Soil Nutrients and Traditional Agriculture on Young Volcanic Soils of Ta'ū, American Samoa

by

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Abstract

Soils and agriculture are inextricably linked, in the past as well as today. How and where people developed agriculture based on soil and landscape properties has not been well developed in the Pacific. Pacific Islands, which often represent nicely organized gradients of substrate age, rainfall, and soil type, represent excellent study systems to understand this interaction between people and soils. Agriculture in Polynesia has been mostly subsistence, in the past and, in many islands, still today. While some agricultural forms have received intensive study, others still lack information and knowledge, particularly those that experienced abandonment following European contact. This is the case of extensive rainfed agricultural systems in the Manu'a islands of American Samoa. To understand prehistoric agricultural systems, we sampled along transects that crossed through intensive agriculture infrastructure in the upland of Fiti'uta on Ta'ū island. Soils were analyzed for several soil fertility properties that have been proposed as indicators of Polynesian agricultural intensification in related systems seen in Hawaii and Rapa Nui. Surveys of remnant economic plants were conducted along the same transects. Data suggest that the previously identified soil fertility indicators aligned well with the agricultural infrastructure on Ta'ū except for exchangeable calcium, which was significantly more depleted than other intensified agriculture in the Pacific. The soil fertility results also correlated well with the vegetation agricultural survey, specifically with the younger Ta'ū soils.

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List of Abbreviations

Ca	Calcium
BS	Base Saturation
P	Phosphorus
OM	Organic Matter
CEC	Cation Exchange Capacity
ECEC	Effective Cation Exchange Capacity
Nb	Niobium
LiDAR	Light Detecting and Ranging
LOI	Loss on Ignition
BD	Bulk Density
Al	Aluminum
Mn	Manganese
Fe	Iron
S	Sulfur
K	Potassium
B	Boron
Na	Sodium
OC	Organic Carbon
NH_4-N	Ammonium-Nitrogen
Mg	Magnesium

1.0 Introduction

Soils and agriculture are inextricably linked, in the past as well as today. How and where people developed agriculture based on soil and landscape properties has been a topic of substantial interest. While much of the discussion has occurred in the field of anthropology, such investigations have new relevance from the perspectives of sustainable agriculture and agroecology. Pacific islands, which often represent nicely organized gradients of substrate age, rainfall, and soil type, represent excellent study systems to understand this interaction between people and soils (Kirch, 2007). Agriculture in Polynesia has been mostly subsistence, in the past and, in many islands, still today (Quintus and Cochrane, 2018b). While some locations have received intensive study like the Hawaiian Islands, others still lack information due to lack of records, minimal field studies, and rapid abandonment following European contact (Quintus and Cochrane, 2018a). This is the case of extensive rainfed agricultural systems in the Manu'a islands of the Samoan archipelago. To understand the distribution of prehistoric agricultural systems, we examine patterns of soil fertility and agricultural development on Ta'ū, an island in the Manu'a group of American Samoa.

Soil fertility is an important factor in the decision to develop and maintain cultivation systems (Vitousek et al., 2004, 2009), along with the local climate. The ability of the soil to sustain plant growth, in providing essential nutrients, sufficient water and other properties the plant needs, that will result in sustain and consistent high-quality yield is critical, even more so prior to the development of granular fertilizers (Stockdale et al., 2002; Vitousek et al., 2009). Soil properties determine the supply and retention of essential nutrients and water necessary for plant growth, which are primarily influenced by climate, parent material and other forming factors. Currently, there is lack of information on soil fertility for the Samoan islands, due to the lack of investigation

(Naidu et al., 1997). Samoa soils are formed from volcanic basalt (Asghar et al., 1986). Potassium (K), calcium (Ca) and phosphorus (P) are often the limiting nutrients due to leaching and low initial concentration in the parent material, and aluminum and manganese toxicity are common problems (Chand, 2002; Guinto et al., 2015).

Agriculture in the Pacific is often accompanied by physical infrastructure, such as terracing, rock walls, lithic mulch, embankments, and mounds. Such infrastructure can now be remotely sensed using Light Detecting and Ranging (LiDAR) analysis, which uses laser pulses to measure variable distances to the earth (NOAA). LiDAR is effective even in some heavily vegetated areas, which makes it suitable for the dense areas of Ta'ū. LiDAR analysis provided datasets of archaeological remains of man-made terraces and stone walls, that were distinctive here relative to other islands of Manu'a (Quintus et al., 2017).

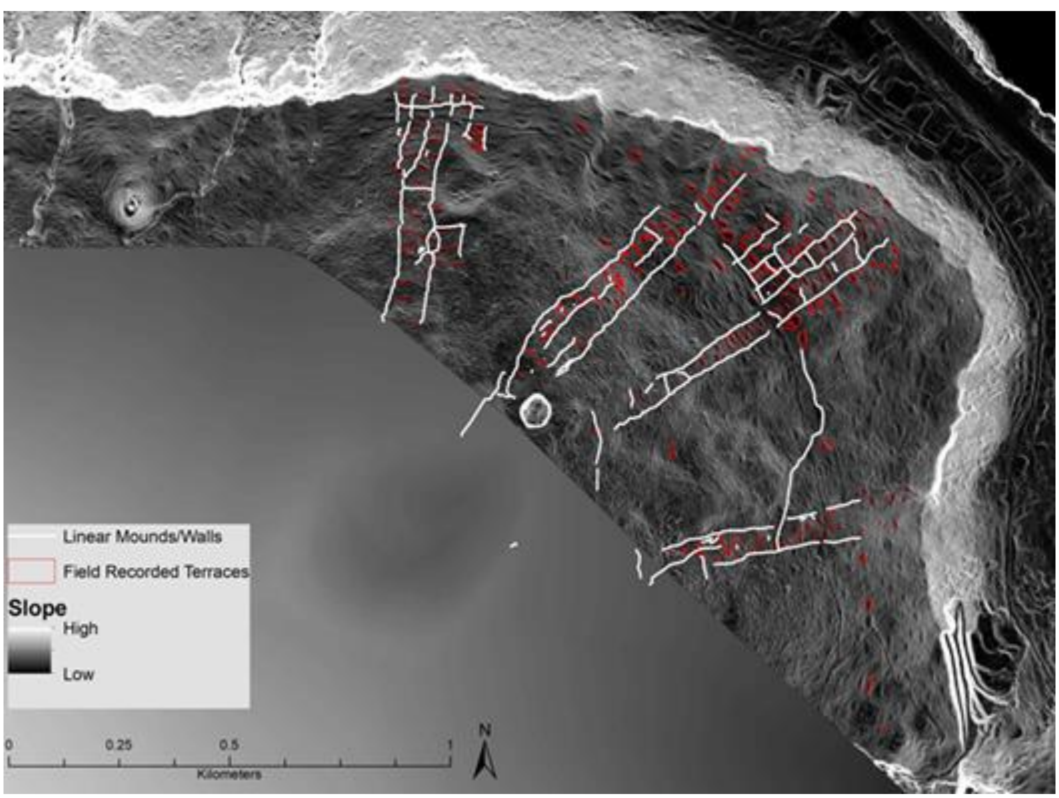

Figure 1: LiDAR image of the project area with mapped stone walls (white) and terraces (red) (from Quintus et al. (2017).

These archaeological features are thought to have been constructed for various reasons, such as for the foundation of houses or agriculture gardens, to mark boundaries of agricultural plots or land ownership, and serve to reduce erosion or act as surfaces for cultivation (Quintus, 2018).

<u>Research questions</u>

Traditional agricultural practices in the past were adapted to past soil conditions and influenced present soil conditions. The goal of this study is to understand prehistoric agricultural systems, by exploring the relationship between soil fertility and the development of agriculture on Ta'ū. Our design explores (1) if soil fertility indicators developed for other rainfed Polynesian agricultural systems hold in the very wet environment of Ta'ū island, and (2) does the agriculture or the economic vegetation adapt to patterns of soil fertility on Ta'ū island.

The objectives of this study are to:

- Evaluate the suite of soil fertility indicators as defined by Vitousek et al., (2014) for Ta'ū soils. These soil fertility indicators will indicate areas of agricultural intensification.
- Investigate the agricultural distribution of Ta'ū by mapping and quantifying the extent and intensity of remnant economic vegetation. It is suggested that the economic vegetation will be increasingly dense at lower rainfall (lower elevation, more westward) due to patterning of soil fertility.

2.0 Background

The Samoa archipelago is believed to have been settled ~2,800 years ago (Clark et al., 2006; Petchey, 2001; Petchey and Kirch, 2019) and, along with Tonga, is considered the birthplace of the Polynesian culture (Burley et al., 2010). The islands were first reached by European contact in the 18th century (Petchey, 2001). Samoa is covered with lush vegetation because of its high rainfall, tropical temperatures, and soil fertility (Nakamura, 1984). The Samoa archipelago includes the Independent State of Samoa, which consists of four main islands; Savai'i, Upolu, Manono and Apolima; and the unincorporated territory of the United States, American Samoa which consists of five main islands; Tutuila, Aunu'u and the three islands of the Manu'a group, Ofu, Olosega and Ta'ū.

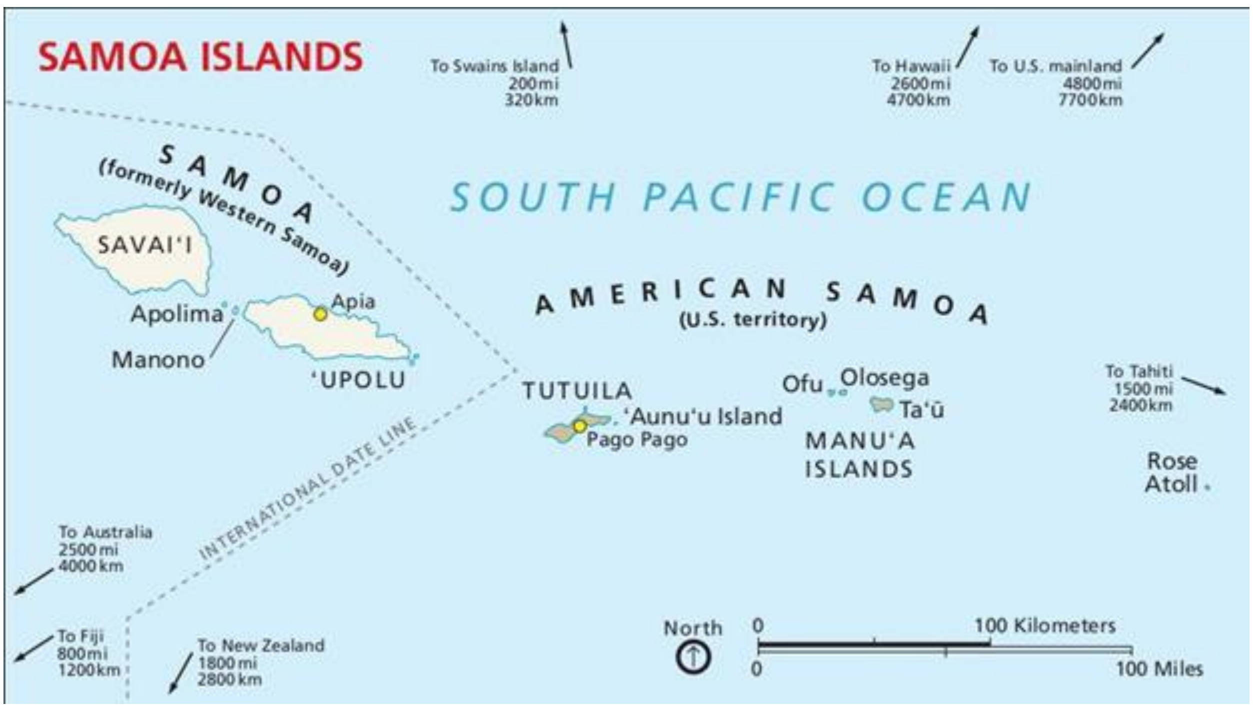

Figure 2: Regional map of the Independent State of Samoa and the United States territory of American Samoa. Map adopted from the National Park Maps (American Samoa Maps).

The islands are a result of volcanic activity resulting from a tectonically driven hotspot (Stice and McCoy, 1968), that moves from east to west, causing the formation of the islands in a generally linear chain, in the same direction of the plate movement. The ages of the islands generally decrease as one moves eastward (McDougall, 2010), making Ta'ū both the eastern most and youngest island of American Samoa and the entire Samoa archipelago. Ta'ū is the second largest island of American Samoa and the largest island of the Manu'a group. The island includes the highest point of American Samoa – Lata Mountain – with an elevation of 966 m (Craig, 2009; Nakamura, 1984). Exact substrate soil ages of the island are unknown, but it was suggested formed slightly less than 100,000 years ago which includes the Lata lava flows, however, while the eroded remnant of a volcanic caldera, the Luatele crater, was suggested formed less than 20,000 years ago (McDougall, 1985; 2010). The island is extremely wet, with rainfall ranging from ~3,175 mm/y near the coast up to ~6,350 mm/y at the summit (Craig, 2009). The island is heavily vegetated, mostly covered with tropical rainforest due to high precipitation. Ta'ū consists of three villages: Ta'ū, Faleāsao and Fiti'uta. The southern half of Ta'ū is maintained by the National Park of American Samoa, including the ancient village of Saua, considered to be the birthplace of Polynesia (National Park Service, 2011). The main agricultural crops are taro, banana, breadfruit, and coconut (Quintus and Cochrane, 2018a). Other common crops are giant taro, yam, lime, papaya, pineapple, and cassava

3.0 Literature Review

Irrigated wetland systems (flooded, terraced) and rain-fed dryland systems ("fixed field" agriculture) are two common agricultural systems throughout Polynesia that represent different classes of agricultural intensification systems: pond-field irrigation systems in the wetlands and cropping cycle systems in the drylands. Previous work has identified essential landscape properties necessary for the intensification of each of these two systems, described how the opportunities for each evolve across geological time, and discussed the socio-political ramifications of reliance on one system or the other (Ladefoged et al., 2009; Kirch and Zimmerman, 2011).

While the opportunities for flooded pond-field agriculture primarily relate to topography and the availability of flowing water, the potential for rain-fed agriculture represent gradients of production and resilience that are primarily driven by rainfall and underlying soil fertility. Such intensive rain-fed agricultural systems have been heavily investigated in the Hawaiian Islands and, to a lesser extent, in Rapa Nui (Easter Island) and Aotearoa (New Zealand). While the agriculture of Ta'ū appears similar to other intensive rain-fed systems, the amount of rainfall received is considerably higher compared to previously studied systems. For instance, in the well-studied Leeward Kohala Field System traditional cultivation occurs in rainfalls ranging from ~750-2200 mm/yr, while the driest locations on Ta'ū receive over 3,500 mm/yr. Therefore, we seek to understand soil properties in Ta'ū from a perspective of thresholds and domains (Vitousek and Chadwick, 2013), and test if the indicators of Polynesian agricultural intensification developed from work in Hawaii and Rapa Nui are applicable to the much wetter system of Ta'ū.

3.1 Thresholds and Domains

<u>Rainfall thresholds</u>

Water is one of the most important environmental controls for soil processes. Insufficient water slows soil weathering processes and makes it difficult for plants to uptake nutrients, while excess water leads to high weathering intensity and loss of nutrients via leaching. The changes in soil properties in response to rainfall are non-linear and marked by thresholds (Chadwick et al., 2003). The rainfall intensity at which these soil thresholds occur vary with the substrate age.

The Hawi climosequence of Kohala, Hawai'i Island, is about 150,000 years old and spans a rainfall gradient of ~160 to 3,500 mm/y. At relatively low rainfall (<1,300 mm/y), base saturation and soil pH were high (>80% and >6.5, respectively), attributed to the presence of carbonates which is often the case for less weathered soils or high rich carbon soils (Chadwick et al., 2003). Between a rainfall of ~1,300 and 2,000 mm/y, base saturation and pH decline rapidly with increasing rainfall. At rainfall above 2,000 mm/y, base saturation and soil pH reached a minimum (~10% and 4.5, respectively) and stabilized as rainfall increased to >3,500 mm/y. Similarly, effective cation exchange capacity (ECEC) was generally low (<40 cmol$_c$/kg) at rainfalls <500 mm/y, presumably due to minimal weathering activity and secondary clay minerals. As rainfall increased (>500 mm/y), ECEC increased (20-50 cmol$_c$/kg) until ~1,300 mm/y, at which point ECEC decreased dramatically (<5 cmol$_c$/kg) until reaching a minimum at ~2,000 mm/y. For this 150ky flow series, drastic changes in the relationship between soil properties and rainfall occur at ~1,300 mm/y (change in magnitude of relationship) and ~2,000 mm/y (soil properties bottom out and remain constant).

Soil processes domains

According to Vitousek & Chadwick (2013), soil processes domains are referred to as regions between thresholds that have a relatively constant relationship to environmental forcing. Major changes to soil processes within each domain are buffered by chemical reactions; when this buffering is exhausted the soil exhibits a non-linear shift, as outlined above, and enters a new, relatively stable, domain. Using different substrate ages (Hawi substrate on Hawaii island, 150 ky and an older substrate on Kauai island, 4,100 ky), Vitousek & Chadwick (2013) demonstrate that soil process domains shift in terms of rainfall gradients as shown in Figure 3. This suggests that the location of soil thresholds vary in time as well as space, with progressively older soils attaining more chemically weathered domains at progressively lower rainfalls (Bateman et al., 2019). However, on very young substrates the temporal patterns break down, with flows <20ky demonstrating an inverted trend of thresholds occurring at progressively higher rainfalls with increasing age (Lincoln et al., 2014). This is hypothesized to be due to the developing surface area in young, coarse soils (Lincoln et al., 2014), with an inflection point in the temporal patterns occurring at ~20ky (Bateman et al., 2019). However, additional sampling and analyses would be needed to strengthen these perspectives.

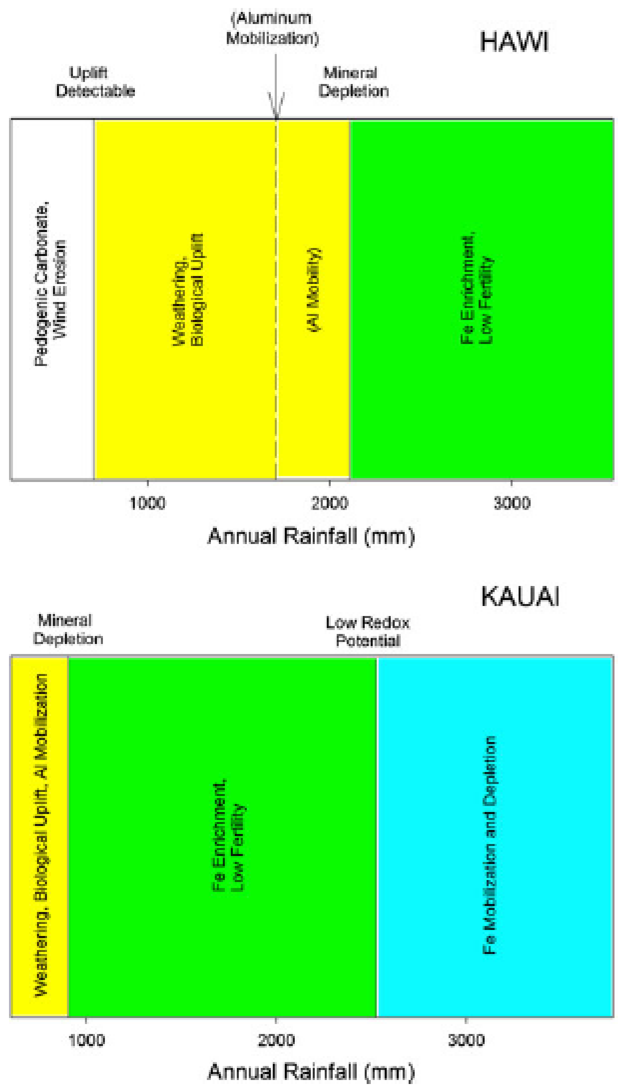

Figure 3: Hawi (young) and Kauai (old) substrates showing the distribution of rainfall thresholds and soil process domains (Vitousek and Chadwick, 2013).

Compared to the well-studied Hawi soils, the study area on Ta’ū is a much younger substrate (<20ky vs. 150ky), but also much, much wetter (~3,500-7,000 mm/y vs. 160-3,500 mm/y). While the age of the Ta’ū soils should increase their resistance to rainfall-driven thresholds, the extreme wetness of the Ta’ū soils could easily overcome the chemical buffering of the soils. Studies from volcanic soils in Hawai’i can help us form expectations for Ta’ū, however soils this young and this wet have not been well documented. This study can help understand different domains that occur at different rainfall thresholds.

3.2 Soil fertility properties

The ability of the soil to function well to support and sustain agricultural plant growth is highly influenced by soil fertility properties. It was noticed that the domain defined by active weathering and biological uplift by Vitousek & Chadwick (2013), aligned almost perfectly with the indigenous Hawaiian agricultural intensification in Kohala. Further study suggested that the ocean-side (drier) limitations to agriculture were defined by inadequate rainfall for crop development, but that the mountainside (wetter) limitations to agriculture followed the boundary of the soil process domain identified (Vitousek et al., 2004), above which numerous soil properties bottomed out (Chadwick et al., 2003). This suggested that Polynesian farmers only intensively cultivated areas that had fertile soil. Soil properties were evaluated in Hawai'i as "indicators" of sufficient soil behavior for intensified Polynesian agriculture (Vitousek et al., 2014). The resulting soil fertility indicators demonstrated a high capacity to predict where Polynesians intensified agriculture, with exchangeable calcium (Ca) being the most reliable indicator (Table 1). The table shows that below a threshold of these soil fertility indicators, agricultural intensification was found to cease, presumably due to declining returns in yield. Values that fall on or above these soil fertility thresholds, indicated fertile soils and resulted in agriculture intensification. These indicators were further validated in Rapa Nui, with rainfed agricultural systems that are similar to Hawaii (Ladefoged et al., 2013). Rapa Nui rock gardens were also found to align well with the soil fertility thresholds except for exchangeable Ca, which values were below 10 cmolc/kg. It is uncertain whether these fertility indicators will also hold for Ta'ū because Ta'ū exceeds the rainfall gradients of both rainfed systems.

Table 1: Soil properties identified as "indicators" of sufficient soil quality for intensified Polynesian rainfed agriculture (from Vitousek et al., 2014)

Soil Property	**All seven Transects**		**Five 'Best' Transects**	
	Value at Boundary	Coefficient of Variation (%)	Value at Boundary	Coefficient of Variation (%)
Exchangeable Ca ($cmol_c$/kg)	10.20	20	10.20	13
Base Saturation (%)	28.30	28	29.50	30
Soil pH	5.69	31	5.68	15
P Remaining (%)	99.00	40	102.00	42
Resin Extractable P (mg/kg)	57.00	46	50.00	39

3.3 Agricultural development

<u>Modeled systems</u>

According to Meyer et al., (2007), large rainfed systems in Hawaii occur in areas that represent "sweet spots" of rainfall and soil fertility. These "sweet spots" are characterized by areas with adequate supply of soil nutrients and water. The effects of leaching from continuous rainfall over time, would reduce these "sweet spots" and eventually disappear. Mapping, modeling, and quantifying agricultural systems through GIS can help understand the relationship between people and land by identifying where agriculture was developed in the past (Ladefoged et al., 2009). In Hawai'i, where extensive study has occurred, the potential to build and test models is high. Building upon the concept that traditional Hawaiian rain-fed agriculture was primarily confined by (1) climate and weather (mainly rainfall, but also temperature) and (2) soils, a predictive model of where Hawaiian agricultural intensification would have taken place was developed (Ladefoged et al., 2009). Remote and field mapping of archaeological features, validation demonstrated that a high percentage of the mapped rainfed systems (90% in Kohala, 99% in Kalaupapa) aligned with the modeled extents. Such modeling of agricultural systems can be used elsewhere in Polynesia where rainfed agriculture is common.

It is important to note that agricultural developments in specific regions represent development over time and space. Temporal patterns of development is another way of understanding the interaction between ecosystems and human behavior, as is the "form" of the agricultural system. Intensive cultivation of sweet potato and taro was common in the past for dryland rainfed systems of the Hawaiian Islands, however, there were other systems, such as swidden/shifting cultivation, agroforestry, and arboriculture (Lincoln & Vitousek 2017). Such systems filled different niches in the ecological landscape, often encompassing areas that were too infertile or otherwise unsuitable for intensive tuber production. Breadfruit (*Artocarpus altilis*) had long been an important staple food in the Pacific region (Ragone, 2001), and extensive plantations of breadfruit ('ulu) agroforestry were shown to occupy a biogeochemical niche in the Kona region (Lincoln & Ladefoged, 2014). Candlenut trees (*Aleurites moluccana*) or commonly known as kukui, have been shown to support unique agricultural systems with extensive mulching practices that occupied soils in Hamakua that were not fertile enough for intensive tuber cropping (Lincoln, 2020, Lincoln et al., 2020). The documentation and exploration of these systems demonstrate that the soil indicators of "Polynesian rainfed cultivation" (Vitousek et al., 2014) are specifically representing areas of intensive tuber production, and in areas where soils are too "infertile" as defined by the soils indicators can still be cropped using alternative cropping systems.

Mobile and immobile elements

"Mobile" and "immobile" elements are used to refer to the relative mobility of individual elements in soil. They can be used to help understand changes in agricultural systems over time (Ladefoged et al., 2018). Highly immobile elements, such as Niobium (Nb), Zirconium (Zr), and Titanium (Ti), can be used as a reference to understand the relative loss or gain of an element compared to the parent material. Assuming that all the highly immobile element from the rock is retained in the soil substrate, it can be used as a reference measure to compare other elements against. Such approaches can be used to examine the rates of element loss over time, or relative flows of nutrients within a system. For instance, calculating phosphorus (P) remaining in the soil of the Leeward Kohala Field Systems of Hawaii Island demonstrates that cultivated areas have more than 100% of the phosphorus that was present in the rock, suggesting that phosphorus is highly retained within the soils, is effectively cycled from deeper in the soil profile, or has external inputs that allows for the accumulation of P. However, human activities also play a part in reducing these sweet spots. Phosphorus (P), for instance, can be used to understand the influence of human activity, such as continuous planting and crop harvesting that would lead to a decrease in P availability, in the soil (Ladefoged et al., 2018; Meyer et al., 2007; Vitousek et al., 2004). Indeed, prior work has demonstrated measurable depletion of phosphorus over time, calling into question the sustainability of these systems (Meyer et al., 2007). Immobile elements can also be used to "align" soil depth profiles where surface alterations have occurred. It was found that traces of Nb can be used to alter alignment of soil surfaces and interpret the location of ancient ground surfaces (Ladefoged et al., 2018). This can allow for the direct comparison of soils in cultivated and uncultivated landscapes.

4.0 Materials and Methods

4.1 Site Description

Ta'ū has the largest area of the Manu'a group of about 45.5 km^2 (Nakamura, 1984; Craig, 2009). It is located about 10 km^2 southeast of the smaller Manu'a islands of Ofu (7.3 km^2) and Olosega (5.4 km^2) (Craig, 2009). The selected area of study is situated above the village of Fiti'uta, downslope and northeast of the Luatele crater, on Ta'ū island of the Manu'a group (Fig. 4).

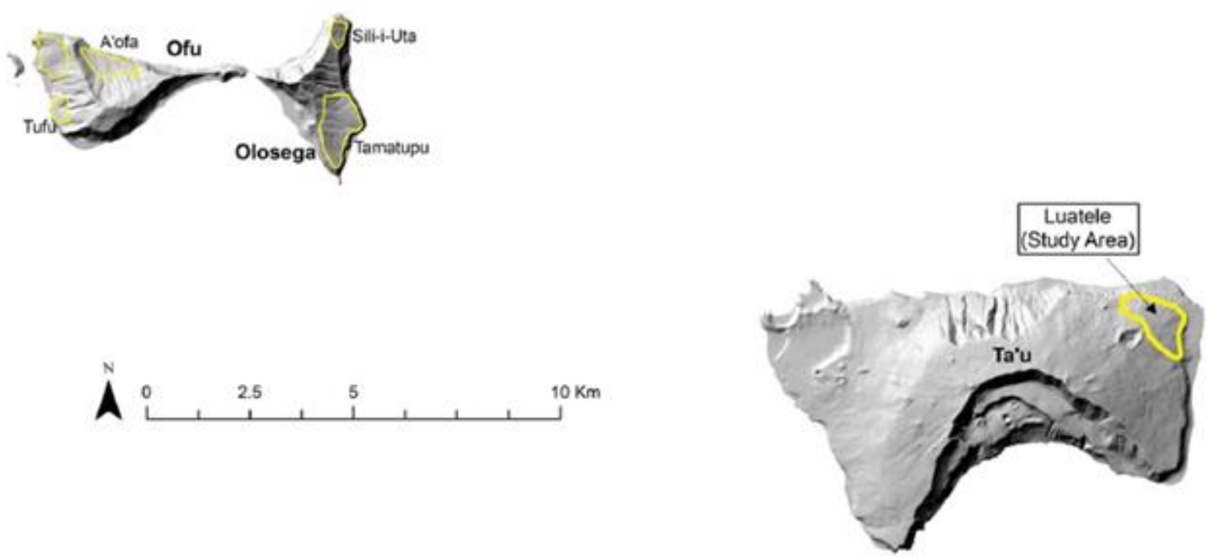

Figure 4: Manu'a Islands with selected project study area (adapted from Quintus et al. 2017.

The site can be reached by following the trail to Lata Mountain, the highest point on the island. The southern part of the island was presumably collapsed, revealing spectacular cliffs that are all but inaccessible. The area is mostly covered with young lava flows stemming from the Luatele crater (Fig. 5) that were suggested formed less than 20,000 years ago, and the periphery of the study area situated on older lava flows that originate from the Lata summit area, suggested formed slightly less than 100,000 years ago (McDougall, 1985; 2010).

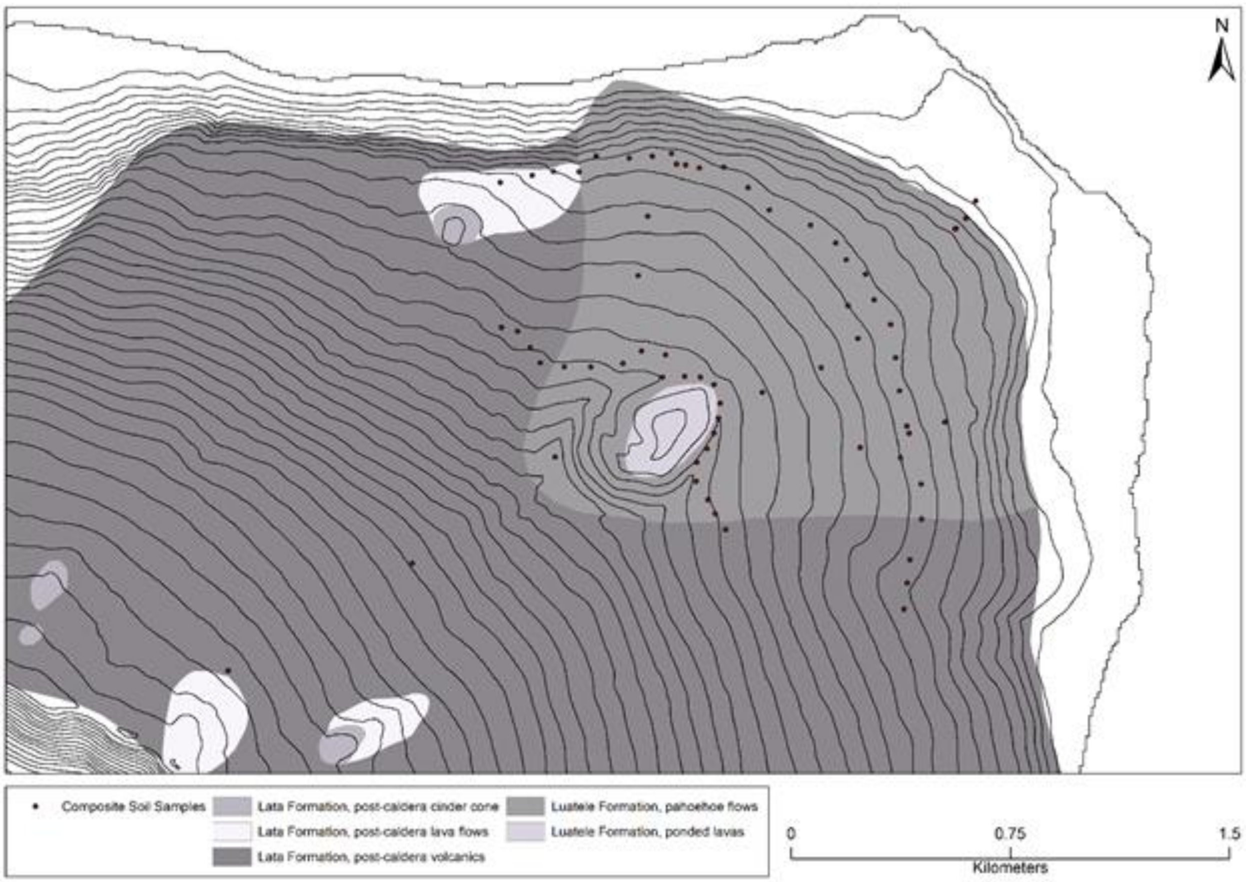

Figure 5: Map indicating the Luatele flow, <20,000 years old (light grey) and the Lata flow, <100,000 years old (dark grey).

The island has a rainfall gradient that varies from ~3,175 mm/y near the coast up to ~6,350 mm/y at the summit (Craig, 2009). The soil series is classified as Olotania family and taxonomic class described as medial, amorphic, isohyperthermic Hydric Hapludands (USDA, 1981). These soils are well drained on mountainsides and considered to be formed from volcanic ash and cinders.

4.2 Soil Sampling

Soil samples were collected along transects, primarily below the Luatele crater (Fig. 6). Three main transects were conducted. One transect ran vertically (north-south) near the coast to the summit of Lata mountain with composite samples collected in triplicate to a depth of 0-30 cm at every 50 m of elevation, starting at 50 m above sea level (n = 20). Two transects ran horizontally (east-west), one located just below the Luatele crater at ~380 m above sea level (n = 22) and another located near the coastal edge of the agricultural system at ~225 m above sea level (n = 28). Composite soil samples were collected in triplicate at 0-30 cm depth. The horizontal transects ran past the first major riverbed on either side of the Luatele lava flow, which in all cases we presumed extended the transects onto the Lata soil substrates.

Figure 6: Soil sampling transects.

Sporadic sampling for bulk density was conducted using bulk density cores at 10-15 cm depth. Soil samples were also collected from excavation units at different soil layers or profiles. Samples were transferred into zip lock bags, air dried for 1-2 days depending on how wet the soil samples were, and then shipped to Sherman Lab at UH Manoa, Honolulu for soil physical and chemical analysis.

4.3 Botanical Survey

Three vegetation surveys were conducted. One followed the soil sampling transects, with the presence and abundance of all economic crops collected in a 5 m radius around each soil sample location. A second survey followed pedestrian archaeological surveys, with the presence of economic crops recorded for each of the archaeological terraces mapped during four vertical (north-south) transects. A third survey intensely surveyed the exact location of all economic plants within an intensive sampling area that surrounded the core excavation units conducted by the archaeology team. Dense vegetation covered the project area, comprising secondary forest (Quintus et al., 2017). Most of the project area is covered by secondary forest, including *Hibiscus tiliaceus* (fau), *Rhus* species and common agricultural crops such as *Artocarpus altilis* (breadfruit), *Cocos nucifera* (coconut), *Cordyline fruticosa* (Ti) and *Morinda Citrifolia* (noni) (Liu et al., 2011).

4.4 Soil Physical and Chemical Analyses

Soil samples were air-dried and sieved using a 2 mm soil sieve before soil physical and chemical analysis. Some analyses were conducted in the Sherman Laboratory and others were sent to the UH Analytical Laboratory in Hilo. The analyses were as follows:

<u>Exchangeable Base Cations</u>

Exchangeable cations were measured using 1 g of soil rinsed with 50 ml of ammonium acetate (NH_4OAc) buffered at pH 7. NH_4OAc was rinsed out using 100 ml of 80% ethanol. The soil was rinsed with 20 ml of 1 *M* KCl and brought to a final volume of 20 ml. This gives an estimate of the soil's capacity to retain non-acid cations under field conditions (Soil Survey Laboratory Staff, 1992).

Cation Exchange Capacity (CEC)

CEC is the total capacity of the soil to hold exchangeable cations. 1g of soil was rinsed with 50ml of 1 *M* ammonium acetate (NH_4OAC) buffered at pH 7. Ammonium was rinsed out using 100 ml of 80% ethanol. Soil was then rinsed with 20ml of 1 *M* KCl, which was brought to a final volume of 20ml. CEC was calculated as (NH4-N (mg/L) extract-blank) / (sample weight*14).

Base saturation

Base saturation (%) is defined as the percentage of cation exchange sites occupied by Ca^{2+}, Mg^{2+}, K^+ and Na^+. It is influenced by the concentrations of these cations and by soil acidity which represents an integrated measure of the availability of nutritional cations (Vitousek et al., 2004). Base saturation was calculated as the sum of (Ca/CEC*100) + (K/CEC*100) + (Mg/CEC*100) + (Na/CEC*100).

Soil pH

Soil pH is the foundation of essentially all soil chemistry and nutrient reaction, which is a measure of soil acidity or alkalinity. Soil pH was calculated using the standard soil to water ratio of 1:2. 5 g of soil was immersed in 10 ml of water and shook for 30 mins on the shaker. The sample was left for a few minutes for the soil particles to settle before measuring the pH with a pH electrode (WD-35805-05, Thermo Fisher Scientific, Waltham Massachusetts) (Soil Survey Laboratory Staff, 1992).

Total Elemental Analysis

Total Elemental (Al, Mn, S, B, Nb, Na, Mg, Fe, K, P and Ca) Analysis followed the acid digest outlined in method EPA 3050b and analyzed on an inductively coupled plasma mass spectrometry (MS-ICP) (Arsenic et al., 1996).

Resin Extractable Phosphorus (Resin P)

Resin P (mg/kg) is a measure of phosphate (PO_4^{-3}) as an index of labile P (Robertson et al., 1999). This was a simplified procedure in using ion exchange resin membranes or bags to react with the ions in the soil. The resins are assumed to simulate the ion uptake action of plant roots, and like active pools, provide a strong sink of P released into solution. 5 g of soil and a resin bag was mixed with 50 ml of water for 16 hours. The resin bag was transferred and mixed with 40 ml of 0.5M HCl for 1 hour. The acid and resin bag were then brought to a final volume of 50 ml. The samples were then analyzed using an ICP.

Soil Moisture

Soil moisture (%) was determined by using the gravimetric soil moisture method. 25 g of soil was measured and oven-dried at 105°C. Soil moisture was calculated from the weight difference of the soil before and after oven drying (Johnson, 1962).

Soil moisture (%): (moist soil – oven dried soil) / (oven dried soil *100)

A standardized soil moisture was measured to understand how much water the soil can hold, by saturating 5 g of soil in water, then draining under 70 psi suction until visible water loss ceased. Soil moisture was then measured.

Organic Matter

Loss on Ignition (LOI) method was used to calculate the organic matter (Robertson, 2011). While not a preferred method of measuring organic matter, due to inaccuracy and uncertainty in correct temperature use, as temperature below 300°C risks not burning off all OM, above 400°C risks burning some of the inorganic materials. We used this method because it was simple and available to us at no cost, and this was not a priority of this study, yet we wanted to explore. 5 g of oven dried soil was weighed into crucibles and placed in the muffle furnace for 16 hours at temperature of 375°C. Final calculation:

OM% = (pre-ignition weight – post-ignition weight) / (pre-ignition weight x 100)

Organic carbon (OC%) was calculated by multiplying the LOI-OM% by 0.58%, which is based on the assumption that organic matter contains 58% organic C (Kellogg Soil Survey Laboratory Methods Manual, 2014).

Bulk density

Bulk density (g/cm^3) is defined as the dry weight of soil per unit volume including both the solids and the pore spaces (USDA, 2008). Measuring bulk density is important in reflecting the soil's ability to function for structural support, water and solute movement and soil aeration. Bulk density formula:

Bulk Density (g/cm^3) = (oven dried soil mass) / (volume of cylinder)

4.5 Statistical analysis

Summary statistics, ANOVA, linear and non-linear regressions of soil properties and total elemental analysis were analyzed using the R statistical software. Segmented R package (Muggeo, 2008) was used to determine the breakpoints in soil properties and total elemental concentrations patterns against elevation. The economic survey was recorded and mapped through ArcGIS.

5.0 Results

The results of this study have been divided into two sections which consist of tables and graphs to help understand the biogeochemical and fertility of the study area. The first section includes summary statistics, ANOVA analysis, linear regression, and segmented analysis of soil fertility properties, including additional soil properties and total elemental concentrations. The soil properties and total elemental concentrations have been characterized along the vertical and horizontal transects of the Lata and Luatele lava flows, followed by their fertility breakpoints against elevation. The final section presents the percent occurrence table of identified economic plants along the vertical and horizontal transects, showing the relationship between the infrastructure and soil fertility.

1. *Soil Properties*

   i) Summary statistics of soil properties

Soil fertility properties and fertility thresholds identified by Vitousek et al., (2014), are presented in Table 2 along the upper and lower transects of the Lata and Luatele flows of Ta'ū rainfed system. The table shows the standard errors and mean values of identified soil properties, along with the soil fertility thresholds. Mean values for each flow and transect indicates whether soil properties fall below or above the fertility thresholds.

Table 2: Summary statistics of the five soil fertility indicators identified by Vitousek et al., 2014, analyzed along the lower and upper transects of each flow.

Soil property	Transect	Flow	Mean	Std Err	Fertility threshold (Vitousek et al., 2014)
Exchangeable Ca (cmol$_c$/kg)	Lower	Lata	9.23	0.37	10.2
		Luatele	7.48	0.47	
	Upper	Lata	4.54	1.39	
		Luatele	3.05	0.43	
Base saturation (%)	Lower	Lata	75.68	5.17	29.5
		Luatele	63.44	2.20	
	Upper	Lata	43.25	5.53	
		Luatele	33.07	3.42	
Soil pH	Lower	Lata	5.69	0.15	5.68
		Luatele	6.10	0.05	
	Upper	Lata	5.77	0.15	
		Luatele	5.28	0.10	
	Lower	Lata	7.18	0.96	102

P Remaining (%)		Luatele	181.06	20.42	
	Upper	Lata	10.35	2.76	
		Luatele	109.75	21.35	
Resin Extractable P (mg/kg)	Lower	Lata	39.44	4.45	50
		Luatele	56.44	5.78	
	Upper	Lata	31.98	1.78	
		Luatele	33.32	2.21	

*Mean values in blue are above the fertility threshold.

Additional soil analyses were analyzed along the lower and upper transects of the Lata and Luatele flow are presented in Table 3. Cation Exchange Capacity (CEC) and Effective Cation Exchange Capacity (ECEC) showed low mean values below 25%, and moisture holding capacity showing very high mean values at the upper transect. Organic matter displayed a high percentage as well along each flow. Niobium mean values were lower at the Luatele flow, while phosphorus and calcium concentrations were higher at the lower transect of Lata and Luatele.

Table 3: Summary statistics of other soil fertility properties analyzed along the lower and upper transects of each flow.

Soil property	Transect	Flow	Mean	Std Err
	Lower	Lata	17.27	1.14

Cation Exchange Capacity (cmol$_c$/kg)		Luatele	18.26	0.59
	Upper	Lata	19.93	1.89
		Luatele	15.65	0.46
Effective Cation Exchange Capacity	Lower	Lata	13.24	1.52
		Luatele	11.61	0.61
	Upper	Lata	8.81	1.86
		Luatele	5.31	0.62
Moisture Holding Capacity (% at 70 kPa)	Lower	Lata	71.89	2.35
		Luatele	78.36	2.33
	Upper	Lata	96.96	35.68
		Luatele	130.39	7.01
Organic Matter (LOI-OM %)	Lower	Lata	37.54	1.08
		Luatele	38.71	0.81
	Upper	Lata	39.72	4.19
		Luatele	45.58	0.61
Niobium (mg/kg)	Lower	Lata	16.84	2.15
		Luatele	0.81	0.06
	Upper	Lata	12.93	5.19

		Luatele	1.14	0.14
Phosphorus (mg/kg)	Lower	Lata	731.10	52.77
		Luatele	787.54	39.56
	Upper	Lata	603.01	69.64
		Luatele	555.78	24.46
Calcium (mg/kg)	Lower	Lata	3088.83	450.13
		Luatele	4198.01	261.75
	Upper	Lata	1792.43	373.54
		Luatele	2036.11	223.97

ii) Transect analysis comparing the flows by horizontal transects

Table 4 shows the comparison of soil fertility indicators on the lower and upper horizontal transects along each flow. The analysis identifies if there are significant differences in soil properties along each horizontal transect. Base saturation showed significant differences in the lower transect with soil pH. P remaining was statistically significant for both the lower and upper transect, while Resin Extractable P and exchangeable Ca indicated no significant relationships.

Table 4: ANOVA comparison of flows by horizontal transects of each soil fertility indicator identified by Vitousek et al., 2014.

Soil property	Transect	R squared	P value

Exchangeable Ca ($cmol_c$/kg)	Lower	0.0905	0.1127
	Upper	0.0792	0.1932
Base saturation (%)	Lower	0.1616	0.0306*
	Upper	0.0726	0.2137
Soil pH	Lower	0.2816	0.0037*
	Upper	0.1420	0.0838
P remaining (%)	Lower	0.3520	0.0007*
	Upper	0.1732	0.0483*
Resin Extractable P (mg/kg)	Lower	0.0557	0.2095
	Upper	0.0032	0.7941

*Statistically significant at $p<0.05$

Comparison of other soil analyses between the lower and upper transect of each flow are presented in table 5. The table showing R squared and P values to determine significant relationships. CEC, ECEC and organic matter only showed significant differences in the upper horizontal transect. Moisture holding capacity did not show any significant relationship with the lower or upper horizontal transects. P values indicated significant differences only between niobium with the lower and upper transect.

Table 5: ANOVA comparison of flows by horizontal transects of other soil fertility properties.

Soil property	Transect	R squared	P value
Cation Exchange Capacity ($cmol_c$/kg)	Lower	0.0183	0.4843
	Upper	0.3460	0.0032*
Effective Cation Exchange Capacity	Lower	0.0416	0.2884
	Upper	0.1907	0.0372*
Moisture Holding Capacity (% at 70kPa)	Lower	0.0568	0.2221
	Upper	0.1060	0.1393
Organic matter (LOI-OM %)	Lower	0.0157	0.5248
	Upper	0.2780	0.0117*
Niobium (mg/kg)	Lower	0.9181	<.0001*
	Upper	0.5819	<.0001*
Phosphorus (mg/kg)	Lower	0.0141	0.5390
	Upper	0.0273	0.4513
Calcium (mg/kg)	Lower	0.1084	0.0812
	Upper	0.0103	0.6448

*Statistically significant at $p<0.05$

iii) <u>Transect analysis distinguishing the flows – Lata vs. Luatele</u>

Table 6 shows the comparison of the identified soil properties with the Lata and Luatele flows. The analysis identifies significant differences of soil properties between the Lata and Luatele flows by comparing each flow along the upper and lower horizontal transects. Analysis of variance analysis showed significant differences between Lata and Luatele flows with soil properties, exchangeable Ca and base saturation. The analysis also showed significant relationships between soil pH, P remaining and resin extractable P with the younger Luatele flow.

Table 6: ANOVA comparison of horizontal transects by flow for soil fertility indicators identified by Vtiousek et al., 2014.

Soil property	Flow	R squared	P value
Exchangeable Ca ($cmol_c$/kg)	Lata	0.6527	0.0084*
	Luatele	0.5277	<.0001*
Base saturation (%)	Lata	0.7215	0.0038*
	Luatele	0.5941	<.0001*
Soil pH	Lata	0.0246	0.7106
	Luatele	0.5819	<.0001*
P remaining (%)	Lata	0.1684	0.2727
	Luatele	0.1225	0.0214*
Resin Extractable P (mg/kg)	Lata	0.2216	0.2009
	Luatele	0.2133	0.0014*

*Statistically significant at $p<0.05$

Comparing the lava flows along the upper and lower horizontal transects with other soil properties through ANOVA analysis are displayed in table 7. Each soil property showed significant differences with the Luatele flow. Lata flow showed no significant differences with the soil properties.

Table 7: ANOVA comparison of horizontal transects by flow for other soil fertility properties.

Soil property	Flow	R squared	P value
Cation Exchange Capacity ($cmol_c$/kg)	Lata	0.1864	0.2459
	Luatele	0.2161	0.0017*
Effective cation exchange capacity	Lata	0.3316	0.1046
	Luatele	0.5564	<.0001*
Moisture Holding Capacity (% at 70kPa)	Lata	0.1320	0.3763
	Luatele	0.5903	<.0001*
Organic matter (LOI-OM %)	Lata	0.0650	0.5423
	Luatele	0.5183	<.0001*
Niobium (mg/kg)	Lata	0.0755	0.4743
	Luatele	0.1191	0.0534*
Phosphorus (mg/kg)	Lata	0.2425	0.1781
	Luatele	0.3478	<.0001*

Calcium (mg/kg)	Lata	0.3947	0.0700
	Luatele	0.4741	<.0001*

*Statistically significant at p<0.05

iv) <u>Linear regressions against elevation</u>

Linear regression analysis of soil fertility indicators against elevation are shown in table 8. The analysis determined significant differences for all the soil fertility indicators against elevation except for P remaining and Resin Extractable P in the older Lata flow.

Table 8: Linear regression against elevation by flow for soil fertility indicators identified by Vitousek et al., 2014.

Soil property	Flow	R squared	P value
Exchangeable Ca ($cmol_c$/kg)	Lata	0.5873	0.0266*
	Luatele	0.5320	4.272e-08***
Base saturation (%)	Lata	0.8090	0.002*
	Luatele	0.6078	1.174e-09***
Soil pH	Lata	0.0072	0.8416
	Luatele	0.5864	3.462e-09***
P remaining (%)	Lata	0.0207	0.7338
	Luatele	0.1288	0.0196*

Resin Extractable P (mg/kg)	Lata	0.2882	0.1701
	Luatele	0.2065	0.0025**

*Statistically significant at p<0.05

Table 9 shows the linear regressions between other soil properties against elevation along the Lata and Luatele flow. The linear regression showed no significant differences of niobium against elevation on both flows. However, significant differences were observed for Calcium on both flows, as well as CEC, ECEC, WHC, LOI-OM and P on the lower Luatele flow only.

Table 9: Linear regression against elevation by flow for other soil fertility properties.

Soil property	Flow	R squared	P value
Cation Exchange Capacity ($cmol_c$/kg)	Lata	0.0766	0.5068
	Luatele	0.2039	0.0027*
Effective cation exchange capacity	Lata	0.3761	0.1059
	Luatele	0.5632	1.051e-08***
Moisture Holding capacity (% at 70kPa)	Lata	0.1475	0.3476
	Luatele	0.5973	2.008e-09***
Organic matter (LOI-OM %)	Lata	0.0496	0.5959
	Luatele	0.5168	8.232e-08***
Niobium (mg/kg)	Lata	0.0123	0.7934

	Luatele	0.1079	0.0337
Phosphorus (mg/kg)	Lata	0.2449	0.2125
	Luatele	0.3909	9.579e-06***
Calcium (mg/kg)	Lata	0.5506	0.0350*
	Luatele	0.4886	2.62e-07***

*Statistically significant at p<0.05

v) Segmented regression analysis

Table 10 shows the segmented analysis of soil fertility properties against the Lata and Luatele flows by using elevation as a proxy for rainfall, as there was no reliable rainfall data for Ta'ū. The table displays the elevation breakpoints in which a change occurred for each soil fertility property. Elevation breakpoints along the Lata flow were more scattered compared to the Luatele flow. The Lata breakpoints occurred mostly around 300-400 m elevation, while some were between 500-600 m elevation. The Luatele breakpoints were closely clustered together around 200-300 m elevation. However, there was no breakpoint determined for Resin Extractable P for the younger Luatele flow, although there was a significant relationship.

Table 10: Segmented breakpoints of soil fertility properties along the Lata and Luatele flows.

Soil Property	Lata	Luatele
Exchangeable Ca (cmol/kg)	478.014***	248.633***
Base saturation (%)	406.097***	208.000***

Soil pH	612.813***	229.665***
P remaining (%)	357.000*	364.784
Resin Extractable P (mg/kg)	258.815***	No breakpoint***
Cation Exchange Capacity ($cmol_c$/kg)	326.495***	373.326***
Effective Cation Exchange Capacity ($cmol_c$/kg)	498.626***	248.360***
Moisture Holding Capacity (% at 70kPa)	673.593	325.000***
Organic matter (LOI-OM %)	587.986	325.241***
Niobium (Nb-mg/kg)	278.195*	327.417
Phosphorus (P-mg/kg)	237.248***	299.568***
Calcium (Ca-mg/kg)	420.274**	229.206***

*Statistically significant at p<0.05, **Statistically significant at p<0.01, ****Statistically significant at p<0.001

2. *Economic Vegetation*

Table 11 shows the percent occurrence of identified plant species that were recorded along the vertical and horizontal transects of the Ta’ū rainfed system. Plant species were a variety of tree crops and agricultural plants. Fau (*Hibiscus tiliaceus*) was the most dominant along the vertical and horizontal transects. Higher percent occurrence for most plants fell at the lower horizontal transect. Two crops, Ulu (*Artocarpus altilis*) and Niu (*Cocos nucifera*) were found almost exclusively at the lower horizontal transect. More contemporary fruit trees, like Mago (*Mangifera indica*) and Tipolo (*Citrus medica*) were primarily found along the vertical central transect.

Table 11: Percent occurrence of each plant from the botanical survey.

% Occurrence							
			Horizontal		Vertical		
No.	Species	Common name	Lower	Upper	East	Central	West
1	*Zingiber officinale*	Fiu	0	0	0	1.21	0
2	*Theobroma cacao*	Koko	0	0	0	0	1.59
3	*Inocarpus fagifer*	Ifi	0	0	1.52	0.61	0
4	*Pandanus tectorius*	Fala	0	0	0	0	1.59
5	*Hibiscus tiliaceus*	Fau	89.29	54.55	46.97	39.39	26.98
6	*Dysoxylum gaudichaudianum*	Ivory Mahogany	35.71	9.10	0	0	0
7	*Alyxia stellate*	Lau maile	10.71	9.10	0	0	0
8	*Macaranga harveyana*	Laupata	0	22.73	0	0	0
9	*Citrus aurantifolia*	Tipolo	0	4.55	0	0	0
10	*Mangifera indica L.*	Mago	0	0	0	0.61	0
11	*Dysoxylum moata* Rein.	Maota	0	4.55	0	0	0

12	*Ficus tinctoria* Forst.f.	Mati	64.29	45.45	0	0	1.59
13	*Cananga odorata* (Lam.)	Mosooi	0	4.55	0	0	0
14	*Cocos nucifera*	Niu	35.71	0	25.76	23.03	7.94
15	No point	-	10.71	40.91	22.73	39.39	60.32
16	*Morinda citrifolia* L.	Noni	39.29	18.18	0	3.64	1.59
17	*Schizostachyum glaucifolium* (Rupr.)	Ofe	0	0	0	0.61	1.59
18	-	Palapalai	0	0	0	0.61	0
19	*Securinega flexuosa*	Poumuli	0	0	0	1.21	0
20	*Adenanthera pavonine* L.	Lopā	3.57	9.09	0	0	0
21	*Tamarindus indica* L.	Tamaligi	39.29	9.09	0	0	0
22	*Cordyline terminalis* L.	Ti	78.57	54.55	36.36	44.85	28.58
23	*Alphitonia zizyphoides* (Spreng)	Toi	46.43	36.36	0	0	0
24	*Cyathea spp.*	Oli'olī	67.86	54.55	0	0	0
25	*Dioscora spp.*	Ufi	0	9.09	0	0	0
26	*Artocarpus altilis*	Ulu	71.43	4.55	36.36	27.27	14.29

27	*Caladenia marginata*	Oketi pa’epa’e	0	9.09	0	0	0

*No point: vegetation was not recorded.

6.0 Discussion

Soil fertility indicators

For the soil properties and fertility thresholds reported by Vitousek et al., (2014), we see that, in general, the farmed soils of Lata substrate fall above the critical values, while more often the generally unfarmed Lata substrate soils are below the critical level (Table 2). This suggests that the application of the soil fertility indicators perform reasonably well for the study area. However, exchangeable calcium, which was considered the most reliable indicators for Hawai’i and Rapa Nui, indicates that no areas would have been farmable within the study area.

For both Lata and Luatele flows, all base-saturation values fall above the fertility threshold. Surprisingly, the older flow of Lata has substantially higher values than the younger Luatele flow. Furthermore, the CEC values for Lata flows were also substantially higher when compared to Luatele flows, indicating that both the magnitude and the occupancy of cation exchange sites were elevated on the older flows. This result is similar to results from Kona, Hawai’i where values were lower on the younger flows than the older flows (Lincoln et al., 2014). It was suggested that exchange capacity was constrained by coarse minerals with low surface area. Minerals with low surface area reduces mineral and water reactions and could increase the transport of materials. It is also important to recognize that the “older” soil substrates stemming from the Lata flows are still fairly young. At less than 100ky, Lata volcanic are younger than the Kohala substrates and so may account for their relatively high exchange capacity despite the extremely high rainfall.

All soil pH values were slightly acidic ranging from pH 5 – pH 6, with soils being more alkaline in the lower transect. Percent P remaining and resin extractable P followed a similar pattern with values significantly higher at the Luatele flow. Possible explanations for these high P values could also be related to soil mineralogy. Ta’ū soils are very wet Andisols derived from volcanic ash and contain amorphous minerals/clay that have a high specific surface, high surface reactivity (affinity) to P, and high capacity to occlude P. For these reasons, amorphous minerals adsorb the largest quantities of P (Sanchez, 2019; Uehara & Gillman, 1985). The decrease in soil solution P with absorption by plant roots is buffered by both inorganic and organic P fractions in soils. Primarily and secondary P minerals dissolve to resupply $H_2PO_4^-$ and HPO_4^{-2} in solution. Inorganic P in soil solution P pool ($H_2PO_4^-$, HPO_4^{-2}) absorbed on mineral and clay surfaces can also desorb to buffer solution P. The amount of $H_2PO_4^-$ and HPO_4^{-2} present in solution depends on soil pH. Soil solution required by plants depends on crop species and level of production (Sanchez, 2019).

Measurements of exchangeable Ca were consistently low, with all transects, on average, falling below the critical level identified by Vitousek et al. (2014). In crop production, Ca concentrations in the soil were specifically low (2-5 $cmol_c$/kg) at the upper transect, while in moderate levels (5-10 $cmol_c$/kg) at the lower transect (Norton, 2013). Based on previous studies, Ca was often a limiting nutrient in Samoan soils due to leaching and low initial concentration in the parent material (Chand, 2002; Guinto et al., 2015). Taro has a high Ca demand, but despite being a core staple crop in the Samoan islands and around the Pacific, it was not observed or recorded within the project area. It is possible that the low available Ca constrained the productivity of the site and may not have been able to support intensified taro and tuber production. Although the area is certainly "intensified" rainfed agriculture as evidenced by the substantial stone infrastructure, some alternative or hybrid form of cropping system may have been applied in order to overcome the Ca limitations.

Other soil properties investigated indicated Ta'ū soils with high loss on ignition - organic matter content (LOI-OM %) between 37-46 % (Table 3). High organic carbon was calculated, ranging from 21-26 % with the younger Luatele flow having higher percent organic matter on both transects compared to the older Lata flow (Appendix, table 1). This is not surprising since the project area is highly vegetated with rainfall gradients much higher than the Hawaiian Islands. Cation exchange capacity ranged between 15-19 $cmol_c/kg$, with decreasing Effective Cation Exchange from the lower to the upper transect. The high organic matter would suggest a higher CEC (>25 $cmol_c/kg$) with marginal fertility and clay content to hold cations, however, the results suggest loss of cations through erosion and leaching from the high precipitation. Bulk density results (Appendix, table 6) were very low and fluctuated along the vertical and horizontal transects. The low bulk density values as expected for udic Andisols indicate higher clay and silt content of Ta'ū soils, the high organic matter and organic carbon supports this.

Summary statistics of total elemental concentrations (Table 3) clearly indicated Niobium (Nb) as the best indicator in identifying the flow boundaries between Luatele and Lata. The Luatele flow of both transects had very low values (0.81, 1.14) while the Lata flow showed higher values (16.84, 12.93). The higher Nb concentrations suggest much higher mass loss of more mobile elements on the Lata flow, concentrating the immobile Nb in the soils. However, it is important to note that there were very few samples collected from the Lata flow. Phosphorus and calcium values were quite high with both being higher in the lower transect and lower in the upper transect of both flows.

In comparison to the National Resource Conservation Survey (Appendix, table 7), conducted in 1981, the Olotania series data presented similarities and differences to the current data. Similarities include the slightly acidic soils with high clay and silt content, and higher organic carbon in the first 0-20 cm topsoil. Bulk density was much higher at 2.320 g/cm^3, which showed a much more compacted soil before. The differences occurred in the CEC and base results, which in the NRCS data were much higher. The change in bulk density and CEC changed overtime with extremely high rainfall and much more weathered soils.

Fertility patterns within the study site

The linear regressions with soil fertility properties against elevation showed statistically significant relationships with most of the soil fertility indicators for both Luatele and Lata flows, except for remaining P and resin extractable P on the Lata flow (Table 8). Other regressions showed statistically significant relationship against elevation, mainly on the Luatele flow (Table 9). While the rainfall records for Ta'ū are poor, rainfall clearly and substantially increases with elevation, and these changes in bulk soil properties are associated with the increased rainfall. Though most of the Lata flow analysis showed no significant differences against elevation, the older Ta'ū flows receive higher rainfall and therefore influences change in soil fertility properties.

The younger Ta'ū flows which receive less rainfall clearly showed statistically significant relationship with almost all soil fertility properties. At a given elevation, there was also a declining trend in soil properties as one went from west to east. With consistent easterly trade winds throughout the year, it can be assumed that the more easterly slopes of the mountain receive more rainfall. Presumably, the rainfall differences from east to west across the site are strong enough to drive measurable differences in the soil properties. These differences were noticeable in the soil sampling, with stronger aggregation and lower clay content occurring in the western portion of the study site. Therefore, rainfall increases and soil fertility declines both from west to east, and from low elevation to high elevation.

Soil Domains on Ta'ū

Segmented regression of soil properties and elemental concentrations was conducted (table 10) to gain insights into the locations of the soil domains as proposed by Vitousek & Chadwick (2013). For Lata flows, breakpoints clustered at ~200 m elevation (Resin Extractable P, Nb and P), and ~400 m (Exchangeable Ca, base saturation, ECEC and Ca). Above 400 m, breakpoints were determined for organic matter-LOI (~500 m) and soil pH (~600 m). Between 200-400 m, P remaining and CEC breakpoints occurred (~300). The visual patterns of soil properties and elemental concentrations suggest that Lata flows exhibit similar soil domains to the Hawi series soils in Kohala, Hawai'i. The three soil domains described for Kohala are of pedogenic carbonate (<750 mm/y), active weathering and uplift (750-2200 mm/y), and iron enrichment (>2200 mm/y) and characterized by multiple shifts in soil properties. However, in the domain of iron enrichment, most soil properties (e.g., base saturation, pH, resin exchangeable P) have reached very low levels and stabilized. Our data set demonstrates falling values of these properties at lower elevations, and low, stabilized levels at higher elevations, suggesting that the transition between the active weathering domain and iron enrichment domain is observed. However, the sparse sampling on the Lata flow series makes statistically defining the breakpoint difficult.

It is possible that in the extreme wetness we are observing a different set of domains and soil functions, but the increasing concentrations of metals (Al and Fe; Appendix, table 1) suggest that high mobilization of Fe is not occurring, a characteristic trait of the next domain observed in Hawai'i or alternatively, the fact that Ta'ū site is extremely wetter that there are no more "threshold domains" as defined by Vitousek and Chadwick (2013).

For Luatele soils, breakpoints clustered around 200-300 m elevation (~200 m: exchangeable Ca, base saturation, soil pH, ECEC and Ca, while the rest of the soil properties breakpoints determined at 300 m, except resin extractable P which had no breakpoint). The consistently declining values for most of the soil properties would suggest that the soils are situated entirely within the active weathering and uplift domain, with the low fertility zone of iron enrichment not obtained.

In both the Lata and Luatele cases, the soils appear to be behaving as if they are drier than we would expect. In the Hawi soils (150 ky), the transition between the uplift and the iron enrichment domain occurs at 2200 mm/y rainfall. Yet on the Lata flows, this transition appears to occur at ~5,500 mm/y rainfall (based on a rudimentary rainfall map produced by the Samoa National Park). Even accounting for the age difference in the soils, we expected that the extreme wetness of Ta'ū would create a system of high weathering and leaching, potentially even with anaerobic subsurface conditions that would lead to high mobilization and loss of elements and increased acidity. Yet, the soils remain largely fertile.

Remnant Crops

Fau (*Hibiscus tiliaceus*) is commonly known as sea hibiscus and recorded as the most common tree or shrub along all transects (Table 11). Native to coastal areas and invasive, its domination of the project area could suggest that people have been moving and planting Fau on higher grounds.

In addition to Fau being commonly found, Ti (*Cordyline fruticosa*), Noni (*Morinda citrifolia*), Ulu (*Artocarpus altilis*) and Niu (*Cocos nucifera*) were observed and recorded throughout the project area along the transects except for Niu on the upper horizontal transect (Fig. 7). Ti, an important plant that Samoan people grow around their houses as either allocating boundaries and medicinal purposes along with Noni, were commonly found in the eastern region on the study site. Ulu is a staple tree crop in Samoa and throughout the Pacific, likewise Niu widely known as the tree of life as all its parts can be used for multiple purposes, were reported commonly at the lower horizontal transect.

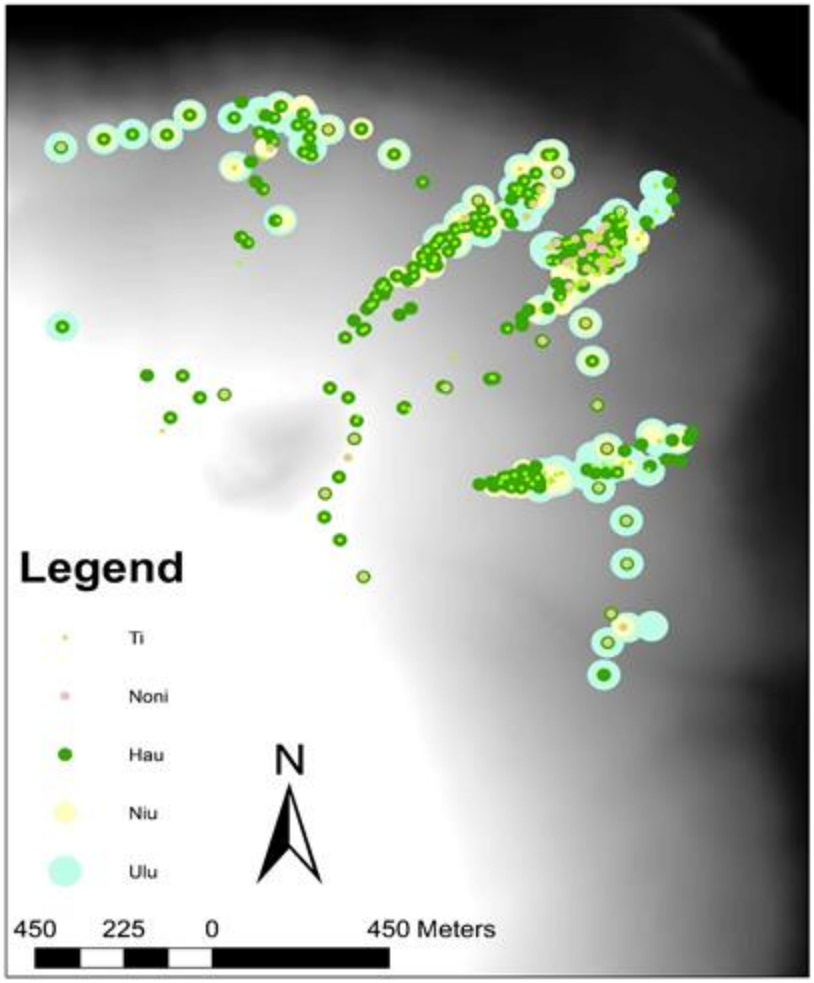

Figure 7: Map showing the distribution of five main plants along all transects.

All five crops/plants occur more on the lower horizontal transect, as well on the eastern and central region of the vertical transect which is suggested influenced by rainfall. Since wind and rainfall come from the north eastern direction, it is suggested that the influence of more rain on that particular side, gives more opportunity for these common plants to survive. It also correlates with the recorded terraces and stone walls, which were more common towards the central and eastern side of the project area. This perhaps would suggest human interaction with the land because not only were these crops found more commonly along these archaeological structures, but majority are agricultural crops which could have been established there for consumption. The extent of these plants everywhere on the project site suggests farmable lands despite declining fertility at higher elevation (as identified from our soil data).

The distribution and high occurrence of Ulu and Niu along the lower horizontal transect, correlates with the soil fertility results, and supports the high fertility at the lower younger Luatele flow. The strong partitioning of the trees into the lower elevations and the increased occurrence of all crops as one moves east were clear patterns. Denser plantings occurred in the lower elevations are expected, both because it is closer to the more densely inhabited shoreline and because, as mentioned, the soils are more fertile. However, Noni and Ti found at the upper transect, along with a single Ulu tree recorded, suggest farmable areas on higher elevation, which supports marginal fertility observed with the understanding that the older Lata flows are young Andisols compared to Kohala.

Other important crops are the fruit trees and others that provide food for consumption and other uses. These include the Tahitian chestnut or Ifi (*Inocarpus fagifer*), found along the wetter side of the vertical transect (east and central). Ifi is a legume tree with edible fruits which has been reported introduced into Samoa (Whistler, 2015). Along the west and central vertical transect, Koko (*Theobroma cacao*), Mago (*Mangifera indica*) and Ofe (*Bambusoideae*) were recorded. These trees were found on the drier side of the transect. The upper horizontal transect found Moso’oi (*Cananga odorata*). On the lower and upper transect also, Red bead tree or Lopā (*Adenanthera pavonina*) were recorded. Other trees present are good for building traditional Samoan houses such as Poumuli (*Flueggea flexuosa*).

7.0 Conclusion

In conclusion, soil fertility indicators reported by Vitousek et al., (2014) in general, aligned well with the study area except for exchangeable Ca. The lower Luatele flows indicated fertile soils with values falling above the fertility threshold. The Lata flows suggest soils with marginal fertility with the understanding that the Lata flows are still fairly young soils compared to the older substrates of Kohala and Kona of the Hawaiian Islands. Niobium was the best indicator in identifying the boundaries between the older Lata flows and the younger Luatele flows. The extreme rainfall would create a system of high weathering and leaching, with increased acidity, yet the soils remain largely fertile. Through mapping and quantifying the extent and intensity of the agricultural infrastructure, the survey supported the fertility of the younger Luatele flow. The occurrence of economic crops such as Ulu, Niu, Ti and Noni dominating at the lower Luatele flow supports this fertility. Thus, suggests a positive relationship between soil fertility and the agricultural infrastructure. Overall, Ta'ū soils are largely fertile and the occurrence of economic crops suggest people have lived and farmed in these historical sites.

8.0 Limitation

There was no rainfall data available for the study area. The rainfall data could have identified rainfall thresholds or breakpoints to compare with previous studies and define the relationship with soil properties clearly. There were also not enough soil samples collected from the horizontal transects of the older Lata flows, to really extend these transects. This could better identify the differences between the soil properties of the younger and older soils and clearly identify the boundaries between the flows.

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10.0 Appendix

Table 1: Summary statistics of total elemental concentrations, ammonium, exchangeable base cations and organic carbon.

Soil property	Transect	Flow	Mean	Std Err
Al (mg/kg)	Lower	Lata	29748	1584.132
		Luatele	27258	821.0127
	Upper	Lata	33827	2241.977
		Luatele	32184	920.6513
Mn (mg/kg)	Lower	Lata	795.0	41.8739
		Luatele	670.7	15.87434
	Upper	Lata	839.9	29.83196
		Luatele	599.7	58.85449
S (mg/kg)	Lower	Lata	658.5	60.26397
		Luatele	745.3	16.30204
	Upper	Lata	613.6	134.608
		Luatele	885.6	26.49341
B (mg/kg)	Lower	Lata	45.00	2.538825
		Luatele	2.652	0.3477693
	Upper	Lata	31.97	15.73422
		Luatele	2.732	0.2684211

Na (mg/kg)	Lower	Lata	80.475	23.28385
		Luatele	104.00	9.800304
	Upper	Lata	92.66	18.18746
		Luatele	85.19	6.237894
Mg (mg/kg)	Lower	Lata	10016	369.5873
		Luatele	12401	332.6608
	Upper	Lata	7454	1330.582
		Luatele	7899	622.0247
Fe (mg/kg)	Lower	Lata	42941	2974.037
		Luatele	38147	1185.377
	Upper	Lata	50982	4824.988
		Luatele	48960	1238.531
K (mg/kg)	Lower	Lata	157.634	15.31256
		Luatele	94.62	28.27128
	Upper	Lata	190.4	22.81428
		Luatele	107.93	11.82406
NH4-N (mg/L)	Lower	Lata	242.6	16.12358
		Luatele	256.9696	8.579515
	Upper	Lata	275.3	36.93554

		Luatele	219.6	6.478414
Exchangeable K ($cmol_c$/kg)	Lower	Lata	0.126	0.05334791
		Luatele	0.1274	0.01849279
	Upper	Lata	0.2333	0.0779601
		Luatele	0.1211	0.008125289
Exchangeable Mg ($cmol_c$/kg)	Lower	Lata	4.468	0.5057213
		Luatele	3.938	0.1983137
	Upper	Lata	3.760	0.6735231
		Luatele	2.029	0.1996238
Exchangeable Na ($cmol_c$/kg)	Lower	Lata	0.208	0.05471746
		Luatele	0.09826	0.009485837
	Upper	Lata	0.1667	0.03711843
		Luatele	0.1042	0.007145759
OC (%)	Lower	Lata	21.77	0.6240112
		Luatele	22.45	0.4689011
	Upper	Lata	23.03667	2.42677
		Luatele	26.44	0.3522759

Table 2: ANOVA comparison of the lower and upper transects by flows of total elemental concentrations, ammonium and exchangeable base cations.

Soil property	Transect	R-squared	P-value
Al (mg/kg)	Lower	0.0611	0.2046
	Upper	0.0214	0.5161
Mn (mg/kg)	Lower	0.2806	0.0037**
	Upper	0.1116	0.1287
S (mg/kg)	Lower	0.1301	0.0594
	Upper	0.3546	0.0035**
B (mg/kg)	Lower	0.9748	<2.0e-16***
	Upper	0.5946	2.664e-05***
Na (mg/kg)	Lower	0.0195	0.506
	Upper	0.0070	0.7185
Mg (mg/kg)	Lower	0.2845	0.0035**
	Upper	0.0036	0.7918
Fe (mg/kg)	Lower	0.0961	0.1084
	Upper	0.0157	0.5786
K (mg/kg)	Lower	0.0447	0.3211
	Upper	0.2753	0.0176*
NH4-N (mg/L)	Lower	0.0196	0.4769
	Upper	0.2627	0.0147*

Exchangeable K (cmol$_c$/kg)	Lower	3.4571e-05	0.9763
	Upper	0.3562	0.0034***
Exchangeable Mg (cmol$_c$/kg)	Lower	0.0440	0.2838
	Upper	0.3220	0.0059**
Exchangeable Na (cmol$_c$/kg)	Lower	0.3194	0.0017
	Upper	0.2820	0.011*

*Statistically significant at $p<0.05$

Table 3: ANOVA analysis in distinguishing the Lata and Luatele flows by the horizontal transects of total elemental concentrations, ammonium and exchangeable base cations.

Soil property	**Flow**	**R-squared**	**P-value**
Al (mg/kg)	Lata	0.2796	0.1778
	Luatele	0.2858	0.0003***
Mn (mg/kg)	Lata	0.0854	0.4824
	Luatele	0.0385	0.2131
S (mg/kg)	Lata	0.0204	0.7357
	Luatele	0.3533	3.136e-05***
B (mg/kg)	Lata	0.1647	0.3184
	Luatele	0.0076	0.8621
Na (mg/kg)	Lata	0.0385	0.8037
	Luatele	0.0561	0.1309

Mg (mg/kg)	Lata	0.4796	0.0569
	Luatele	0.5283	5.028e-08***
Fe (mg/kg)	Lata	0.2769	0.1803
	Luatele	0.4961	1.936e-07***
K (mg/kg)	Lata	0.2045	0.2606
	Luatele	0.0042	0.706
NH4-N (mg/L)	Lata	0.1302	0.3798
	Luatele	0.2197	0.0017
Exchangeable K ($cmol_c$/kg)	Lata	0.1878	0.2834
	Luatele	0.0021	0.7715
Exchangeable Mg ($cmol_c$/kg)	Lata	0.1071	0.4288
	Luatele	0.5308	4.51e-08***
Exchangeable Na ($cmol_c$/kg)	Lata	0.0449	0.6144
	Luatele	0.0058	0.6313

*Statistically significant at p<0.05

Table 4: Linear regressions of Lata and Luatele flow against elevation of total elemental concentrations, ammonium and exchangeable base cations.

Soil property	**Flow**	**R-squared**	**P-value**
Al (mg/kg)	Lata	0.3143	0.1483

	Luatele	0.3145	0.0001***
Mn (mg/kg)	Lata	0.1580	0.3298
	Luatele	0.0250	0.3175
S (mg/kg)	Lata	0.0590	0.5621
	Luatele	0.3470	4.064e-05***
B (mg/kg)	Lata	0.1141	0.4133
	Luatele	0.0009	0.8521
Na (mg/kg)	Lata	0.1090	0.6699
	Luatele	0.0601	0.1175
Mg (mg/kg)	Lata	0.5487	0.0356*
	Luatele	0.5325	4.184e-08***
Fe (mg/kg)	Lata	0.3605	0.1155
	Luatele	0.4916	2.325e-07***
K (mg/kg)	Lata	0.1162	0.4085
	Luatele	0.0084	0.5949
NH4-N (mg/L)	Lata	0.0754	0.5104
	Luatele	0.2051	0.0026**
Exchangeable K ($cmol_c$/kg)	Lata	0.1393	0.3624
	Luatele	0.0014	0.8171

Exchangeable Mg ($cmol_c/kg$)	Lata	0.1443	0.3533
	Luatele	0.5321	4.215e-08***
Exchangeable Na ($cmol_c/kg$)	Lata	0.0461	0.6097
	Luatele	0.0050	0.6595

*Statistically significant at p<0.05

Table 5: Segmented elevation breakpoints of total elemental concentrations, ammonium and exchangeable base cations.

Soil property	**Lata**	**Luatele**
Al (mg/kg)	311.612**	358.764***
Mn (mg/kg)	280.745	205.994
S (mg/kg)	268.996	325.096***
B (mg/kg)	355.449**	199.990
Na (mg/kg)	No breakpoint	230.000**
Mg (mg/kg)	211.663**	199.999***
Fe (mg/kg)	265.806*	325.013***
K (mg/kg)	254.042	349.503
NH4-N (mg/L)	326.577**	No breakpoint***
Exchangeable K ($cmol_c/kg$)	212.477	230.000

Exchangeable Mg ($cmol_c$/kg)	359.585***	242.658***
Exchangeable Na ($cmol_c$/kg)	475.014*	226.056

*Statistically significant at p<0.05, **Statistically significant at p<0.01, ****Statistically significant at p<0.001

Table 6: Bulk density results along the vertical and horizontal transects.

Soil ID	Description	Bulk Density (g/cm3)	Bulk Density (ave)
BD01-a		0.1658735748	
BD01-b		0.2095217799	
BD01-c	S003a	0.162248136	0.1792
BD02-a		0.3676766784	
BD02-b		0.2456982024	
BD02-c	S006a	0.294921007	0.3028
BD03-a		0.1403395698	
BD03-b		0.1843386238	
BD03-c	S010a	0.1680826236	0.1642
BD04-a		0.1053846214	
BD04-b		0.1117518796	
BD04-c	S014-Sa	0.1561927434	0.1245
BD05-a		0.1439780031	
BD05-b		0.1999708925	
BD05-c	S019-Sa	0.1537238065	0.1659
BD10-a		0.188938643	
BD10-b		0.2178511933	
BD10-c	S224 (Hor-West-Low)	0.167965674	0.1913
BD11-a		0.2231659048	
BD11-b	S228 (Hor-East-Low)	0.1334525353	0.1795

BD11-c		0.1817527373	
BD21-a		0.2498824006	
BD21-b		0.2229320055	
BD21-c	S230 (Hor-East-High)	0.1680436404	0.2136
BD21-a		0.1125315439	
BD21-b		0.08563312638	
BD21-c	S227 (Hor-West-High)	0.155023247	0.1177

Table 7: Ta'ū soil results obtained from the NRCS website.

Soil Series	**Taxonomic Class**	**Depth (cm)**	**PSDA & Rock Fragments**			**Bulk Density & Moisture**		**Carbon & Extractions**			**CEC & Bases**	**pH & Carbonates**
			Clay	**Silt**	**Sand**	**Water Content (kPa)**	**Air Dry-Oven Dry (Ratio)**	**OC(WB)**	**C/N Ratio**	**Al+1/2Fe (%)**	**CEC8 (Sum Cats)**	**pH (H2O)**
Sogi	Medial over ashy, amorphic, isohyperthermic Eutric Hapludands	0-25	16.9	32.5	50.6	29.6	1.105	4.29	10	5.06	73.4	6.2
		25-53	11	28.5	60.5	26.9	1.084	2.34	11	5.55	57.8	6.4
		53-66	0.4	18.5	81.1	7.6	1.023	0.43	-	3.02	22.7	6.6
		66-102	-	5	95	11.5	1.036	0.34	-	2.51	33.5	6.7
Iliili	Medial-skeletal, amorphic, isohyperthermic Lithic Hapludands	0-3	19.1	47.4	33.5	59.9	1.126	20.8	12	5.01	103.6	-
		0-13	-	48.1	51.9	37.5	1.091	8.53	9	5.67	58.6	6

		13-23	-	44.6	55.4	29.7	1.091	6.9	10	6.35	54.4	6.2
Pavaiai	Medial-skeletal, amorphic, isohypertermic Eutric Fulvudands	0-18	17.1	54.7	28.2	38.6	1.109	7.54	10	4.36	65.3	6
		18-30	9.6	54.2	36.2	35.7	1.115	5.95	11	5.92	67.7	6.1
		30-66	-	24.3	75.7	30	1.132	3.97	-	4.71	52.8	6.2
		66-97	-	29.1	70.9	30.2	1.143	3.51	-	7.54	54.1	6.2
Leafu	Fine, halloysitic, isohyperthermic Cumulic Hapludolls	0-10	19.8	55.8	24.4	23.8	1.052	2.44	13	2.03	39.8	6.3
		10-32	22.3	63.3	14.4	25.6	1.062	1.81	12	1.67	39.7	6.3
		32-48	13	49.3	37.7	24.3	1.065	1	11	2.09	43.1	6.3
		48-92	23.4	53.9	22.7	25.7	1.069	1.58	-	2.13	46.8	6.3
		92-112	25.2	59.9	14.9	24.7	1.068	2.13	-	2.15	55.5	6.4
		112-153	29.2	62.9	7.9	27.1	1.069	0.9	-	2.08	50	6.2
Fagasa	Fine, halloysitic, isohyperthermic Andic Hapludolls	0-13	35.6	49.9	14.5	26.4	1.053	4.37	11	1.78	43.3	5.8
		13-30	38.5	45.9	15.6	24.2	1.052	2.59	10	1.74	37.3	5.8
		30-73	34	35.9	30.1	24.4	1.057	1.47	-	1.64	32	5.9
Ofu	Very-fine, ferruginous, isohyperthermic Typic Acroperox	0-41	56.3	34	9.7	26.6	1.028	2.61	10	-	29.5	5.8
		41-79	27	23.4	49.6	26.8	1.025	0.83	11	-	15.6	6.2
		79-114	26.9	28.8	44.3	25.5	1.024	0.39	-	-	13.2	6.3

		114-140	19.8	33	47.2	24.8	1.023	0.19	-	-	12.5	6.2
Olotania	Medial, amorphic, isohyperthermic Hydric Hapludands	0-20	33.8	57.6	8.6	126.3 (Prep-M)	2.320 (Prep-M)	10.23	13	-	86.3	5.4
		20-64	15.7	53.5	30.8	88.1 (Prep-M)	2.210 (Prep-M)	2.49	11	-	39.2	6.3
		64-152	24.2	48.2	27.6	76.3 (Prep-M)	2.060 (Prep-M)	0.85	-	-	35.5	6.7

(NRCS, 1981)