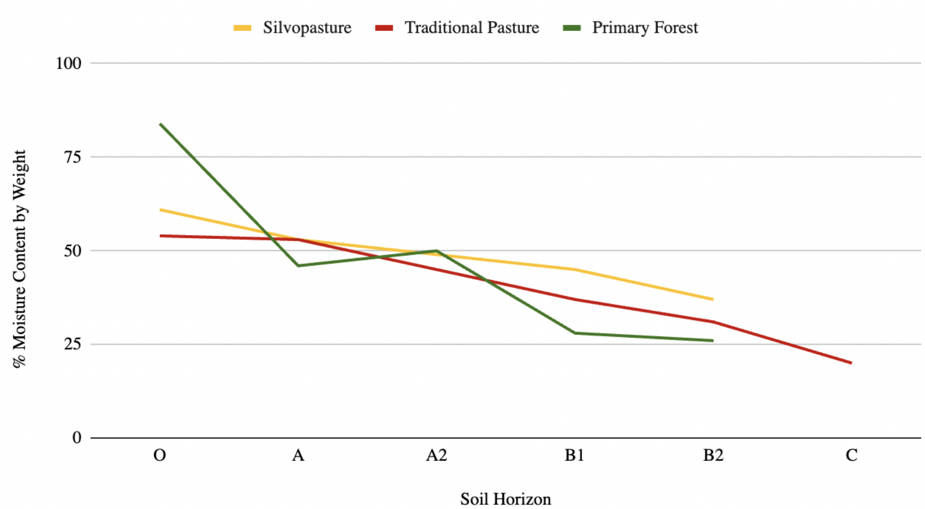


Figure 10: Graph showing mean soil moisture content in relation to depth in active pastures and primary forest. R^2 values are 0.969 (TP), 0.98 (SP) and 0.823 (PF).

This graph shows an extremely high negative correlation between moisture content and soil depth in all site types– in pasture sites, the relationship is nearly linear. The O horizon holds the most moisture by weight in each site type, the primary forest's holding the most at 84%. The traditional pasture's C horizon has the lowest moisture content of any layer, with water accounting for just 20% of its weight.

Figure 11: Bulk Density of Pasture and Forest Soils with Depth

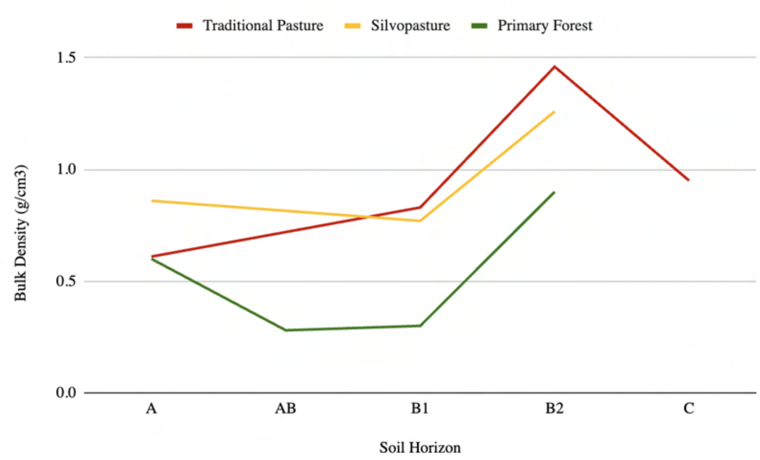


Figure 11: Graph showing mean bulk density in relation to depth in active pastures and primary forest. R^2 values are 0.407 (TP), 0.399 (SP) and 0.165 (PF).

Results show bulk density to have a greater correlation to depth in grazed soils compared to those left undisturbed. With R^2 values of 0.407 for traditional pasture and 0.399 for silvopastures, this correlation remains only moderate. The three sites show a similar increase in bulk density from the B1 to the B2 horizon, with increases of 0.63, 0.49 and 0.60 g/cm3 in pasture, silvopasture and forest sites respectively. Mean bulk density decreases from horizons A to B1 in both silvopasture and forest sites. In contrast, traditional pasture bulk density increases from the A to the B1 horizon. BD is the highest in the B2 horizon of traditional pastures at 1.46 g/cm3.

Figure 12: Particle Density of Pasture Soils with Depth

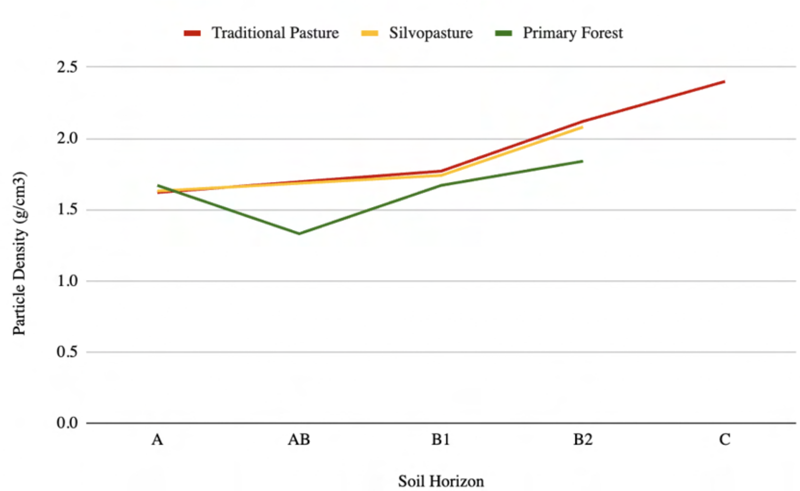


Figure 12: Graph showing mean particle density in relation to depth in active pastures and primary forest. R^2 values are 0.896 (TP), 0.789 (SP) and 0.263 (PF).

Particle density is strongly positively correlated to depth in pasture soils but shows no significant correlation to depth in the primary forest site. Mean particle density is comparable in the A horizon of each site type, increasing along an extremely similar trendline in traditional pastures and silvopastures. Excluding the first A horizon, particle density is lower in all primary forest sites than in any pasture site. The traditional pasture's C horizon has the highest bulk density at 2.40 g/cm3.

Figure 13: Mean Organic Matter Depth of Pasture Soils

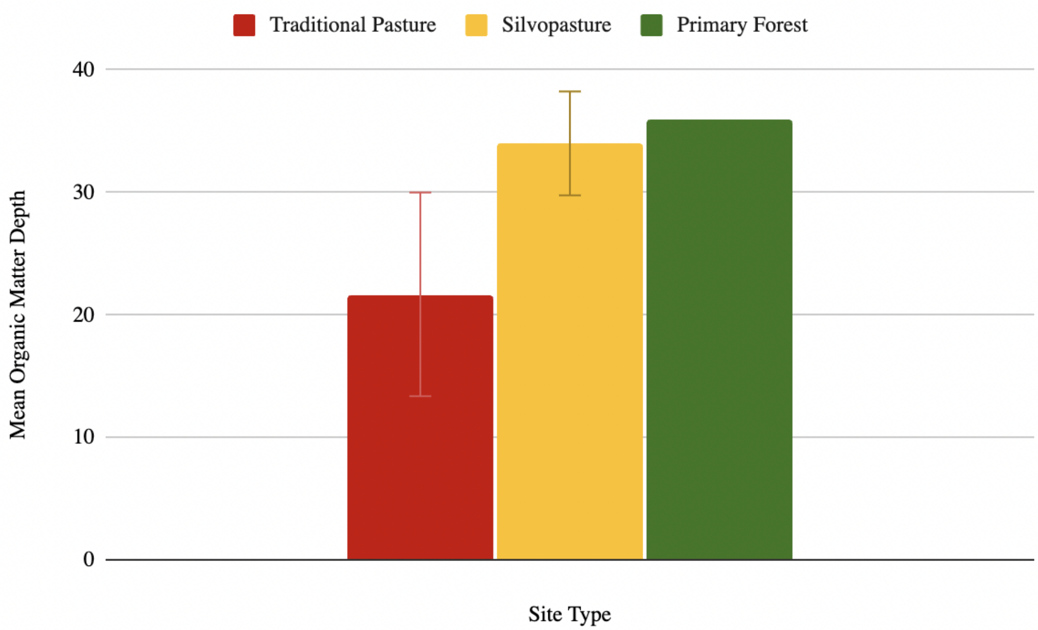


Figure 13: Graph showing mean organic matter depth of pasture and forest soils. Here, organic matter depth refers to the combined depth of horizons O to AB, the layers whose principal component is organic matter. Error bars represent standard deviation. SD = 8.32 for TP and 4.24 for SP. Since only one primary forest site was sampled, the dataset has no standard deviation.

Although a trend is visible, there is no statistically significant difference in organic matter depth between the three site types.

Changes in abandoned pasture soil properties with recovery

Figure 14: Physical Properties of Abandoned Pasture Soils Over Time

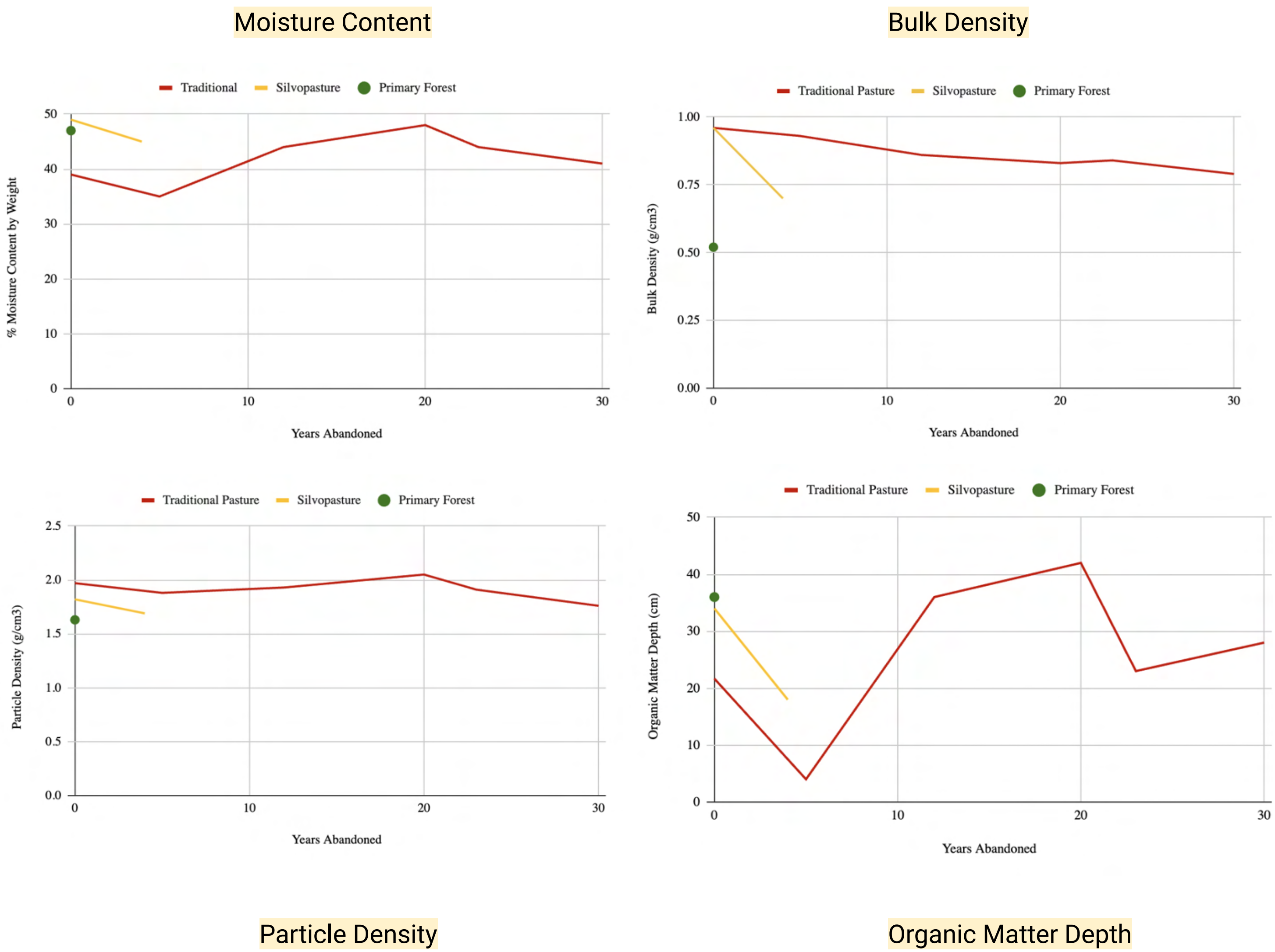


Figure 14: Graphs showing mean moisture content, bulk density, particle density, and organic matter depth in relation to pasture abandonment time. Primary forest data shown for comparison. R^2 values for traditional pasture sites are 0.294 for moisture content, 0.946 for bulk density, 0.161 for particle density and 0.206 for organic matter depth. As in Figure #, organic matter depth refers to the combined depth of horizons O to AB.

There is no significant correlation of particle density, moisture content, or organic matter depth with pasture abandonment time. There is an extremely high correlation between bulk density and abandonment time ($R^2 = 0.946$). The mean bulk density of an active traditional pasture is 0.96 g/cm3, which decreases at an average of just under 0.02 g/cm3 a year before reaching its low of 0.79 g/cm3, 30 years after abandonment. In the silvopasture sites, this decrease is more rapid, from 0.96 g/cm3 to 0.70 g/cm3 in just four years. Decreases in moisture content and particle density between the active and abandoned silvopasture sites were also observed. Mean organic matter depth fluctuated in abandoned pastures, beginning at just under 22 cm in active pastures and dropping to 4 cm in the five-year abandoned site. This value showed an upward though non-linear trend in the longer-abandoned sites, rising above the primary forest's value of 36 cm in one instance. In silvopastures, organic matter depth showed an initial decrease of similar proportion to that of traditional pastures, with a 16 cm reduction between the active and abandoned sites.

External variables
Composition, particle density, bulk density, and moisture content were all cross-analyzed with each other using an R^2 regression. No significant correlations were found between them.

ANALYSIS & DISCUSSION

Trends in active pasture and primary forest soil properties

Summary of soil characteristics
Our analysis of physical soil characteristics on the reserve is consistent with the expected soil type, allophanic andisols. This is based on observations of color, texture, aggregate structure and low bulk density. Pasture soils had higher particle and bulk densities than undisturbed soils, as well as a lower mean depth of organic horizons. Traditional pastures showed lower moisture content than undisturbed soils while silvopastures showed higher. Of the three soil components, sand content was most correlated to depth. It showed a high positive correlation with depth in both traditional pastures and primary forest, but was not correlated with depth in silvopastures. Sand content was lower than expected in all sites– soils appear to be characterized more by the ecosystem's high level of decomposition (creating silt) than by their parent material. Silt content was negatively correlated with depth in traditional pastures. Clay content showed a strong negative correlation with depth in primary forest, and a small negative correlation with depth in silvopastures.

Particle density
Particle density showed a strong correlation to depth in both types of active pastures. Since it has been demonstrated to be independent of soil composition, differences in PD between pasture and forest can be most likely attributed to the changes in composition *distribution*. This is to say that the act of grazing a plot of land changes the distribution of sand, silt and clay throughout the soil horizons, sorting particles by density through processes of compaction and erosion. This is not only true for particle density. With the exception of moisture content, which was strongly negatively correlated to depth in all site types, variables examined in this study showed fewer correlations to depth in the undisturbed site compared to pastures. This suggests that grazing homogenizes pasture soils, ordering their components by depth in some way. Further analysis is needed to confirm this hypothesis.

Drainage

Moisture content had a significant correlation to depth in all active pasture and primary forest sites. The primary forest profile showed the greatest change in moisture content with depth, from 84% in the O horizon to 26% in the B2 horizon. This was followed by traditional pasture at a decrease of 34 percentage points and silvopasture with a difference of 24 percentage points. Soils with poor drainage show a concentration of moisture at the top of the profile, in the surface layers (Gilley, 2005). The logical conclusion based on this assumption is that the primary forest soil profile is the most poorly drained of the three, a finding inconsistent with the site's low levels of compaction. There are several possible explanations for this. One is that water concentrates in the upper layers of primary forest soils because of these layers' high clay content– clay holds more water than sand or silt. Another possibility is that the significant differences in O horizon moisture content between the sites are altering the data. If we look at just the A horizons, primary forest has the lowest moisture content at 46%. Both pastures show 53% A horizon moisture content. This is more consistent with predicted drainage patterns, and all the more significant considering the horizon's high clay content. Visually, all three traditional pasture profiles showed signs of poor drainage– GAC1's took the form of mottled B horizons and iron illuviation. GAC2 and GAC3 had abrupt transitions from horizons A to B, indicating an extreme change in drainage properties between the layers. This is a phenomenon known as surface sealing, and is caused by compaction (Gilley, 2005). Reduced water infiltration between the layers likely prevents the mixing of A horizon organic matter with B horizon mineral soil. Neither the active silvopasture nor the primary forest profiles showed signs of poor drainage.

Recovery of abandoned pasture soils

Erosion

As expected, there is a period of soil degradation in terms of erosion in the initial stages of abandonment. The five-year abandoned pasture sampled lacks an A-horizon, and the site shows the lowest total organic layer depth of any profile in the study. This is consistent with a finding by Mendoza-Vega et al. (2020) that showed an initial decline in soil quality during the process of remediation from agricultural land to forest. Although Mendoza-Vega et al.'s study does not specifically mention increased erosion, they discuss decreases in cation exchange capacity and organic carbon, high levels of which are indicators of good soil quality. Mendoza-Vega et al. attribute this to possible disturbance caused by reforestation of their sites. This explanation is not applicable to our study– the site in which this degradation was observed has not been reforested. In our site, the presence of an O-horizon without an A-horizon below it suggests that decomposition is occurring on the soil surface but that this organic matter is eroded before it can develop further into an A-horizon. The presence of the unique purple clay B horizon suggests the site has been heavily eroded. This layer was informally observed in other highly eroded areas of the reserve– primarily at the bottom of exposed trail walls. It is likely that this same clay lies below layers of volcanic ash everywhere in the region, and is only visible here due to erosion of the loose and easily-transported volcanic parent material. However, the possibility that this layer's presence is due instead to geologic differences cannot be dismissed without further investigation. After 12 years of abandonment, pastures started to show recovery from erosion. The presence of an AB horizon in pastures abandoned 12 years or longer shows that organic matter is accumulating and staying in the soil. The development of these layers is crucial for the soil's ability to retain moisture and nutrients, support root growth, and prevent future erosion (USDA). The abandoned silvopasture also showed evidence of erosion– organic matter depth saw a decrease of similar proportion to that of traditional pastures. Sand content decreased significantly during this time, further suggesting erosion– sand particles are the most easily eroded of the three sand components. This contradicts the rise in sand content observed in the first five years of abandonment in traditional pastures. It's possible that elevated sand levels in GAB5 are due to differences in mineral composition between the sites, but this can not be stated for certain without further mineralogical analysis.

Compaction

Compaction was observed in both active and abandoned pasture sites. Normal bulk density values for allophanic andisols range from 0.3-0.9 g/cm3 (Juo & Franzluebbers, 2003). Bulk densities observed in the undisturbed site were comparable to these values, ranging from 0.28 g/cm3 in the AB horizon to 0.9 g/cm3 in the B2 horizon with an overall mean of 0.52 g/cm3. Active pastures showed elevated bulk densities, with an average of 0.96 g/cm3 for both traditional and silvopastures. Consistent with existing literature, compaction appeared to have more of an effect on the B-horizons of traditional pastures (van den Akker, 2005). Although their surface layers showed normal bulk density values, the B-horizons of these sites had BD values well above the normal range. Bulk density was strongly correlated ($R^2 = 0.946$) to the length of time a pasture had been abandoned, suggesting a causal link between soil compaction and grazing (past and present) on the reserve. Data shows a slow recovery from compaction, with bulk density values 0.27 g/cm3 higher in abandoned pastures *even after 30 years of recovery.* Bulk density was the only variable to show a strong correlation with recovery time in abandoned pastures.

Composition

Clay was the only soil component to show a significant correlation to recovery time in abandoned pastures, rising from a mean of 14% in the active sites to 25% in the 30-year abandoned pasture. The correlation was strong, suggesting that disturbance from grazing reduces soil clay content. This conclusion is further supported by the high clay content of the undisturbed forest profile– at 29%, this site had the highest mean clay content of any in the study. This is inconsistent with a finding from Peco et al., which observed a decrease in soil clay content following pasture abandonment. It's possible that these discrepancies are due to differences in soil types– the other study was conducted in the Guadarrama range of central Spain, where soils are distric cambisols (Peco et al., 2006). Returning to our study, it's interesting to note that much of this clay is concentrated in the site's A and AB horizons, whereas clay content had no correlation to depth in traditional pasture sites and only a small correlation to depth in silvopastures. This homogenization of clay distribution is further evidence of pasture compaction, which is known to cause illuviation of A-horizon clay into the B-horizons.

Preliminary trends in silvopasture recovery

Silvopastures show similar recovery trends to traditional pastures in the one abandoned silvopasture sampled. For particle density, moisture content, and organic matter depth, recovery happens at a nearly identical rate. This is based on the slope of the lines between data points from 0 to 4 years of recovery in silvopastures and 0 to 5 years of recovery in traditional pastures. In each composition graph, the line showing changes in silvopasture soil composition with depth more closely mirrors that of the unaltered primary forest than that of the traditional pasture, suggesting that silvopasture soils are less altered from their natural state than traditional pastures. Since their physical properties are intermediate to those of traditional pasture and undisturbed forest soils, silvopasture soils have a head-start on recovery. Because of their observed thicker layers of topsoil (O and A horizons), silvopastures are likely more resilient to erosion than traditional pastures. Preliminary data shows they are also likely to recover faster in terms of compaction– the abandoned site's bulk density values recovered more in four years than the traditional site did in thirty. It appears either that grazing has less of an impact on silvopasture soils to begin with, or that transforming these pastures from pure grass to silvopasture has jump-started this recovery process. Further research is needed to determine the more long-term effects of grazing on silvopastures specifically.

CONCLUSION

Our analysis found compaction to be the most important force of pasture degradation on the reserve. Soils in this study were found to be high in silt, which tends to resist compaction because of its high organic matter content and elasticity (van den Akker, 2005). Despite this, compaction was observed to be long-lasting, its effects visible even after thirty years of soil recovery. Soil compaction is known to prevent proper drainage, aeration and root penetration, hindering productivity in terms of agriculture or future return of the land to its natural state. Grazing likely has more severe and long-lasting compaction effects on soils that lack these protective mechanisms of high organic matter content and a sandy parent material. Finding an ideal soil for grazing poses a challenge because the characteristics that make it most resistant to compaction– high sand content– also make it most vulnerable to erosion (van den Akker, 2005). Organic matter is the one component that has been shown to protect against both these processes of soil degradation (Gilley, 2005).

Results supported the hypothesis predicting an initial increase in erosion following pasture abandonment. This finding has significant implications, showing that taking actions to support soil recovery is most critical in the early stages of abandonment– that is when a former pasture is most vulnerable. Analysis shows silvopasture soils to be less affected by grazing than traditional pasture soils in terms of compaction and erosion. Preliminary data supports the hypothesis that they recover faster from compaction than traditional pastures. This is potentially due to the increased presence and diversity of large plant roots, which promote soil drainage and aeration as well as increasing soil elasticity, preventing compaction (van den Akker, 2005). Whether silvopastures' demonstrated greater organic matter depth causes a reduction in erosion, or whether the reduction in erosion is due to the greater presence of organic matter is unclear and requires further investigation. It's likely that erosion and organic matter loss together form a positive feedback loop that accelerates soil degradation. These findings support the idea that less disturbed pastures are more resilient to the soil degradation processes of compaction and erosion. This highlights the importance of building resiliency in pastures, so that when they are eventually abandoned and left to turn into forest again, their soils recover quickly and completely, and the land is left better than it was before.

Possible sources of error

For greater accuracy, soil composition was analyzed using both a feel-in-hand test and a sedimentation test. The results of these two tests did not always agree, and while differences in results are most likely due to errors in estimating texture in hand, inaccuracies in sedimentation test results are also possible. In sedimentation, the border between the sand and silt layer was not always clear. In these instances it was still able to be estimated with some degree of accuracy and confidence. Because of their greater degree of precision in determining percent composition, sedimentation test results were chosen for the analysis.

Determining where one horizon ends and another begins in the soil profile is sometimes difficult and somewhat subjective. Horizons usually change in color and texture to some degree from top to bottom, and what one researcher might classify as simply a color gradient another might split into two-sub horizons. Small inconsistencies in horizon classification are possible, especially toward the beginning of the investigation when the researcher was less familiar with the process. In an attempt to mitigate this, soil profile photographs were compared to each other at the end of the investigation and cross-referenced with notes taken on-site to check for classification inconsistencies. Changes were made accordingly.

Bulk density was measured using powder displacement, a method of the researcher's own invention. Logic tells us it should be reliable, and it appeared to be, yielding consistent and significant results within the normal range. It is, however, possible that this method is unreliable, as its success has not been replicated in other studies.

Finally, differing sample sizes were used for active pasture and primary forest sites because of site availability. The researcher recognizes this may have an effect on analyses where a mean was considered, and suggests that future studies examine an equal number of sites of each type.

Suggestions for future research

It would be interesting to look at the abandoned pastures again in five or ten years to see if they are following the observed trends in recovery. This could prove especially insightful in the case of the abandoned silvopasture, which– at four years– is the longest (and only) abandoned silvopasture on the reserve. Should a researcher want to study this site in the future, they should note that the upper part of the pasture is still actively grazed– only the bottom part is abandoned. This also goes for site GAB5, the traditional pasture abandoned 5 years ago. More details can be obtained by consulting director of the reserve Noé Morales or founder Vicente.

Some silvopastures on the reserve are grazed by mules, and others by cows. Pastures examined in this study are grazed exclusively by mules. An investigation focused on the differences between these two types of silvopasture would provide valuable insight into how the grazing practices themselves affect soil quality. From what the reserve staff has said, mule silvopastures are better maintained and have smaller-size herds grazing them, which may have a positive impact on soil health.

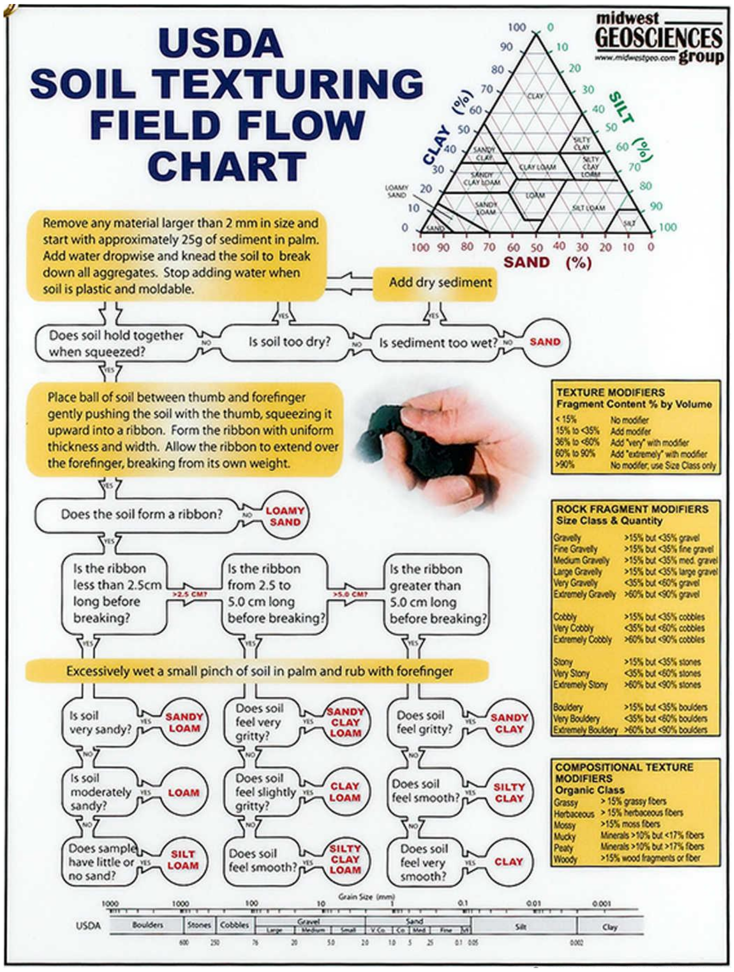
It's possible that the steep slope of pastures on the reserve increases erosion, as water likely has a tendency to run down the slope instead of infiltrating, carrying soil material with it. Future research could look at differences in observable erosion between flat and differently sloped sections of pasture to see exactly what effect this has. Future research could investigate the potential correlation between pasture slope and visible erosion– i.e, depth of the organic horizons. Studies including more replicates instead of large profiles could potentially yield more reliable or significant data.

Finally, little research has been conducted on the subject of SLCR's geology. Informal observations of soil layer sequences on exposed trail walls showed soil types not encountered in this investigation. I am so curious to know these layers' origins, as they lie under the ash and are therefore pre-volcanic. This type of study would yield valuable information about the western Andes' geologic history, providing insight into how stratovolcanic activity changes a region's geology, and how these parent materials continue to affect soil composition and properties in the Ecuadorian cloud forest. If you are reading this and decide to conduct a study on this topic, please let me know what you find.

ACKNOWLEDGEMENTS

I'd like to extend my thanks to Holger Beck, who advised this project and kept me on track to answer the investigation's central question, reminding me that now was not the time for geology queries. A huge thank you to Noé Morales, Don Vicente and Holger Beck once again for sharing their *conocimiento* of the reserve's pasture sites and for their patience for that never ending question: "Okay, and how long has this section been abandoned?" I couldn't have done it without you. Thank you to all the Santa Lucía staff: Graciela, Gloria, Denisse, Leyder, Luis, Fernando, Nely, and Edison for welcoming me into their community. An extra thanks to Noé again for letting me dig holes on his reserve. Thank you to Ana María Ortega, Diana Serrano and Xavier Silva for their endless support of my learning and for sharing your never-ending wealth of knowledge about Ecuador and the cloud forest. And of course a thank you to Anya Mitton-Fry, my colleague who I shared this month with, for her patience with my questions and antics and for showing me what it is to see a project through to the end.

APPENDIX



Appendix 1: USDA's Soil Texturing Flow Chart, used in this study for feel-in-hand texturing of samples. *Source: Forestry Suppliers, Inc.*

Appendix 2: Site Horizon Depths and Munsell Colors

Site Soil Horizon	Depth (cm)	Munsell Color	Site Soil Horizon	Depth (cm)	Munsell Color	Site Soil Horizon	Depth (cm)	Munsell Color
GAC_1			**SAC_2**			**BP**		
A	0-12	10YR 5/4 yellowish brown	O	0-7		O	0-7	
B1	12-44	10YR 7/6 yellow	A	7-31	10YR 4/3 brown	A	7-25	7.5YR 2/3 dark brown
B2	44-78	10YR 7/6 yellow	B1	31-68	10YR 7/6 yellow	AB	25-36	10YR 5/4 yellowish brown
C	78-100	10YR 5/6 yellow	B2	68-100	10YR 5/4 yellowish brown	B1	36-81	10YR 6/6 brownish yellow
GAC_2			**SAC_3**			B2	81-100	10YR 6/6 brownish yellow

Site Soil Horizon	Depth (cm)	Munsell Color	Site Soil Horizon	Depth (cm)	Munsell Color	Site Soil Horizon	Depth (cm)	Munsell Color
O	0-1		O	0-4		**GAB_5**		
A	1-28	7.5YR 4/2 brown	A	4-37	10YR 5/4 yellowish brown	O	0-4	
B1	28-48	10YR 7/6 yellow	B1	37-71	10YR 7/6 yellow	B1	4-70	7.5YR 4/3 brown
B2	48-100	10YR 6/6 brownish yellow	B2	71-100	2.5Y 4/4 olive brown	B2	70-100	7.5YR 5/4 brown
GAC_3			**SAB_4**			**GAB_23**		
O	0-2		O	0-1		O	0-3	
A	2-24	10YR 4/3 brown	A	1-10	10YR 5/4 yellowish brown	A	3-10	10YR 4/4 dark yellowish brown
B1	24-53	10YR 6/6 brownish yellow	AB	10-19	10YR 5/4 yellowish brown	AB	10-23	10YR 6/6 brownish yellow
B2	53-100	10YR 5/4 yellowish brown	B1	19-68	10YR 5/4 yellowish brown	B1	23-50	10YR 7/6 yellow
GAB_12			B2	68-100	10YR 6/4 light yellowish brown	B2	50-84	10YR 6/4 light yellowish brown
O	0-5		**GAB_20**			C	84-100	2.5YR 5/3 light olive brown
A	5-15	10YR 4/3 brown	O	0-3		**GAB_30**		
AB	15-36	7.5YR 5/4 brown	A	3-14	10YR 4/3 brown	O	0-5	
B1	36-58	10YR 6/4 light yellowish brown	AB	14-42	10YR 5/4 yellowish brown	A	5-17	10YR 4/3 brown
B2	58-89	10YR 6/6 brownish yellow	B1	42-79	10YR 5/4 yellowish brown	AB	17-28	10YR 5/3 brown
C	89-100	2.5Y 5/3 light olive brown	B2	79-100	10YR 5/4 yellowish brown	B1	28-63	10YR 7/6 yellow
						B2	63-100	10YR 5/4 yellowish brown

Appendix 3: Soil Texture Classifications

Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification
GAC_1		**SAC_2**		**BP**		**GAB30**	
A	loam	A	sandy clay	A	clay	A	loam
B1	loam	B1	silt loam	AB	sandy clay loam	AB	loam
B2	sandy loam	B2	sandy clay loam	B1	loam	B1	silt loam

Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification	Site Soil Horizon	Soil Texture Classification
C	sandy loam	**SAC_3**		B2	sandy loam	B2	sandy clay
GAC_2		A	sandy loam	**GAB_23**		**GAB_12**	
A	silt loam	B1	loam	A	loam	A	silt loam
B1	silty clay loam	B2	loam	AB	sandy clay loam	AB	loam
B2	silt loam	**SAB_4**		B1	silt loam	B1	silt loam
GAC_3		A	clay loam	B2	sandy clay loam	B2	silt loam
A	silt loam	AB	silt loam	C	sandy clay loam	C	sandy loam
B1	silt loam	B1	silt loam	**GAB_20**		**GAB_5**	
B2	loam	B2	sandy clay loam	A	loam	B1	silt loam
				AB	loam	B2	sandy clay loam
				B1	silt loam		
				B2	silt loam		

Appendix 4: Site Coordinates

Site Soil Horizon	Coordinates	Site Soil Horizon	Coordinates
GAC1	0°07'00"N 78°36'24"W	GAB5	0°06'56"N 78°36'02"W
GAC2	0°06'58"N 78°36'17"W	GAB12	0°07'05"N 78°36'31"W
GAC3	0°06'57"N 78°36'02"W	GAB20	0°07'04"N 78°35'54"W
SAC2	0°07'03"N 78°36'44"W	GAB23	0°06'58"N 78°36'51"W
SAC3	0°07'04"N 78°36'46"W	GAB30	0°07'02"N 78°36'36"W
SAB4	0°07'05"N 78°36'37"W		
GAB5	0°06'56"N 78°36'02"W		

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